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Sustainable Afforestation Strategies: Hybrid Multi-Criteria Decision-Making Model in Post-Mining Rehabilitation

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Abstract: This article describes an effective approach for selecting suitable plant species for afforestation in post-mining rehabilitation. The research was conducted in the Western Black Sea region of Turkey. The aim of the research is to perform accurate criteria weighting and species prioritization for afforestation in post-mining degraded areas. This helps to ensure consistent conditions for the future use of the site as a forest, sustainability of nature, and selection of appropriate species adapted to the difficult post-mining conditions. In this study, which is a multi-criteria decision-making problem (MCDM), the weights of the criteria were determined by stepwise weight assessment ratio analysis (SWARA), and the priority ranking of the species was determined by the analytic hierarchy process (AHP). Analyses were carried out with 10 afforestation criteria and five tree species. According to the analysis, the top three ranked criteria are Economic Efficiency > Carbon Stock and Credit > Reducing Afforestation Cost. The five species' priority ranking is *Robinia pseudoacacia* L. (0.456) > *Alnus glutinosa* subsp. *glutinosa* (0.248) > *Populus nigra* subsp. *nigra* (0.146) > *Salix alba* L. (0.103) > *Quercus robur* subs. *robur* (0.048). The hybrid approach is expected to increase the effectiveness of post-mining rehabilitation works.

Keywords: post-mining rehabilitation; reforestation; multi-criteria decision-making; SWARA-AHP hybrid approach

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1. Introduction

Terrestrial ecosystems, covering 31% of the Earth's surface [1], have an important position in achieving sustainable development and combating climate change. Terrestrial ecosystems and forests, which cover 30% of the world's land and are the source of livelihood for about 1.6 billion people, including 70 million indigenous peoples, are among the most studied topics in achieving sustainable development goals, particularly in attaining Goal 13 (climate action) and Goal 15 (terrestrial life) [2]. Mature forests are utilized as carbon stores. Deforestation leads to a reduction in biodiversity, damage to human utilization, the destruction of carbon sinks, and thus increased climate change impacts. One of the factors that causes the destruction of forests is the mining sector. Especially wild mining causes permanent damage to the forest ecosystem. The number of abandoned mines worldwide is hundreds of thousands [3]. Although mining is a temporary activity, its environmental impact continues long after the mine site is closed. Mining is a sector that is constantly developing and growing in our age. While trying to meet raw material needs, the mining sector is also taking measures to address increasing environmental and social concerns. For this reason, the rehabilitation of mine sites is recognized as an important part of sustainable development strategies in many countries [4]. Rehabilitation efforts are aimed at eliminating the environmental damage caused by mining sites [5,6].

Post-mined land rehabilitation is defined as the restoration of mining sites to their original condition. Planting, land management, spatial planning, physical restoration, land use planning, species selection, soil characteristics, and pre-mining land use status are taken into account [7,8]. Rehabilitation works at mining sites start when mining activities start and continue with the activities. Post-mined land rehabilitation works should be completed when the mining permit period ends [9]. For this reason, mine closure and the subsequent rehabilitation process is the last stage of mining activities. Rehabilitation works should be compatible with the final land use and morphology of the area [10]. Afforestation is one of the best methods to minimize damage to the environment during mining activities and prepare the land for subsequent use [11]. The plant species selection process is the main factor affecting the success of rehabilitation works.

Post-mining afforestation contributes to improving air quality and protecting biodiversity by sequestering carbon. It plays a critical role in mitigating climate change. Afforestation offers many benefits for the environment and local communities. Trees act as natural air purifiers, filtering pollutants and improving air quality. Afforestation provides aesthetics to the site and contributes to creating an ecosystem on site, increasing the trees' resistance to plant diseases and insects. Tree roots stabilize soils, reducing erosion and preventing further soil degradation. Afforestation with species that are suitable for the region increases success and reduces the cost of additional planting or completion. Afforestation initiatives give local communities a sense of ownership. It also enables them to participate in environmental protection efforts [12,13]. In addition to all these, the fact that a site has negative qualities, such as barrenness and inefficiency in the pre-use period, is not an excuse for not rehabilitating the area [14].

