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Multicriteria Decision-Making Tools for the Selection of Biomasses as Supplementary Cementitious Materials

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Abstract: Using biomass ash to partially replace cement reduces the cement industry's environmental impact and prevents these agro-industrial wastes from ending up in landfills, eroding soils, or being openly burned. This research aims to select three biomasses to produce supplementary cementitious materials (SCM) through the analytic hierarchy process, considering expert judgments from different domains. Complementary to up-to-date research, we evaluated biomasses taking into account biomass production, ash obtained from combustion, and logistics processes for supplying concrete plants with SCM. We also dealt with an industrial context instead of a laboratory one and validated our approach on a real case study using Colombian data. The results indicate experts count the technical viability of biomass (concrete properties) as the most crucial criteria, followed by the availability and transport characteristics of the waste (production criteria) and the combustion process as the least important criteria. In the baseline scenario (all experts' judgments having the same weights), we found that cane bagasse is the best alternative, thanks to its large and highly concentrated production, even if it is not the biomass with the best pozzolanic properties. We also analyzed other scenarios in which we changed the weights of the experts' judgments and the importance of the criteria. We found that cane bagasse, rice husk, and palm rachis remain the three biomasses selected as SCM, showing the robustness of the proposed multicriteria decision-making (MCDM) methodology. The results provide a methodological reference to appraise biomasses for SCM nationally, using a MCDM framework in a group decision-making context.

Keywords: supplementary cementitious materials; biomasses; multicriteria decision-making; analytic hierarchy process; group decision-making

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Citation: Álvarez-López, G.; Múnera, A.M.; Villegas, J.G. Multicriteria Decision-Making Tools for the Selection of Biomasses as Supplementary Cementitious Materials. *Sustainability* **2023**, *15*, 10031. https://doi.org/10.3390/su151310031

Academic Editor: José Ignacio Alvarez

Received: 9 May 2023
Revised: 1 June 2023
Accepted: 6 June 2023
Published: 25 June 2023

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1. Introduction

The cement and concrete industries face fundamental challenges in reducing their environmental impact. Among the many available alternatives [1,2], CO_2 capture, alternative aggregate and pozzolanic materials, alternative energy sources, or the use of supplementary cementitious materials (SCM) obtained from, biomass ashes (BA) stands out as a promising alternative. The partial replacement of Portland cement by different BA is an eco-friendly alternative that reduces both the building industry's environmental impact and the impact of these agro-industrial wastes in landfills, soils, health, etc. [2–4]. Moreover, the use of BA as SCM also improves the mechanical or chemical properties of concrete. For instance, the compressive strength of concrete, containing rice husk ash (RHA) as SCM, increases as the RHA content increases to a certain level [4]. Similarly, the use of cane bagasse ash or RHA improves the properties and workability of fresh concrete [5].

The literature reports several BA that can be used as SCM and come from agricultural wastes such as rice husk, palm oil fuel, cane bagasse, wood waste, bamboo leaf, corn cob, olive biomass fly ash, agave, coconut shell, paper sludge, wheat straw, cork, among

others [3,6–8]. Most of the studies and reviews on these materials have focused on the physical-chemical properties of the SCM and the mechanical and rheological properties of the resulting concrete and mortars.

However, selecting the best SCM from biomasses is a complex decision since other criteria need to be considered, such as biomass availability and production volume, combustion process to obtain the ash, and the logistics processes needed to include these ashes as raw material in concrete production. Therefore, in this paper, we resort to multicriteria decision-making (MCDM) tools to include these other criteria in this complex decision.

The use of MCDM methods has increased considerably in the last decades since their appearance in the 1970s [9] because they provide a transparent and flexible framework in complex decision-making processes [10]. MCDM techniques can be used to select an alternative or rank among several options, which may involve multiple conflicting criteria, stakeholders' interests, and different data sources. MCDM methods leverage expert assessments, and secondary information sources, with high levels of uncertainty [9,11].

The areas of application of MCDM techniques in civil engineering include water resources, transportation, infrastructure projects, building construction, etc. [12]. These methods have been widely used in the last domain to support decisions for selecting building materials, suppliers, and contractors. In general, they can be helpful in the initial stages of selecting materials, equipment, and processes, among others, enabling more agile, accurate, and less expensive decision-making processes [13].

The analytic hierarchy process (AHP) is undoubtedly the MCDM technique that has been used the most, solely or in hybrid methods [12,14,15], in different areas, sectors, and disciplines [9,10,16–18], because of its simplicity and great flexibility [18,19]. Moreover, AHP allows decision-makers to recognize the variables involved and easily include stakeholders' opinions [10,17,20], and it is a valuable and robust procedure for checking the consistency of decision-makers' evaluations [21].

Different works resort to AHP to support the selection and evaluation of materials. For instance, ref. [22] implemented a model based on the fuzzy extended analytical hierarchy process approach. This model was validated through a case study in the UK to select a roofing material in a residential building considering criteria related to environmental impact, life cycle cost, resource efficiency, waste minimization, performance, and social benefit. In [23], the authors also used a fuzzy MCDM approach to select sustainable materials in mass housing projects, including economic, environmental, social, and technical indicators, and evaluated their methodological proposal in a case study in Iran.

In addition, many of these works have focused on evaluating materials in concrete production. In [24], the AHP supports the selection of repair material for patching concrete deteriorated by chloride, considering only quantitative requirements related to chemical and physical material performance. Moreover, in [13] AHP, TOPSIS, and ELECTRE are used to select the optimal design of a concrete mix considering raw materials, environmental impact, compressive strength, and concrete mix density criteria.

AHP has also been used to select the best cement type and mixture to produce high-performance concrete [25]. Similarly, ref. [26] combines AHP, TOPSIS, and the optimal scoring method to include technical, environmental, social, and economic sustainability criteria in selecting concrete supplementary material.

