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A Framework for Assessing Hydrochars from Hydrothermal Carbonisation of Agrowaste with the Use of MCDA: Application with the Hierarchical SMAA-PROMETHEE Method

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Abstract: Large amounts of hydrochar have been produced during the last decade by various hydrothermal carbonisation (HTC) processes. While the products of HTC seem to have widespread acceptance as valuable and efficient materials with advantages in their energy and environmental applications, which include soil improvement, heavy metal recovery, and many more, a comprehensive framework for the assessment of the different hydrochars based on their characteristics is missing. In this study, a framework for the assessment of hydrochars is proposed with the utilisation of Multi-Criteria Decision-Aiding (MCDA) methodologies. A hierarchical structure of independent criteria is established on a comprehensive level including three lines of evidence (LoE), i.e., Environmental, Economic, and Social LoE, which further include the assessment criteria. Hierarchical-SMAA-PROMETHEE is proposed as the most suitable MCDA methodology to be applied for assessing hydrochars based on the proposed framework. A case study is performed to demonstrate the utility of the framework and the advantages it offers to analysts and decision-makers. Hierarchical-SMAA-PROMETHEE is a non-compensatory method that enables exploring the decision problem on more than one level (comprehensive vs. LoE) and includes robust recommendations on the preference model and the elicitation of weights.

Keywords: hydrothermal carbonisation; hydrochar; waste-to-energy; MCDA; SMAA; PROMETHEE; hierarchical assessment

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1. Introduction

Biomass valorisation and utilisation via thermal and biological processes is considered a renewable energy source that can largely contribute to the achievement of the environmental and energy aims of the EU. We may consider the biodegradable fraction of products, waste, and residues of biological origin from agriculture, stock farming, forestry, and other related industries, as well as from industrial and municipal solid waste, as biomass [1]. Various processes, either thermal or biological, may be utilised for the valorisation of biomass, including incineration, pyrolysis, gasification, carbonisation, anaerobic digestion, and composting, among others. Each process may differ in various terms, such as the raw materials that can be used, the suitability of raw materials for use based on the scale of the facility (e.g., laboratory- or industrial-scale), the types of products and residues, and the conditions of treatment of the residues. Despite the differences between the various processes, the major topics of recent research are related to the analysis and assessment of their products, considering the possible uses of the residues and their valorisation based on ecotoxicological, biological, and physicochemical characteristics, as well as economic, ethical, and social aspects [2,3].

Hydrothermal carbonisation (HTC) is a process by which organic materials, such as agrowaste, are converted into a solid, carbon-rich material via exposure to high pressure and temperature conditions. The resulting material is known as hydrochar. Recent research has focused on the analysis of hydrochar types and typically involves a number of techniques to determine their physical and chemical properties. These can include measurements of hydrochar's carbon content, pH, ash content, and moisture content, as well as more detailed characterisation of its chemical composition using techniques such as gas chromatography, Fourier transform infrared spectroscopy, and nuclear magnetic resonance spectroscopy. The results of these analyses may provide insight into the potential uses and applications of hydrochar, as well as information about the efficiency and effectiveness of the HTC process.

The recent literature is focused mostly on the analysis of hydrochars using material characterisation, the assessment of their physicochemical properties for environmental applications, and reviews of possible energy and biorefinery applications of these promising products, which can be used as fuels, soil amendments, compost, and more [4]. Nevertheless, a holistic analysis of hydrochars should take into consideration not only the physicochemical properties of hydrochars, but also other environmental aspects together with the assessment of possible economic and social aspects. A holistic assessment may support the evaluation of the sustainability of such products and assist researchers and policymakers in further understanding the products of HTC in connection with sustainable development and circular economy perspectives. In this study, we focus on the development of a framework that can be utilised for the assessment of hydrochars by taking into consideration all the aforementioned properties with the use of Multi-Criteria Decision Aiding (MCDA; [5]). In the next sections, we first describe the need and motivation for the developed framework and then analyse the multiple relevant criteria that were selected (Section 2.1). We propose a MCDA methodology based on hierarchical SMAA-PROMETHEE (Section 2.2) and present a case study that demonstrates the suitability and usefulness of the methodology (Section 3). Finally, we discuss the results, draw conclusions, and identify possible future research in Section 4.