In post-mining afforestation, determining the appropriate criteria and selecting or prioritizing tree species based on these criteria is a multi-criteria decision-making (MCDM) process. Many studies in the literature have been undertaken using the MCDM method [15]. Due to its flexibility and high efficiency in analyzing decision problems, MCDM has been used in many prioritization studies for forest creation [16–19]. On the other hand, it can be stated that many post-mining rehabilitation and afforestation projects utilize the MCDM process. Several studies focus on limiting factors for plant growth [20,21] and different land use preferences in post-mining rehabilitation [11,22–37]. Some post-mining land use studies, as represented by References [3–7], begin with a structured problem and apply a combination of methods or methodologies. In the study conducted by Soltanmohammadi et al. [3–5], a framework is established for the suitability of the mined area for new use. Evaluations are based on 50 attributes across four main criteria and are used to assess 23 specific alternatives categorized into eight land use categories. These referenced studies employ a hybrid approach: the analytic hierarchy process (AHP) is utilized for criterion prioritization, while other techniques, such as the technique for order preference by similarity to ideal solution (TOPSIS), elimination and choice expressing reality (ELECTRE), and the preference ranking organization method for enrichment evaluation (PROMETHEE), are employed as alternative assessments.

Studies on MCDM methods in the mining sector are utilized in various domains. However, there exists a research gap in the literature regarding the evaluation of tree species alternatives for post-mining rehabilitation using hybrid MCDM techniques, such as SWARA and the AHP. Filling this gap constitutes the motivation behind this research. Therefore, this study focuses on post-mining afforestation. The forest is a crucial step in some post-mining land use types. Selecting suitable plant species is pivotal in achieving the goals of mine reclamation. As previously mentioned, afforestation is the optimal alternative in this context, primarily aimed at forest formation in reclamation. Hence, the research was conducted in the Gürgenpınar–Topluca mining fields in Bartın province, Turkey, which have significant mining areas. The selection of the best plant species for forestry purposes was made in this study. The study aims to apply the AHP and SWARA methods to analyze plant species selection using integrated multi-attribute decision-making. A hybrid approach of the AHP and SWARA methods was employed to weigh the criteria and prioritize the species. Thus, decision-makers (DMs) could objectively evaluate both criterion weights and species priorities.

The main objectives of this article can be outlined as follows:

(i) Development of an integrated SWARA-AHP hybrid method for tree species selection in post-mining afforestation. This method is referred to as the "WPA framework";
(ii) Determining the weights and importance rankings of the main and sub-criteria in selecting alternative species for rehabilitation afforestation;
(iii) Conducting a case study in surface mining areas to demonstrate the feasibility of this method;
(iv) Creating a resource to aid decision-makers in similar problems using the proposed method;
(v) Raising awareness about the use of MCDM methods in post-mining afforestation decision problems.

DM opinions were utilized in the evaluations. In this context, it is demonstrated that it is feasible to determine criterion weights and the most suitable tree species for mine site afforestation using the SWARA-AHP hybrid approach. Furthermore, the study indicates that optimal benefits are achieved in the results of afforestation decision problems evaluated by MCDM methods.

2. Materials and Methods

2.1. Case Study Area

This research was conducted in Bartın province and is considered a case study (Figure 1). Bartın is located in the Western Black Sea region. Bartın is surrounded by the Kure Mountains. The geology of the region is based on limestones and coal mudstones. Due to its climate and geological structure, the mining areas in Turkey's Western Black Sea region have favorable conditions for the growth of many tree species. Summers are hot, and winters are mild in the region. In 2023, the average temperature in the region was 25 °C. The highest temperature was 41 °C in July, and the lowest temperature was −24 °C in January. Annual precipitation in the region is 393 mm. Candidate plants should be able to adapt to these climatic conditions. Bartın is one of the richest regions of Turkey in terms of forest and mineral wealth. The study area is located between the towns of Gürgenpınar and Topluca, between 41°17′ and 41°44′ north longitude and 32°05′ and 32°46′ east latitude. There are several mining operations in the area, processing limestone, marl, cement, limestone, clayey limestone, and mudstone, reaching a size of 1300 ha. There is a 28.4 ha area that has ceased production and is undergoing rehabilitation [38].