There are plenty of works related to the implementation of MCDM methods, AHP and TOPSIS especially, for evaluating concrete mix design using aggregates from industrial wastes as replacement materials, such as [20,26–28]. In [26], the authors evaluated sustainable concrete incorporating ceramic waste as coarse aggregate for replacing conventional aggregate. They considered criteria associated with compressive strength, CO_2 footprint, the quantity of raw materials used to manufacture the specimens, and eight concrete alternatives with different ages and percentages of replacement of conventional aggregate.

In [20], the authors used laboratory tests and MCDM methods to select sustainable concrete, incorporating glass waste as a partial replacement for conventional coarse aggregate. They considered the mechanical and environmental performance of eight concrete mixes and evaluated them based on slump value, density, compressive strength, CO_2 footprint, and volume utilization of glass waste. The results show AHP and TOPSIS identify the same best and worst options.

Similarly, the authors in [27] implemented these techniques for selecting rubberized concrete that can be used for medium to low-strength applications. They used compressive strength, density, raw materials volume, and CO_2 emission as criteria. In [28], the authors also used AHP and TOPSIS for evaluating recycled aggregate concrete and included indicators associated with mechanical, economic, and environmental performance. As in [20], the results show the same ranking for the alternatives is reached through both MCDM methods.

In contrast, ref. [21] presents AHP as a tool to select the mix proportion of bagasse ash (BA) blended high-performance concrete (HPC). The authors conducted laboratory tests at 28 days for mechanical properties and at 90 days for durability properties to establish sub-criteria values for each of the options. They concluded that HPC blended with BA at 20% was the best alternative. In turn, ref. [14] review the application of classical MCDM methods in biomass-related papers that evaluate (mainly) the use of biomass as a bioenergy and biodiesel source.

As this brief literature review shows, most MCDM applications in the building sector evaluate concrete mix design when industrial wastes replace conventional aggregate, and only a few analyze agricultural wastes as possible substitution alternatives. Additionally, their scopes mainly cover laboratory tests and have explored a few sensitivity analyses to validate decision robustness. Moreover, in these works, most of the focus has been put on the criteria related to the concrete properties, neglecting other important criteria of this decision when looking at a national strategy: its production through a controlled combustion process and the subsequent logistics processes needed to supply concrete plants with SCM derived from biomasses.

This paper adopts a complementary view by including these criteria in evaluating biomasses as possible SCM. Through AHP and biomasses available in Colombia as a case study, we show how including these additional criteria highly influences the choice of a biomass as a SCM. We also analyze how expert criteria judgments differ, and we evaluate the decision robustness through judgment consistency evaluation, criteria weight changes, and priority changes of expert assessments. Therefore, the main contributions of this paper are: (i) the incorporation of two additional criteria in the evaluation of biomass ashes as supplementary cementitious materials, namely: the combustion and the production processes; (ii) the incorporation of experts' judgments to evaluate the importance of the criteria in the selection of an SCM with a robust MCDM methodology; and finally, (iii) the validation of the methodology in a case study using Colombian data.

2. Materials and Methods

This research aims to select three biomasses to be used as SCM through AHP. The decision-making team comprised eight experts in concrete properties, combustion processes, renewable sources and energy efficiency, logistics, production, and the R&D director of Colombia's cement and concrete manufacturing company. We used the methodologies described in [17,29] as a reference to develop the decision-making process. Figure 1 depicts the methodology detailing the tools, data sources, and software used in each one of its phases. We followed the four phases described below:

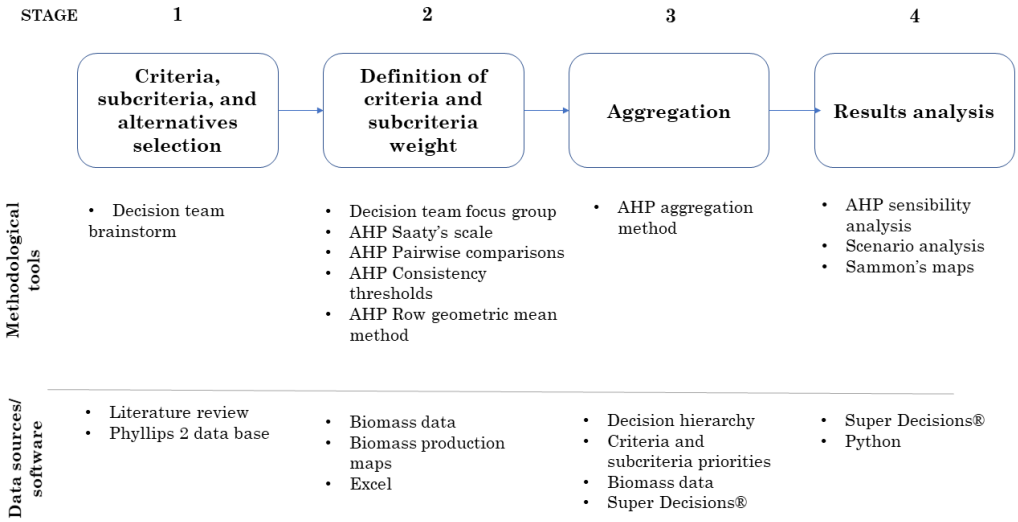

Figure 1. Methodological tools, data sources, and software in the research phases.

Stage 1: Criteria (dimensions), sub-criteria (indicators), and alternatives selection.

The decision-making team brainstormed through their knowledge and previous experiences in this phase. They also considered the works identifying biomasses suitable as SCM, especially the review by [30] and the Phyllis 2 database (https://phyllis.nl/, accessed on 4 November 2020), which characterize different biomasses' physical and chemical properties.

We performed this task to define the criteria, the corresponding sub-criteria or indicators to be considered, and the biomasses to be evaluated. Then, we structured the problem in a hierarchy form through these definitions, which made it easier for decision-makers to focus on the selection. That is: (i) the decision at the first level, (ii) the dimensions at the second level, (iii) the indicators at the third level, and (iv) the options or alternatives at the last level.