2. Materials and Methods

2.1. Hydrochar Assessment and the State-of-the-Art

The specific criteria that are relevant for the creation of a MCDA framework for the holistic assessment of hydrochar produced by HTC depend on the specific decision problem and the context in which the assessment is being conducted. However, potential criteria that could be considered in this context include:

- Technical performance: The technical performance of hydrochar in different applications could be evaluated by examining its physical and chemical properties, such as its moisture content, ash content, and pH, as well as its performance in laboratory or field tests.
- Economic feasibility: The economic feasibility of hydrochar production and use could be assessed by comparing the costs and benefits of different hydrochar applications, such as its use as a soil amendment or fuel source.
- Environmental impacts: The environmental impacts of hydrochar production and use, such as greenhouse gas emissions, water use, and land use, could be evaluated using a life cycle assessment or other environmental impact assessment methods.
- Social and regulatory factors: The social and regulatory factors associated with hydrochar production and use, such as potential public acceptance, safety concerns, and legal requirements, could also be considered in the MCDA framework.

A literature search was performed to identify the state-of-the-art on the assessment of hydrochars (and biochars, as closely related products) during the last decades, during which the production of chars has increased significantly. The biggest fraction of the scientific literature is concerned with the description of the various methodologies for the production of hydrochars from many different types of raw materials, followed by studies on the physicochemical properties of hydrochars. However, there is an extremely low number of studies that evaluate the socio-economic aspects of hydrochar (or biochar more broadly) production and the feasibility of using different products for different purposes.

The most common properties of hydrochars and their production methods that are reported in the literature are the following: temperature (°C), residence time (h), pH, ash content (%), yield (%), elemental composition (e.g., C, N, H, O, S), Volatile Matter (VM—%), Fixed Carbon (FC—%), electrical conductivity, H/C and O/C atomic ratios, heating value, surface area (SSA), particle size distributions, density, porosity, biomass/water ratios, water holding capacity, Cation Exchange Capacity (CEC), the presence of metals (e.g., Ag, Cu, Pb, Zn, Cd, Fe, Mn), and morphological features [6–14]. It is evident that depending on the hydrochar type and production method used, an assessment and comparison of different products could be performed based on their physicochemical characteristics only. Nevertheless, a product that could be acceptable from the environmental point of view does not necessarily ensure the economic viability of the process or social acceptability by the public.

Limited research has been performed on the techno-economic assessment of hydrochars and hydrochar production, as in many cases, HTC has not been scaled up for industrial-scale production yet. The most important identified properties are related to the feedstock prices (EUR/tonne) that may highly influence the HTC process and the hydrochar prices (EUR/tonne) as the final product [7]. In addition, feedstock availability and local/global energy needs for HTC could be taken into consideration [14]. On the other hand, even less research has been performed on the assessment of the social aspects of hydrochar/biochar production, which requires a significant effort to analyse the perception of the public on difficult technical issues and it is usually a quite subjective and qualitative assessment. Despite the challenges, a complete assessment could estimate and take into consideration the following social aspects: the public perception of the usefulness of HTC, the social acceptance of the hydrochars as products, the creation of new jobs in the area where a HTC facility could be established, and the possible odour created by HTC processes [13].

The literature review has shown that no assessment framework has been developed, presented, or utilised so far in the scientific literature that would allow an analyst/decision-maker to assess hydrochars (or other similar products) based on multiple criteria, not only on a comprehensive level but also in terms of various lines of evidence (LoE—e.g., Physicochemical Characterisation, Economic, Social, Ethical, Sustainability). In this view, within this study, a flexible and robust framework is proposed for the assessment of hydrochars from agrowaste. The framework is organised in one comprehensive level (overall assessment of hydrochars) and three LoE (i.e., Environmental, Economic, Social), which are considered the most relevant for the performed analysis. Based on the review, distinct criteria were identified for each LoE. The most representative criteria for each LoE are organised hierarchically and are presented in Table 1. The framework is considered flexible and modular, as an analyst may decide to utilise additional LoE and additional criteria based on the availability of data and the HTC products under analysis. It is important to note that the criteria should be independent and no interactions between them should be considered, to make them eligible to be utilised with the proposed methodology.