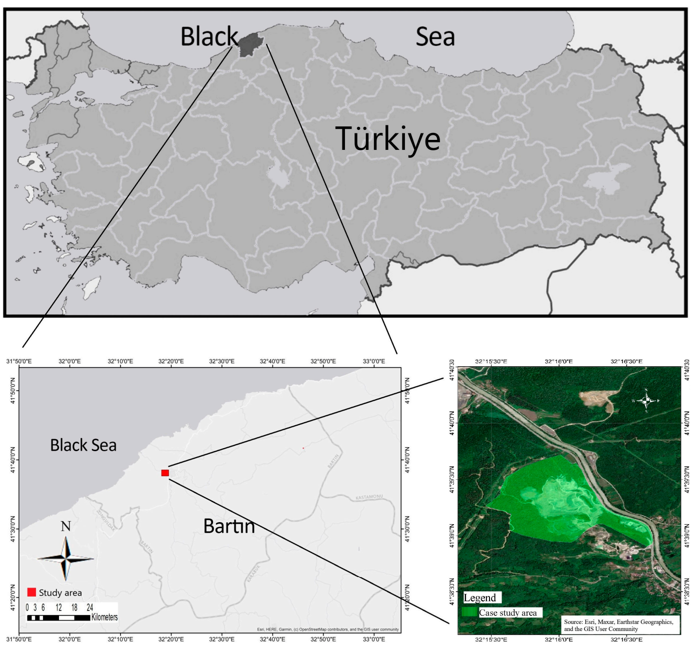

Figure 1. Case study area.

The area is located on the 10 km long Bartın–İnkumu Highway and is close to residential areas. Dust, noise, and explosions during mining activities have a negative impact on the lives of people in the surrounding area. Excavation pits, waste dumping sites, and high slopes disrupt aesthetics and damage the existing green texture. Loss of flora and fauna also occurs in the forested areas damaged during mining. During the extraction, processing, and transportation of minerals, there is pressure on the land, resulting in soil compaction. As a result of the change in topography and drainage patterns, rivers and groundwater are adversely affected. The damage caused by mining in the region is intensely perceived by the local population. Natural balance is completely disrupted in such areas, with sediments carried by wind and water erosion filling lakes, rivers, and dams and polluting drinking water sources, resulting in visual pollution and damage to aquatic life, agricultural areas, and settlements.

2.2. Criteria for Calculating Weights

To determine the weighting of criteria and tree species in post-mining afforestation, 10 people participated as DMs in this research. Information on DMs is given in Table A1. It is recommended that the number of DMs should be three or more in group studies [39]. Their selection process was based on their expertise, practical experience in relevant fields, and general knowledge of post-mined land rehabilitation afforestation. The information about the decision-makers is detailed. Due to the literature review and the opinions of the decision-makers, ten criteria were deemed appropriate for the study (see Table A2). The relevant criteria were categorized under three headings. According to the criteria groups, the criteria are defined as ecological (C1: Resistance, C2: Compatibility, C3: Pollution Prevention, C4: Erosion Prevention, C5: Growth Type and Strength), social (C6: Aesthetic Appearance, C7: Access to Plant Species), and economic (C8: Carbon Stock and Credit, C9: Reducing Afforestation Cost, C10: Economic Efficiency).

2.3. Tree Species to Prioritize

Bartın, which is considered a case study, is one of the richest regions of Turkey in terms of both forest and mining assets. Due to its climate and geological structure, the mining areas in the Western Black Sea region of Turkey have favorable conditions for the growth of many tree species. There are more than ten plant species suitable for rehabilitation afforestation. The main species are *Acer negundo*, *Acer campestre*, *Alnus glu-tinosa* subsp. *glutinosa*, *Ailanthus altissima*, *Carpinus betulus*, *Gleditsia triacanthos*, *Juglans regia*, *Pinus nigra*, *Pinus pinea*, *Pseudotsuga menziesii*, *Populus nigra* subsp. *nigra*, *Quercus robur* subsp. *robur*, *Robinia pseudoacacia* L., *Salix alba*, and *Ulmus minor* [40]. Many of these species can be used in post-mining afforestation in quarries. Tree species with a C/N ratio below 20 are prominent in rehabilitation plantations. For example, *Robinia pseudoacacia*, *Alnus glutinosa*, and *Alnus incana* have proven useful for biological soil remediation due to the nitrogen fixation of their roots and the favorable C/N ratio of their fallen leaves [41,42]. In the WPA framework, the AHP is used together with SWARA. When the number of alternatives in the AHP is high, it becomes difficult to construct comparison matrices. In cases with more than one decision-maker, comparisons can take a long time, as the number of alternatives increases [43]. As the number of comparisons increases, it is extremely difficult to keep the consistency ratio (CR) value within 0.1 [44]. For this reason, considering the AHP constraints, the number of tree species to be considered in the WPA calculations was limited to five.