Stage 2: Definition of the criteria and sub-criteria weights.

In this phase, we established criteria, sub-criteria weights, and indicator values for each alternative. For the latter, we used the following sources: first, a literature review of published scientific papers was conducted, mainly in the 2010–2020 period, and in journals such as *Construction and Building Materials*, *Cement and Concrete Composites*, *Material and Design*, *Biomass and Bioenergy*, *Energy*, and *Energy and Fuels*, among others. This review provides information on each biomass's sub-criteria associated with concrete properties and combustion processes (see Table A1 in Appendix A for the data sources of this phase). Second, we consulted databases and reports from the Ministry of Agriculture and Rural Development and the National Administrative Department of Statistics of Colombia to document indicators related to the production of biomasses.

We used these data following the methods proposed by [31], primarily to get the values through a data-based approach for most indicators. However, a focus group established the priorities of the criteria and sub-criteria and the geographic dispersion evaluation of the alternatives. This focus group included eight experts who evaluated these three elements by pairwise comparison matrices using the fundamental scale of absolute numbers of Saaty.

Once we had the experts' assessments, we calculated the geometric consistency index for all the matrices according to [32], to evaluate the judgments' consistency. Finally, given that it was a group decision-making process, we used the row geometric mean method to synthesize the experts' judgments with priorities assigned to individual ratings [33].

Stage 3: Aggregation

In this stage, to get the local and global priorities of the alternatives, we introduced in Super Decisions® 3.2 (Creative Decisions Foundation, Pittsburgh, PA, USA) the synthesized distributive priorities of the criteria and sub-criteria and the data for the biomasses in each of the indicators. The only exception was the geographic dispersion, for which the focus group's aggregated distributive priority was introduced.

Stage 4: Results analysis

First, we studied similarities or dispersions of the experts' judgments through Sammon's maps implemented in Python [34]. Second, to analyze the sensibility of the results to changes in the input parameters, we leveraged Super Decisions® 3.2 sensibility analysis numerically and graphically. Generally, results are robust, and the final decision is consistent, if the alternatives initially selected are not altered because of these changes [17,29].

3. Results and Discussion

Figure 2 shows the structure defined for the decision-making process. The goal is at the first level, which consists of selecting three biomasses as SCM. The criteria/dimensions are at the second level: combustion process, production, and concrete properties. Their sub-criteria are at the third level. Finally, the alternatives appear at the fourth level. Initially, we identified eighteen biomasses in the literature associated with crops of rice, sugar cane, palm, coffee, banana, corn, wood, and coconut, but complete information was available just for the five options included in the figure (rice husk, cane bagasse, palm rachis, corn cob, and coffee husk).

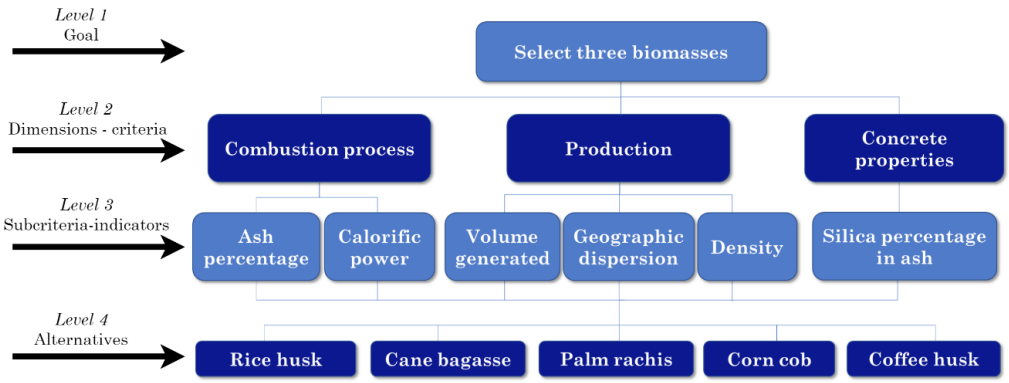

Figure 2. Goal, criteria, sub-criteria, and alternatives considered in the decision process.

Table 1 defines the six sub-criteria of the hierarchy with their corresponding units and associated criterion. As seen in the table, apart from the concrete properties, the hierarchy includes two dimensions related to the production and combustion process. Remarkably, the use of biomasses as cogeneration fuels and the use of the resulting ash as SCM give rise to the inclusion of calorific power as an important sub-criteria in the combustion criteria [35]. Table 2 shows numerical values for these indicators. We got them from the literature (refer to Table A1 in Appendix A for the data sources).

Table 1. Definitions of sub-criteria/indicators for each criterion.

Criteria	Sub-Criteria (Units)	Definition
Combustion process	Ash percentage (p/p)	SCM efficiency after the biomass combustion process. If a first biomass has a higher ash percentage than a second one, the former will have a higher preference.
	Calorific power (MJ/kg)	Chemical energy of a material made of carbon, hydrogen, sulfur, oxygen, and nitrogen released from a combustion process. If a first biomass has a higher calorific value than a second one, the former will have a higher preference.
Production	Volume generated (t/year)	Tons of biomass generated per year in Colombia. If a first biomass has a greater volume generated than a second one, the former will have a higher preference.
	Geographic dispersion	Estimates how concentrated or dispersed the biomass generation is across Colombia. If a first biomass is more geographically concentrated than a second one, the latter will have a higher preference.
	Density (kg/m^3)	Relation between the weight and the volume of the waste. If a first biomass has a higher density than a second one, the former will have a higher preference.
Concrete properties	Silica percentage (%)	Silica content in biomass ash after the combustion process. If a first biomass has a higher silica percentage than a second one, the former will have a higher preference

Table 2. Indicators/sub-criteria for each of the alternatives. * Data or average data for countries different from Colombia.