2.2. MCDA Methodology

MCDA is a well-known sector of Operational Research, which allows the systematic assessment of various types of problems, such as choice, ranking, and sorting of alternatives [15]. The assessment of hydrochars is considered a typical ranking problem, in which hydrochars could be ranked from the best to the worst. In this study, we are interested not only in the overall ranking of hydrochars based on all the identified criteria (comprehensive level) but also on the ranking of hydrochars for each LoE (partial levels) that will allow the analyst to extract useful information for the specific decision problem and context.

Table 1. Lines of Evidence and selected criteria for the assessment framework.

Comprehensive Level		
Environmental (LoE1)	**Economic (LoE2)**	**Social (LoE3)**
pH	Feedstock price/tonne	Public perception
Yield	Hydrochar price/tonne	Social acceptance
Ash	Feedstock availability	New jobs
Volatile Matter (VM)	Production energy need	Odour
Fixed Carbon (FC)		
Temperature		
Density		
Porosity		
Cation Exchange Capacity (CEC)		
PT value		

The choice of a suitable MCDA methodology can be a demanding and complex problem by itself, as each methodology has specific characteristics and may be tailored to fit the specific type of criteria and specific types of problems and can be influenced by the preference model and the way the preferences of the analyst/decision-maker are taken into consideration [16,17]. Complex environmental problems are usually tackled with the utilisation of methodologies that can handle hierarchical criteria, as those can provide additional information for intermediate levels that are very useful for analysts. In addition, non-compensatory approaches (e.g., outranking methods) are greatly preferred as they allow aggregations in which compensation between criteria is not permitted. Based on these considerations, hierarchical-outranking methodologies have been considered the most suitable for the assessed problem. Recent developments in the field have proposed the extension of hierarchical-outranking methodologies with the use of the Stochastic Multicriteria Acceptability Analysis (SMAA), a methodology that allows for the elicitation of vectors of weights for the criteria instead of a single vector of weights, thus increasing the robustness of the methodology [18].

In this view, the proposed methodology for utilising the framework of our study is the hierarchical-SMAA-PROMETHEE method, which satisfies all the basic requirements of the decision problem. Each of the individual methods (Multiple Criteria Hierarchy Process—MCHP, SMAA, and PROMETHEE) is presented in detail in the scientific literature; therefore, we advise readers to consult relevant papers for each methodology (MCHP—[19], SMAA—[20], PROMETHEE—[21], SMAA-PROMETHEE—[22], and hierarchical-SMAA-PROMETHEE—[18,23]).

Validation with MCDA-MSS

To ensure that the choice of the MCDA methodology is suitable for the decision problem we consulted and validated the choice with the use of the MCDA Methods Selection Software (MCDA-MSS, available at http://mcdamss.com (accessed on 10 November 2023)) [16,17].

The MCDA-MSS is a comprehensive tool that allows the selection of the most suitable MCDA methodologies from a pool of 205 methodologies based on 156 characteristics, which are implemented using simple questions that the user may answer, according to the knowledge available on the decision-making challenge at hand. The questions are split into four main categories: (i) problem typology, (ii) preference model, (iii) elicitation of preferences, and (iv) exploitation of the preference relation induced by the preference model. The MCDA-MSS has a user-friendly web interface. The analyst is free to answer the questions that they are comfortable with (i.e., there are no forced choices). Each time one answer is provided, the suitable methods are automatically updated in the second part of the software. This real-time update of the recommendation allows the user to clearly understand the implications of each choice.