	% Ash (p/p) bs	Calorific Power (MJ/Kg)	Volume Generated (Millions of t/year)	Density (Kg/m^3)	% Silica in Ash
Cane Bagasse	4.46	15.87	9.45	90.00	65.66 *
Coffee husk	2.60	15.77 *	0.10	245.00	2.31
Rice husk	18.20 *	15.30 *	0.30	1495.00 *	93.60
Corn cob	2.55 *	16.64 *	0.25	318.14 *	62.80 *
Palm rachis	6.43	17.20	0.42	980.00 *	77.03

3.1. Analysis of Expert Judgments

The eight decision makers (DM) evaluated the preference of the criteria (level 2) and sub-criteria (level 3) through pairwise comparison matrices using the fundamental scale of absolute numbers of Saaty [31]. We show these results in Table 3. As it is standard in the AHP process, we evaluated the judgments of each expert in terms of its consistency using the geometric consistency index. If a DM's comparison matrix surpassed the consistency thresholds defined in [32], we asked the DM to revise their pairwise comparison matrix until reaching a consistent result.

Table 3. Expert judgments on criteria and sub-criteria.

		Decision Makers (DM)								Aggregated Group Weights
		DM1	DM2	DM3	DM4	DM5	DM6	DM7	DM8	
Dimensions-criteria	Combustion process	0.33	0.09	0.06	0.15	0.08	0.07	0.11	0.33	0.15
	Production	0.33	0.17	0.13	0.38	0.16	0.28	0.19	0.60	0.29
	Concrete properties	0.33	0.74	0.81	0.47	0.76	0.65	0.70	0.07	0.56
Combustion process Subcriteria	Ash percentage	0.88	0.88	0.90	0.83	0.88	0.83	0.83	0.89	0.13
	Calorific power	0.12	0.12	0.10	0.17	0.12	0.17	0.17	0.11	0.02
Production Subcriteria	Volume generated	0.33	0.71	0.80	0.60	0.73	0.71	0.58	0.70	0.19
	Geographic dispersion	0.33	0.20	0.10	0.32	0.21	0.22	0.28	0.24	0.07
	Density	0.33	0.09	0.10	0.08	0.06	0.07	0.14	0.06	0.03

Table 3 shows the diversity of the judgments of the different experts in the priorities given to the criteria and in the weights for the sub-criteria. Their diverse areas of expertise could cause this. Therefore, we used Sammon's maps to visualize the resulting priority vectors of different DMs within the group; this fostered the understanding of the process and the achievement of the group decision's common goal [36].

The main goal of Sammon's mapping is to preserve the pairwise distances between data points in high-dimensional space as accurately as possible when projecting them onto a lower two-dimensional space. Since group decision-making is typically more complex than the single-decision-maker case, Sammon's maps enhance AHP to visualize the judgments of various decision-makers [36]. By mapping the data points to a lower-dimensional space while preserving their pairwise distances as accurately as possible, Sammon's mapping provides a visualization that can reveal patterns, clusters, outliers, and relationships within the data. Being a scale reduction of multidimensional data, the axis of these maps lacks any possible interpretation and, therefore, are not labeled in the following figures.

Figure 3 presents the Sammon's map of the priority vectors for the criteria for each of the eight decision-makers. This figure shows an agreement of many of the DMs in most of the criteria. Remarkably, DM1 and DM8 behave differently from the others. While DM1 exhibits equal weights when the comparisons involve more than two alternatives, DM8 prioritized the concrete properties very lowly. That is why DM8 appears isolated in Figure 3.

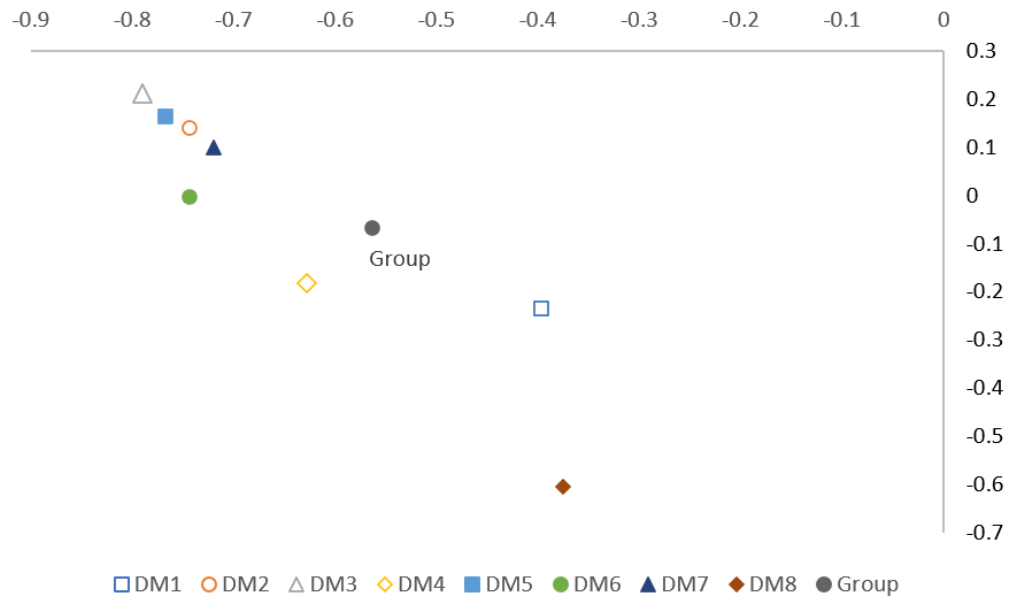

Figure 3. Two-dimensional scaling (Sammon's map) of the expert judgments for the criteria priorities.

In turn, Figure 4 presents the Sammon's map for the priority vectors of the production sub-criteria for each of the eight decision-makers. Once again, this figure shows an agreement of many of the DMs in the production sub-criteria and the disagreement of DM1 caused by its policy of assigning equal weights when the comparisons involve more than two alternatives.

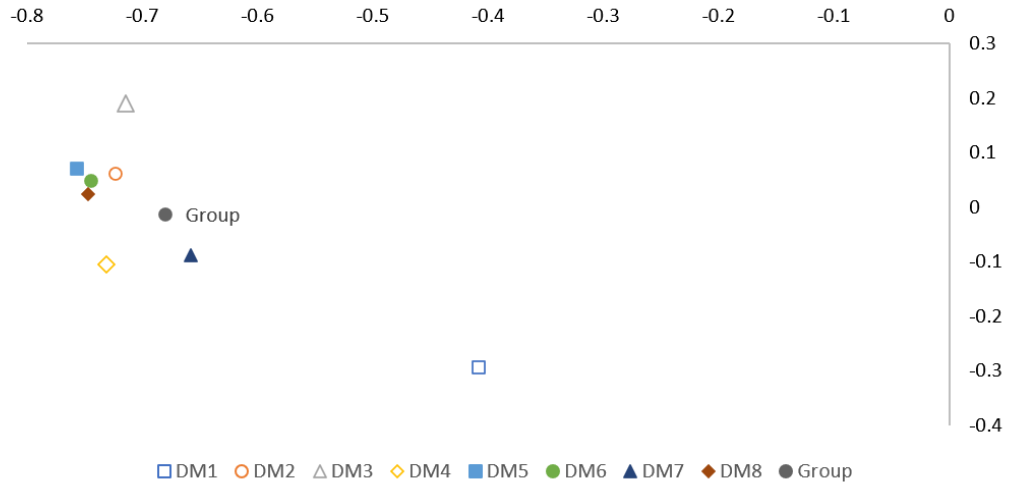

Figure 4. Two-dimensional scaling (Sammon's map) of the expert judgments for the production sub-criteria priorities.

Figures 5 and 6 present two sub-criteria where the Sammon's maps tool reveals interesting group-decision-making cases. First, Figure 5 presents the experts' assessment of the geographical dispersion of the different biomasses. For a difficult-to-evaluate feature like the geographical dispersion of the alternatives, AHP proved its value as a group decision-making tool. Here, the experts' judgments are different and dispersed, but the results of the group priorities appear at the center of Figure 5. The diversity in the judgments for this attribute could result from the number of available alternatives (five) and how this sub-criterion is presented to the decision makers (graphically using a map, refer to Figure A1 in Appendix A).

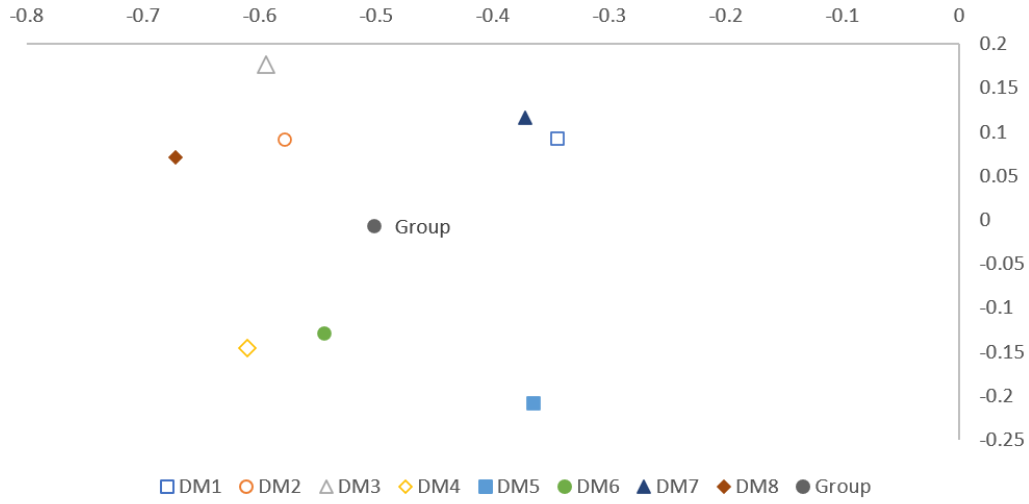

Figure 5. Two-dimensional scaling (Sammon's map) of the expert judgements for the geographical dispersion of the alternatives.

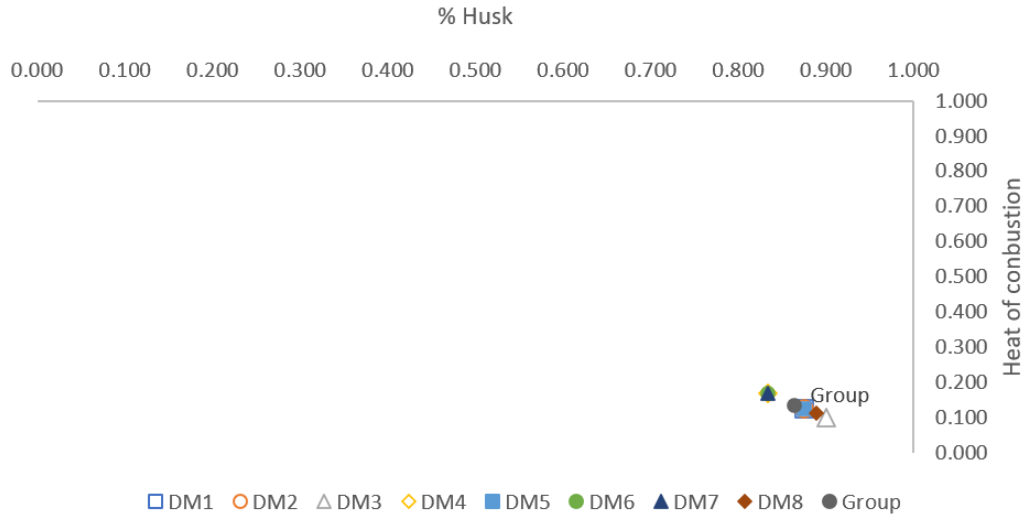

Figure 6. Expert priorities for the combustion process sub-criteria.