For our decision problem, the following characteristics were selected:

- Problem statement: Ranking;
- Order of alternatives: Partial and Complete;
- Criteria structure: Hierarchical;
- Compensation between criteria: Null;
- Type of preference elicitation: Direct.

The MCDA-MSS provided the following three methodologies for the decision problem (in alphabetical order): (i) ELECTRE III-H, (ii) GAIA-SMAA-PROMETHEE-INT, and (iii) MCHP-PROMETHEE, which validates the selection of the hierarchical-SMAA-PROMETHEE methodology for the type of decision problem. We note that in the MCDA-MSS, the hierarchical-SMAA-PROMETHEE is categorised as GAIA-SMAA-PROMETHEE-INT [23]; thus, it is the same methodology, despite the different notation.

3. Case Study—Results

For the demonstration of the utility and value of the proposed framework, a case study was prepared and performed. The assessment of six hydrochars samples was performed with the use of the hierarchical-SMAA-PROMETHEE method on a comprehensive level, as well as on the Environmental and Economic LoE. Due to data limitations, the Social LoE was not taken into consideration since the assessment would require surveys with the public and stakeholders, while the data can be highly area-dependent. In addition, social data would be mostly relevant when the production of hydrochar is scaled up to the industrial level and becomes commercial. Nevertheless, it would be a very important part of any assessment once data become available. The lack of data for the Social LoE does not influence the reliability and validity of the case study, as the framework is modular and allows for the addition or removal of LoE. Taking into consideration the availability of data, eight (8) criteria were selected as representative and used for the comprehensive level, namely, four (4) for each LoE, as presented in Table 2 along with their units of measure.

Table 2. Lines of Evidence and Criteria.

Environmental	Economic
Volatile Matter (VM) (%)	Feedstock price/tonne (EUR/ton)
Yield (%)	Hydrochar price/tonne (EUR/ton)
N (%)	Feedstock availability (qualit.)
Fixed Carbon (FC) (%)	Production energy need (qualit.)

The complete evaluation matrix is presented in Table 3, including the preference and indifference thresholds for each criterion and information on the preference direction of each criterion (minimise vs. maximise). The evaluations of criteria were collected from the scientific literature and complemented with expert elicitation on the estimation of the criteria performance for the qualitative criteria E3 and E4.

For the decision problem at hand, two weight constraints for the LoE are identified, since the Environmental LoE is considered more important than the Economic LoE, while at the same time, the weight of one LoE cannot be equal or very close to 1. They are expressed as follows: WENV > WECON and WENV1 $\leq$ 0.7, and the calculated weighted ranges based on the constraints are presented in Table 4. With the application of the hierarchical-SMAA-PROMETHEE II methodology, we can obtain the Rank Acceptability Indices of all hydrochar samples at comprehensive and partial levels based on the selected criteria and their evaluations. In Tables 5–7, the Rank Acceptability Indices are presented at the comprehensive level, as well as at the levels of the two considered LoE, according to the provided preference information. Following the calculations of the rank acceptability indices, the Pairwise Winning Indices were also calculated and are presented in Tables 8–10 for the comprehensive and partial levels, Environmental and Economic, respectively.

Table 3. Evaluation matrix.

Comprehensive Level									
Categ./LoE	**Environmental (LoE1)**				**Economic (LoE2)**				
Criterion number	PC1	PC2	PC3	PC4	E1	E2	E3	E4	
Criteria	VM	Yield	N	FC	feedstock price/tonne	hydrochar price/tonne	feedstock availability	production energy need	
Unit	%	%	%	%	EUR/ton	EUR/ton	qualit.	qualit.	
Min/max	Min	Max	Max	Max	Min	Max	Max	Min	
Sample									**Ref.**
Wheat straw	70	65	0.4	25.5	230	225	4	3	[4,9,24,25]
Rice husk	52.5	58	0.9	35	275	210	3	2	[4,24–26]
Pine wood	74	65	0.19	23	400	175	2	3	[4,24,25,27]
Poplar wood	66	68.5	0.28	24	305	180	3	4	[4,24,25]
Sewage sludge	53	73	4	0,2	14	200	5	5	[4,24,25,28]
Digested sewage sludge	47	63	7	4.5	45	190	4	4	[4,24,25,29]
Prefer. threshold	10	10	2	5	40	40	1	1	
Indiff. threshold	5	5	0.2	2	10	10	0.5	0.5	

Table 4. Weight ranges.

Categ./LoE	**Environmental (LoE1)**				**Economic (LoE2)**			
Min weight	0.5001				0.3000			
Mean weight	0.6261				0.3739			
Max weight	0.7000				0.4999			
Criterion number	**PC1**	**PC2**	**PC3**	**PC4**	**E1**	**E2**	**E3**	**E4**
Criteria	VM	Yield	N	FC	feedstock price/tonne	hydrochar price/tonne	feedstock availability	production energy need
Min weight	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Mean weight	0.1630	0.1643	0.1501	0.1486	0.0919	0.0912	0.0923	0.0986
Max weight	0.6552	0.6622	0.6601	0.6517	0.4262	0.4240	0.4453	0.4152

Table 5. Rank Acceptability Indices—Global.

Sample	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**
Wheat straw	1.627	27.961	23.13	47.282	0	0
Rice husk	39.698	8.786	30.63	15.923	4.666	0.297
Pine wood	0	0	3.243	3.579	12.631	80.547
Poplar wood	0	0	3.443	11.043	73.858	11.656
Sewage sludge	43.728	19.099	20.475	8.885	2.861	4.952
Digested sewage sludge	14.947	44.154	19.079	13.288	5.984	2.548

Table 6. Rank Acceptability Indices—Environmental.

Sample	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**
Wheat straw	0	2.258	15.391	16.103	66.248	0
Rice husk	36,973	8.924	36.133	6.52	2.783	8.667
Pine wood	0	0	0.001	14.237	13.771	71.991

Table 6. *Cont.*

Sample	#1	#2	#3	#4	#5	#6
Poplar wood	1.18	21.196	18.141	57.598	1.885	0
Sewage sludge	35.742	27.319	19.559	1.596	5.19	10.594
Digested sewage sludge	26.105	40.303	10.775	3.946	10.123	8.748

Table 7. Rank Acceptability Indices—Economic.

Sample	#1	#2	#3	#4	#5	#6
Wheat straw	46.395	39.751	13.854	0	0	0
Rice husk	18.365	25.649	10.447	45.539	0	0
Pine wood	0	0	11.577	3.635	19.645	65.143
Poplar wood	0	0	0	0	72.917	27.083
Sewage sludge	35.151	20.46	16.835	12.386	7.394	7.774
Digested sewage sludge	0.089	14.14	47.287	38.44	0.044	0

Table 8. Pairwise Winning Indices—Global.

Sample	Wheat Straw	Rice Husk	Pine Wood	Poplar Wood	Sewage Sludge	Digested Sewage Sludge
Wheat straw	0	25.904	100	100	24.834	33.195
Rice husk	74.096	0	99.703	94.787	43.454	49.996
Pine wood	0	0.297	0	15.712	7.27	6.239
Poplar wood	0	5.213	84.288	0	7.393	9.379
Sewage sludge	75.166	56.546	92.73	92.607	0	60.043
Digested sewage sludge	66.805	50.004	93.761	90.621	39.957	0

Table 9. Pairwise Winning Indices—Environmental.

Sample	Wheat Straw	Rice Husk	Pine Wood	Poplar Wood	Sewage Sludge	Digested Sewage Sludge
Wheat straw	0	11.846	100	4.906	16.576	20.331
Rice husk	88.154	0	89.992	79.744	42.469	44.424
Pine wood	0	10.008	0	0	14.441	17.799
Poplar wood	95.094	20.256	100	0	19.663	27.175
Sewage sludge	83.424	57.531	85.559	80.337	0	48.194
Digested sewage sludge	79.669	55.576	82.201	72.825	51.806	0

Table 10. Pairwise Winning Indices—Economic.