Finally, Figure 6 presents the data of the priorities given by the decision makers to the combustion process sub-criteria (% of Husk and Calorific power). Note that these data do not require the projection as it is already in two dimensions (i.e., it is not a Sammon's map). Contrary to the criteria, sub-criteria, and geographical dispersion of the previous figures, in a dimension that is easier to evaluate (e.g., the combustion process), the agreement of the decision-makers was almost perfect. This result could be explained by the fact that this dimension only has two sub-criteria, and their data (calorific power and ash percentage) are quantitative, making the pairwise comparison process more straightforward.

3.2. Biomass Selection

We aggregated judgments of the eight experts on the criteria (level 2), summarized in Table 3, following the row geometric mean method by [33], with the same weights to all experts' evaluations. Synthetized results show that the concrete properties dimension is the most crucial criterion (0.56), followed by the production criterion (0.29) and, in the last place, the combustion process (0.15). These results show that the experts give greater relevance to the technical viability of biomass as an SCM, followed by the availability and transport characteristics of the waste. In comparison, properties related to biomass combustion have lower relevance.

Using the priorities of Table 3 for the three dimensions and their indicators, combined with the values of Table 2 for the different alternatives, the (baseline) rank of the five biomasses and their corresponding priorities are cane bagasse (0.35), rice husk (0.28), palm rachis (0.19), corn cob (0.15), coffee husk (0.03). We show the results for the baseline scenario in Figure 7. In the left-hand axis, this figure shows with a bar chart the local priorities obtained by each biomass in each of the six sub-criteria. At the same time, the right-hand axis depicts the overall priorities for the biomasses considered.

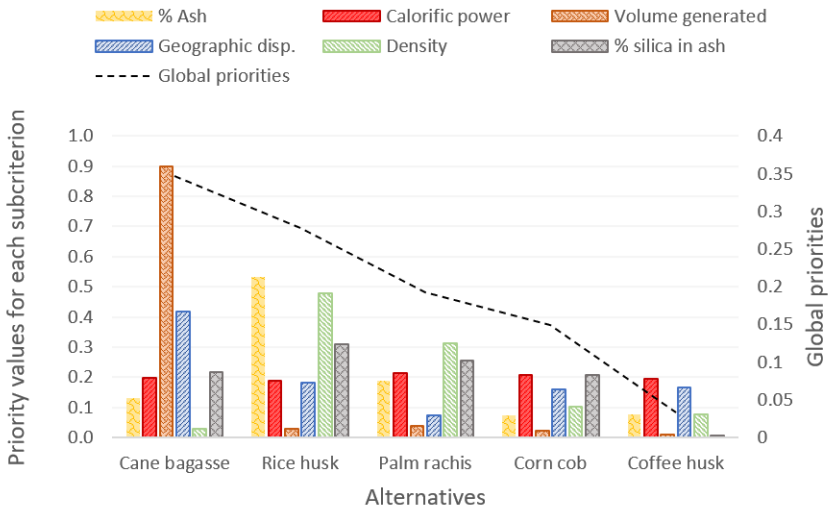

Figure 7. Local and global priorities for each of the biomasses.

As shown in Figure 7, cane bagasse is the best alternative because of its huge production volume and high geographical concentration, making it very appropriate for the logistics process. Rice husk stands out as the second-best alternative thanks to the best percentage of silica in the ash, the greater percentage of ash after combustion, and its highest density. Finally, the palm rachis reached the third place in the ranking thanks to the good balance between its indicators and the superior performance in the density, percentage of ash, and percentage of silica in the ash compared to corn cob. Finally, the last place of coffee husk is mainly due to its low percentage of silica in the ash and volume generated compared to the other alternatives.

3.3. Sensitivity Analysis

We conducted a sensitivity analysis in Super Decisions® 3.2 for each criterion. This analysis was based on Figures 8–10, in which the *x*-axis of these figures corresponds to the dimension's weights, and the *y*-axis corresponds to the global priorities of the alternatives. These figures show that, although there may be changes in the order of the three selected biomasses, for example in Figure 8 when the weight of the combustion criterion is greater than 0.29 or when the importance of the production criterion is less than 0.2 in Figure 9, cane bagasse, rice husk, and palm rachis remain as the three biomasses selected as SCM.

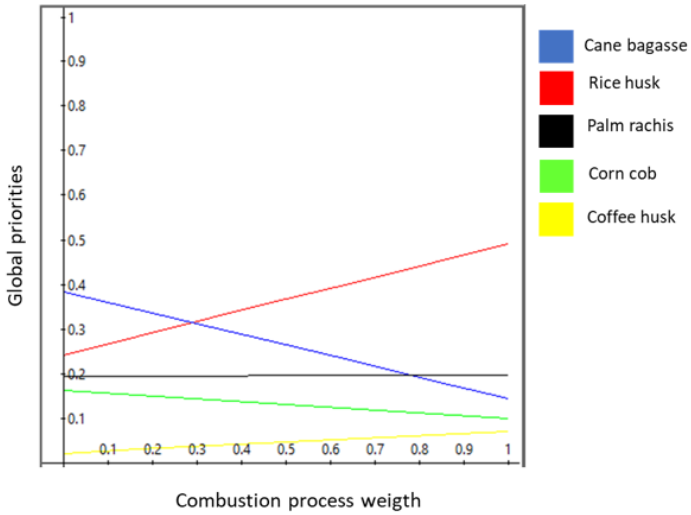

Figure 8. Sensitivity analysis for the combustion process criterion.