Sample	Wheat Straw	Rice Husk	Pine Wood	Poplar Wood	Sewage Sludge	Digested Sewage Sludge
Wheat straw	0	81.635	100	100	64.8	86.106
Rice husk	18.365	0	100	100	44.107	54.368
Pine wood	0	0	0	34.857	15.194	11.595
Poplar wood	0	0	65.143	0	7.774	0
Sewage sludge	35.2	55.893	84.806	92.226	0	72.141
Digested sewage sludge	13.894	45.632	88.405	100	27.859	0

Based on the Rank Acceptability Indices in Tables 4–6, and the Pairwise Winning Indices in Tables 7–9, we may extract very valuable information for the evaluated hydrochar samples.

- Comprehensive level: We observe that two hydrochars are most likely to be ranked in the first two places, namely, 'sewage sludge' and 'rice husk' with 43.728% and 39.698%, respectively, while 'pine wood' and 'poplar wood' have no chance of being ranked 1st or 2nd. The indices provide us with the frequencies with which an alternative obtains a certain rank position, which can provide additional information to an analyst about the possible ranking of an alternative in comparison with a final ranking without intermediate information. In this view, we can observe that 'sewage sludge' can be ranked in the first three positions more frequently (83.3%) followed by 'rice husk' (79.114%), while 'digested sewage sludge' may be ranked 2nd frequently (44.154%), but this performance may be overshadowed by the frequency of 'rice husk' being ranked 1st (39.698%), and in our case study, 'digested sewage sludge' is ranked 3rd in the overall assessment (Table 11). Similarly, we observe that 'poplar wood' and 'pine wood' rank 5th and 6th with a very high frequency of ~80%, respectively, which may trigger us to check which of the criteria are influencing the ranking of these alternatives and ranks them in the last places.
- To further analyse the hydrochar samples, we may look in more detail at the pairwise comparisons. We observe that 'sewage sludge' is preferred to all the other samples with at least 56.546%, which is the probability at which it is preferred to 'rice husk', and it is highly possible that it will be ranked 1st regardless of the variations in the weights. As seen above, we may reconfirm the very fluid situation of 'rice husk' and 'digested sewage sludge' being ranked either 2nd or 3rd, as the probability of 'digested sewage sludge' being preferred to 'rice husk' is 50.004% and, vice versa, 'rice husk' is preferred with probability 49.996%, which shows that small variations in the criteria evaluations of those types of samples may easily change their overall ranking. Therefore, the analyst may consider evaluating further those two types of samples.
- Environmental: Similar to the comprehensive level, we can analyse the samples based on the indices for the Environmental LoE. We observe that in this LoE, 'rice husk' and 'Sewage sludge' can be ranked frequently in the 1st place again, but the frequencies have much smaller differences in comparison with the comprehensive level, 36.973% and 35.742%, while 'digested sewage sludge' may be ranked 1st frequently (26.105%) as well. 'Pine wood' may be ranked last also in this LoE (71.991%), while 'poplar wood' can be ranked 4th (57.598%) and 'wheat straw' can be ranked 5th (66.248%). Regarding the pairwise comparisons, we observe that 'sewage sludge' is preferred to almost all other alternatives for the Environmental LoE, as the probability is over 50% in comparison with the four alternatives and at least 48.194% for the 5th alternative.
- Economic: The results of the economic LoE clearly demonstrate the usefulness of the methodology, which allows for the assessment on partial levels in addition to the comprehensive. We observe that 'wheat straw' ranks 1st more frequently on economic performance (46.395%), followed by 'sewage sludge', which has the second highest frequency to be in the 1st place (35.151%), while 'rice husk' has high probability of ranking 4th (45.539%). In the last two places, 'poplar wood' and 'pine wood' are ranked 5th and 6th, respectively, showing that their hydrochar performance is outweighed by other types of hydrochar not only on environmental performance but also economic, and naturally on the comprehensive level as identified above. Regarding the pairwise indices, 'wheat straw' is preferred by at least 64.8% (which is the probability that is preferred over 'sewage sludge') to all other samples, 'sewage sludge' is preferred by at least 55.893% over the remaining samples, while 'rice husk' and 'digested sewage sludge' are preferred by small margins between them (54.368% vs. 45.632%). The extracted conclusions on the possible rankings of the samples and the identified stability (or instability) of the rankings are just some of the examples of how the 'Rank Acceptability Indices' and 'Pairwise Winning Indices' can be interpreted and, based on the needs of the analyst, a breadth of useful information can be extracted. This information can advise and guide the decision-making processes and allow an

in-depth analysis of the decision problem, which would not be possible without the visualisation of the proposed methodology.

Table 11. Expected rankings summary.

Sample	Global	Environmental	Economic
Sewage sludge	1	1	2
Rice husk	2	2	3
Digested sewage sludge	3	3	4
Wheat straw	4	5	1
Poplar wood	5	4	5
Pine wood	6	6	6

In the last step of the assessment, we calculate the Expected rankings summary [30], which is presented in Table 11 and summarises the 'Rank Acceptability Indices' results. The Expected rankings are estimated both for the comprehensive level and the Environmental and Economic levels. Using the expected ranking of each sample, we can confirm some of the information that was identified in the previous steps. It is noted that 'sewage sludge' is ranked 1st overall at the comprehensive level, followed by 'rice husk'. 'Poplar wood' and 'pine wood' are ranked in the last two places. In addition, useful information can be extracted for the Environmental and Economic levels, as it is clearly shown that the environmental ranking of the six samples is almost similar to the global ranking, as only 'poplar wood' is ranked 4th at the environmental level, while it is ranked 5th overall. On the contrary, it is noted that 'wheat straw' is ranked 5th at the Environmental level and 4th overall. This is due to the 1st-place ranking that it receives at the Economic level, while the rest of the samples have similar rankings at the Economic level vs. the Environmental level, i.e., one place lower at the Economic level ranking in comparison with their ranking at the Environmental level. The Expected rankings for the three levels are visualised in Figure 1 to provide an alternative way to identify important aspects of the rankings of each sample for each level.

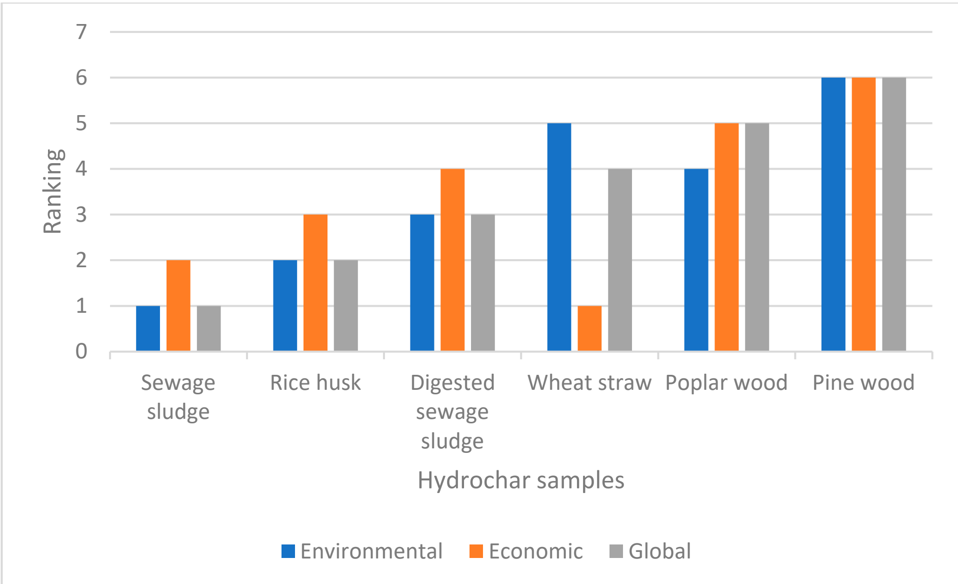

Figure 1. Expected rankings for each hydrochar sample at the comprehensive (global) and intermediate levels (Environmental and Economic).