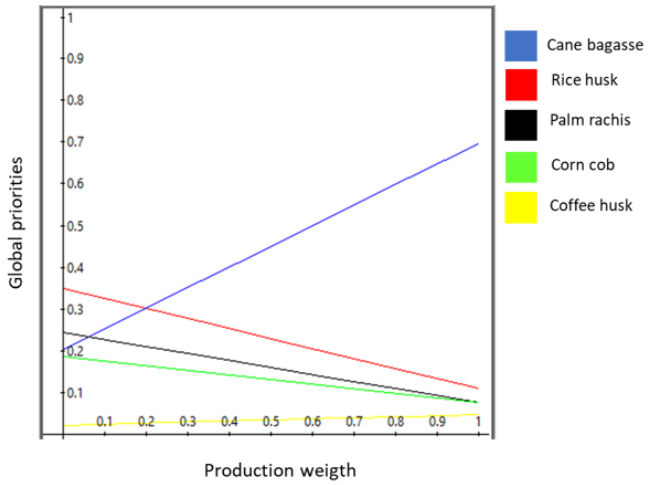

Figure 9. Sensitivity analysis for the production criterion.

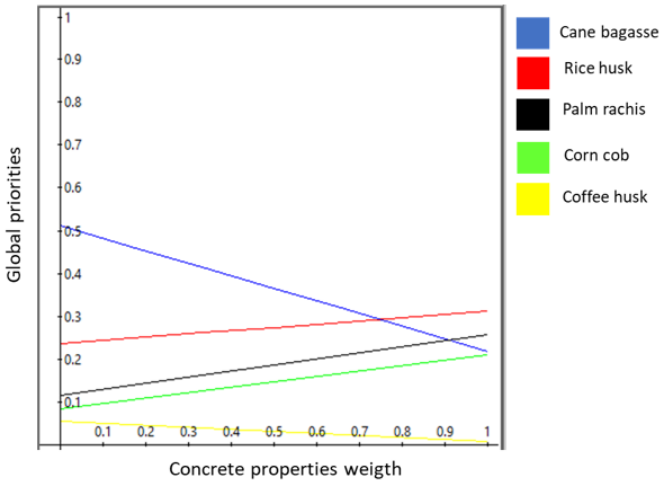

Figure 10. Sensitivity analysis for the concrete properties' criterion.

Moreover, these results reveal that cane bagasse selection as the first alternative is strengthened if the production criterion's weight has a high value (Figure 9). This result is obtained because this biomass has a notable performance in the generated volume and geographic dispersion sub-criterion, and they are the second and fourth most important indicators with weights of 0.19 and 0.07 (respectively). On the contrary, rice husk appears as the best alternative whether the properties of the concrete or the combustion process criterion have a high weight (Figures 8 and 10). This outcome is expected because this biomass has a notable performance in the percentage of silica in ash, which is the most important indicator with a weight of 0.56, and also in the percentage of ash, which is the third most relevant indicator with a weight of 0.13.

Evaluation of Alternative Scenarios

Finally, we defined different alternative scenarios changing the priorities assigned to individual experts' judgments in evaluating the sub-criteria (level 3), before being synthesized, according to the area of the decision-makers expertise. In the baseline scenario, we assumed the weights of the experts' judgments in the evaluations of the sub-criteria were equal. In scenario one, each group evaluated only the sub-criteria corresponding to their expertise. Thus: DM5 and DM6 were in a group of experts in the production dimension, and the other six experts were in the group of combustion process and concrete properties dimensions. As an absolutely different alternative, in scenario two, DMs assessed

exclusively the area in which they are not experts.Table 4 shows the results for sub-criteria weights and global priorities for the three scenarios.

Table 4. Sub-criteria weights and global priorities for the proposed scenarios.

Scenario	Sub-Criteria Weights					Global Priorities				
	Combustion Process		Production							
	% Ash	Calorific Power	Volume Generated	Geographic Dispersion	Density	Cane Bagasse	Rice Husk	Palm Rachis	Corn Cob	Coffee Husk
Baseline	0.13	0.02	0.19	0.07	0.03	0.35	0.28	0.19	0.15	0.03
1	0.13	0.02	0.21	0.06	0.02	0.36	0.27	0.19	0.15	0.03
2	0.13	0.02	0.19	0.07	0.03	0.34	0.28	0.20	0.15	0.03

When we compare the results for scenario 2 with the baseline scenario, sub-criteria outcomes are the same, and global priorities are almost equal. In addition, when we contrast the baseline scenario with scenario 1, in which the sub-criteria associated with production were evaluated exclusively by experts in this domain, the volume generated sub-criterion was slightly favored, which also generated a slight increase in the global priority of sugarcane bagasse, since this biomass is the one with the best performance in this indicator.

These results show that, although there are slight numerical variations in global priorities of the alternatives, cane bagasse remains as the best option, followed by rice husk and palm rachis in the third place (in any of the scenarios), which shows a high consensus among experts regarding preferences, regardless of their particular area of expertise. In sum, the sensibility and scenario analysis unveil the robustness of the proposed MCDM methodology in selecting the biomasses that are suitable as SCM in the Colombian context. As a result of this ranking, a deeper study of these biomasses as possible SCM in the country was launched, with a more in-depth evaluation of the logistic process [37] and analysis of the properties of different concrete mix designs obtained with them [38].

4. Conclusions

This paper illustrates the use of AHP to select biomasses to produce SCM at a national scale. Unlike other studies, we included logistic and biomass ash production criteria in the selection process. By including these criteria, cane bagasse ash appears as a promising alternative in any of the scenarios we evaluated, thanks to its large production volume and highly concentrated production, even if it is not the biomass with the best pozzolanic properties. This result highlights the importance of including other dimensions (apart from chemical/physical properties) for selecting biomass-based SCMs in concrete production.