4. Discussion

The assessment of products from HTC is a complex decision problem, as various aspects should be taken into consideration. A product with environmental potential should be analysed and assessed not only based on its environmental performance but also based on techno-economic analysis, along its life cycle, taking into consideration social, ethical, and risk aspects. In line with the most common frameworks for the assessment of sustainability, a framework for the assessment of hydrochars from agrowaste is proposed. The framework is organised hierarchically, starting from the comprehensive (global) level, which is further divided into three LoE, i.e., Environmental, Economic, and Social. For each LoE, representative criteria are identified using a literature search and personal research of the authors. The criteria list is not meant to be exhaustive, as based on the needs of the analyst/decision maker, the criteria can be adjusted, added, removed, or reorganised to capture as closely as possible the realistic conditions of the decision problem. A specific MCDA method is proposed for applying the framework and extracting the rankings of the assessed alternatives based on the criteria. The MCDA method is the hierarchical-SMAA-PROMETHEE II and is selected so that the addition or removal of criteria does not influence the application of the proposed methodology, as long as the analysts organise the criteria hierarchically, avoid interactions between criteria, and include criteria for which direct elicitation of preferences is possible. The framework and proposed methodology can handle both qualitative and quantitative criteria, with the latter being preferred as their evaluations can be considered more accurate and realistic for environmental applications.

In this study, we apply the framework and the hierarchical-SMAA-PROMETHEE to evaluate six types of hydrochars. Eight criteria belonging to the Environmental and Economic LoE are taken into account to assess the hydrochars at the comprehensive level as well as at two partial levels. Due to data limitations, the third LoE (i.e., Social) has not been taken into consideration for the demonstration. The preference model used to aggregate the multiple criteria evaluations is the one of PROMETHEE II, which permits us to avoid the effect of compensation between criteria. The use of PROMETHEE II permits us to rank all the hydrochars of the case study from the best to the worst, not only at the comprehensive level but also at the level of each LoE. To provide a robust ranking recommendation, the Stochastic Multicriteria Acceptability Analysis (SMAA) is applied, which permits us to find the frequency with which a hydrochar sample reaches a certain rank position at the comprehensive and partial levels, taking into account a large set of the instances of the assumed preference model compatible with the preferences provided by the decision-maker. In our study, these instances are defined by vectors of criteria weights drawn randomly from a feasible set. The results of SMAA were summarized using the Expected rank score proposed, providing a final ranking of the hydrochar samples [18].

The case study is used mainly for demonstration purposes and is not meant to extract definite conclusions on the assessed types of hydrochars. A complete and meaningful assessment, in our opinion, would require many more alternatives (samples of hydrochar) to be taken into consideration and realistic data for all the criteria and all the LoE. The inclusion of the third LoE in the assessment would pose some additional weight constraints, which could be easily defined and evaluated by the analyst and included in the application. This would influence only the weight vectors and the possible ranges that each criterion weight and LoE weight can have but would not influence the way the results are presented and interpreted by the analyst.

The proposed framework has been designed taking into consideration specific characteristics of the decision problem (e.g., hierarchical assessment, non-compensatory behaviour, robust recommendations of elicitation of preferences) and has demonstrated specific advantages with the application of the case study. An analyst may assess hydrochars based on a large set of criteria, which can be organised hierarchically and provide insights into their performance on multiple assessment levels. In this way, specific criteria that influence the quality or performance of a sample can be identified. Furthermore, LoE can be identified in which specific samples may outperform other samples, while their overall assessment may be lower in the comprehensive assessment. The framework can be considered modular, as additional LoE may be included, shall a need appear for a specific type of assessment. On the other hand, a quick adaptation of the criteria list renders the methodology applicable for other types of products from thermal or biological processes. In future research, we aim to expand the framework to be applicable for products from carbonisation (e.g., biofuel-chars), liquefaction (e.g., biofuels—as a hydrochar by-product), and hydrothermal gasification (e.g., biofuels).

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