Extensions of this research could include using a complementary method, such as fuzzy logic, to better estimate the experts' evaluations in the geographical dispersion sub-criterion. Moreover, we intentionally left aside several chemical/mechanical properties of the ash/concrete mix to avoid the need of (probably expensive or time-consuming) laboratory test at the initial stage of selecting an SCM. Including these other criteria could be worth exploring in addition to this work. We could include them as sub-criteria in the concrete properties dimension to analyze their effect in ranking the alternatives. The last extension, however, depends on specific concrete formulations and could be analyzed using the methodology already proposed in [21].

Author Contributions: Conceptualization, G.Á.-L. and J.G.V.; methodology, G.Á.-L., A.M.M. and J.G.V.; software, A.M.M. and J.G.V.; validation, G.Á.-L. and A.M.M.; formal analysis, G.Á.-L., A.M.M. and J.G.V.; investigation, G.Á.-L., A.M.M. and J.G.V.; data curation, G.Á.-L. and A.M.M.; writing—original draft preparation, G.Á.-L. and J.G.V.; writing—review and editing, G.Á.-L., A.M.M. and J.G.V.; visualization, G.Á.-L., A.M.M. and J.G.V.; supervision, G.Á.-L. and J.G.V.; project administration, G.Á.-L. and J.G.V.; funding acquisition, G.Á.-L. and J.G.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Colombian Ministry for Science, Technology, and Innovation-Minciencias via project 115080863589 (166—2019 contract). This paper has been funded by Minciencias, Universidad de Antioqua and Instituto Tecnológico Metropolitano within Minciencias RC288-2022 project.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: We specify the sources to get numerical values for the indicators in Appendix A.

Acknowledgments: The authors gratefully acknowledge Manuel Romero, Juan Martínez, Leyla Jaramillo, Wilmar Echeverri, Cindy Arenas, and Katherine Arango for their support in the data collection process.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A Sources of Information for the Candidate Biomasses in the Different Criteria

Table A1. Sources consulted to get numerical values for the indicators.

Biomass	Ash Percentage	Volume Generated	Density	Calorific Power	Silica Percentage in Ash	Sources
Cane bagasse					X	[5,39–42]
	X			X		[43–47]
			X			[46]
	X					[48]
		X				[45,49]
	X			X		[45,46]
Coffee husk			X			[46]
					X	[50]
		X				[51]
	X			X		[52,53]
	X				X	[54]
					X	[55]
Corn cob	X		X	X		[56]
					X	[57]
			X			[58]
		X				[51]
	X			X		[45]
			X			[59]
Palm rachis	X			X	X	[48,60]
	X					[61]
		X				[48,51]
	X			X		[62]
					X	[63]
	X			X	X	[64]
Rice husk				X		[65]
					X	[66,67]
		X				[51,66]
			X			[68]

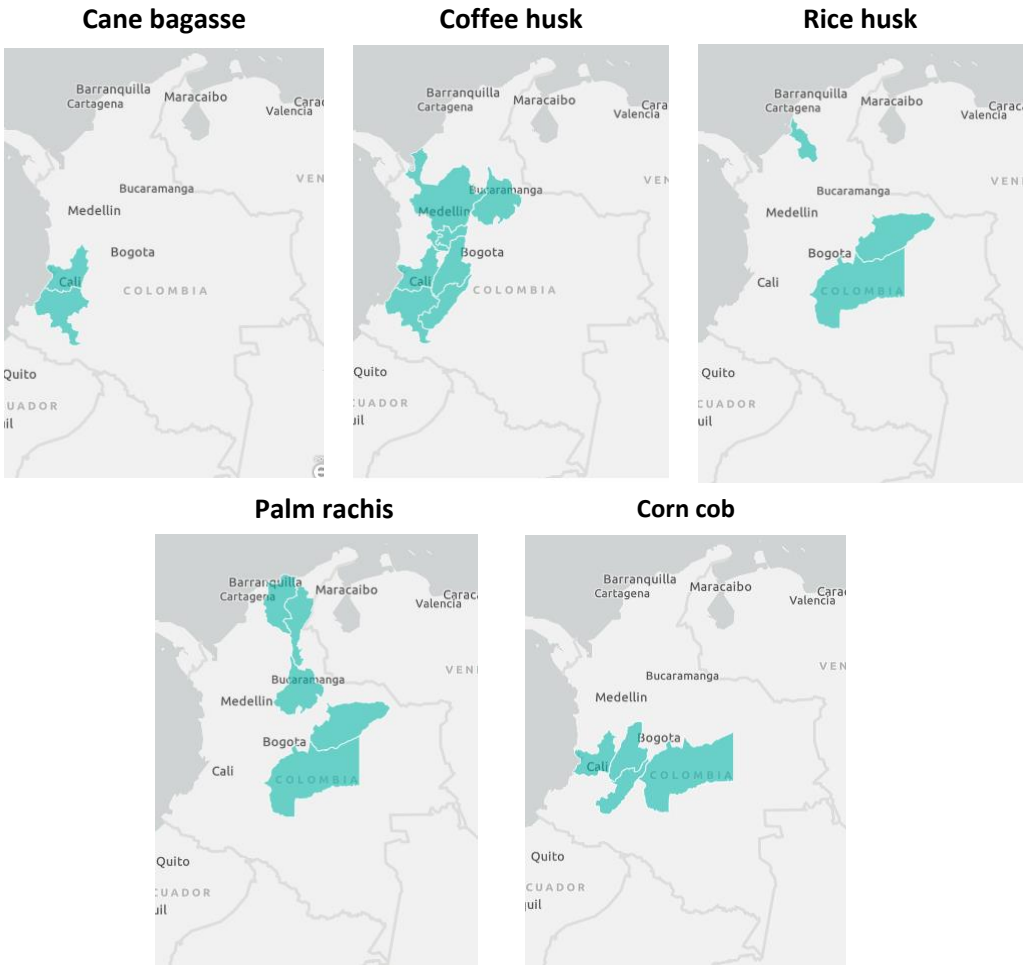

Figure A1. Maps used for experts' judgements on the geographic dispersion sub-criterion.

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