In this research, a list of 15 tree species that have the potential to be used in post-mining afforestation was created. In this context, literature information [41,42] was also used. DMs evaluated these tree species according to the ecological, social, and economic criteria. Evaluations were made on a 5-point Likert-type scale according to the Delphi technique. The Delphi method is one of the basic tools for forecasting values in various types of issues. It uses the knowledge of experts, which is properly aggregated (e.g., in the form of descriptive statistics measures), and returns to the previous group of experts again, thus starting the next round of forecasting [45]. This scale was developed by Mancuso et al. [46]. On the scale, the following statements are included: "very important (5 points)", "somewhat important (4 points)", "somewhat important (3 points)", "I do not expect this (2 points)", and "this does not apply to me (1 point)". At the end of the two-stage process, the arithmetic mean of the DM scores was calculated (see Table A3). Tree species scoring above five (*Robinia pseudoacacia* L., *Alnus glutinosa* subsp. *Glutinosa*, *Populus nigra* subsp. *Nigra*, *Quercus robur* subsp. *Robur*, and *Salix alba* L.) were taken into account in the WPA framework calculations. Brief characteristics of the tree species considered in this context are given in Table 1.

Table 1. Brief characteristics of the tree species [47].

Brief Characteristic	**A1**	**A2**	**A3**	**A4**	**A5**
	***Robinia pseudoacacia* L.**	***Alnus glutinosa* subsp. *glutinosa***	***Populus nigra* subsp. *nigra***	***Quercus robur* subsp. *robur***	***Salix alba* L.**
Plant height [m]:	19.69	19.19	26.13	27.64	21.04
Life span:	Perennial	Perennial	Perennial	Perennial	Perennial
Life form:	Phanerophyte, Tree	Phanerophyte, Tree	Phanerophyte, Tree	Phanerophyte, Tree	Phanerophyte, Tree
Origin:	Neophyte Germany, Hungary, Bulgaria, Turkey	Native Europe, Turkey	Native Southern Europe, Mediterranean, Central Asia, Turkey	Native Europe, Western Caucasus, Turkey	Native United Kingdom, Caucasus, China, Turkey
Humidity relationship:	Dry	Wet	Wet	Mesic	Wet
Reaction relationship:	Slightly acidic to near-neutral	Slightly acidic to near-neutral	Alkaline	Slightly acidic to near-neutral	Alkaline
Nutrient relationship:	Eutrophic	Eutrophic	Eutrophic	Mesotrophic	Eutrophic
Salinity relationship:	Non-saline	Slightly saline or brackish	Non-saline	Non-saline	Non-saline
Broad habitat:	Scrub, Forest	Aquatic, Wetland, Scrub, Forest, Sparsely vegetated (incl. rock and scree)	Wetland, Scrub, Forest	Grassland (non-alpine, non-saline), Scrub, Forest	Aquatic, Wetland, Scrub, Forest, Sparsely vegetated (incl. rock and scree)
Post-mining afforestation relationship:	Successful in preventing erosion and post-mining afforestation [48,49]. The wood is valuable. High aesthetic value.	Successful in post-mining afforestation. Biomass source. It produces nitrogen nodules in its roots. To enrich the soil in terms of plant nutrients [50,51].	Successful in post-mining afforestation Important in the fight against climate change [52]. Cleans heavy metal pollution in the soil [53].	Successful in post-fire afforestation and post-mining afforestation [54]. Suitable for continental climate. Flood resistant [55].	Successful in post-mining afforestation. High phytoremediation efficiency [56].

2.4. WPA Framework

The overall objective of the analysis of weighting criteria and prioritization of species (WPA) is to weight plant species selection criteria and prioritize plant species in a hierarchical structure. This objective is placed at the first level of the hierarchy. At the second level, plant species selection criteria are ranked and weighted. At the third level, plant species are prioritized based on the weight of each criterion (Figure 2).

SWARA was preferred for criteria weighting (Level 2) due to its ease of calculation and application and ranking of the criteria according to their superiority. In species prioritization (Level 3), the AHP was easily used in the calculations since the number of variables evaluated, i.e., the number of species, was three. The SWARA-AHP hybrid approach was preferred for this context, which consists of three stages: objective, criteria weights, and type priorities.

In this paper, post-mined afforestation for the restoration of the Gürgenpınar–Topluca mine site, which was a forest before mining activities, is discussed. The aim is to determine the criteria and tree species to be used in this context. According to the hierarchy in Figure 2, 10 criteria that serve the purpose in Level 1 and the ecological, social, and economic characteristics in Level 2 were weighted. Then, the prioritization of the species given in Level 3 was carried out. In the assessments, ranking, weighting, and prioritization processes were carried out in a hierarchical order.

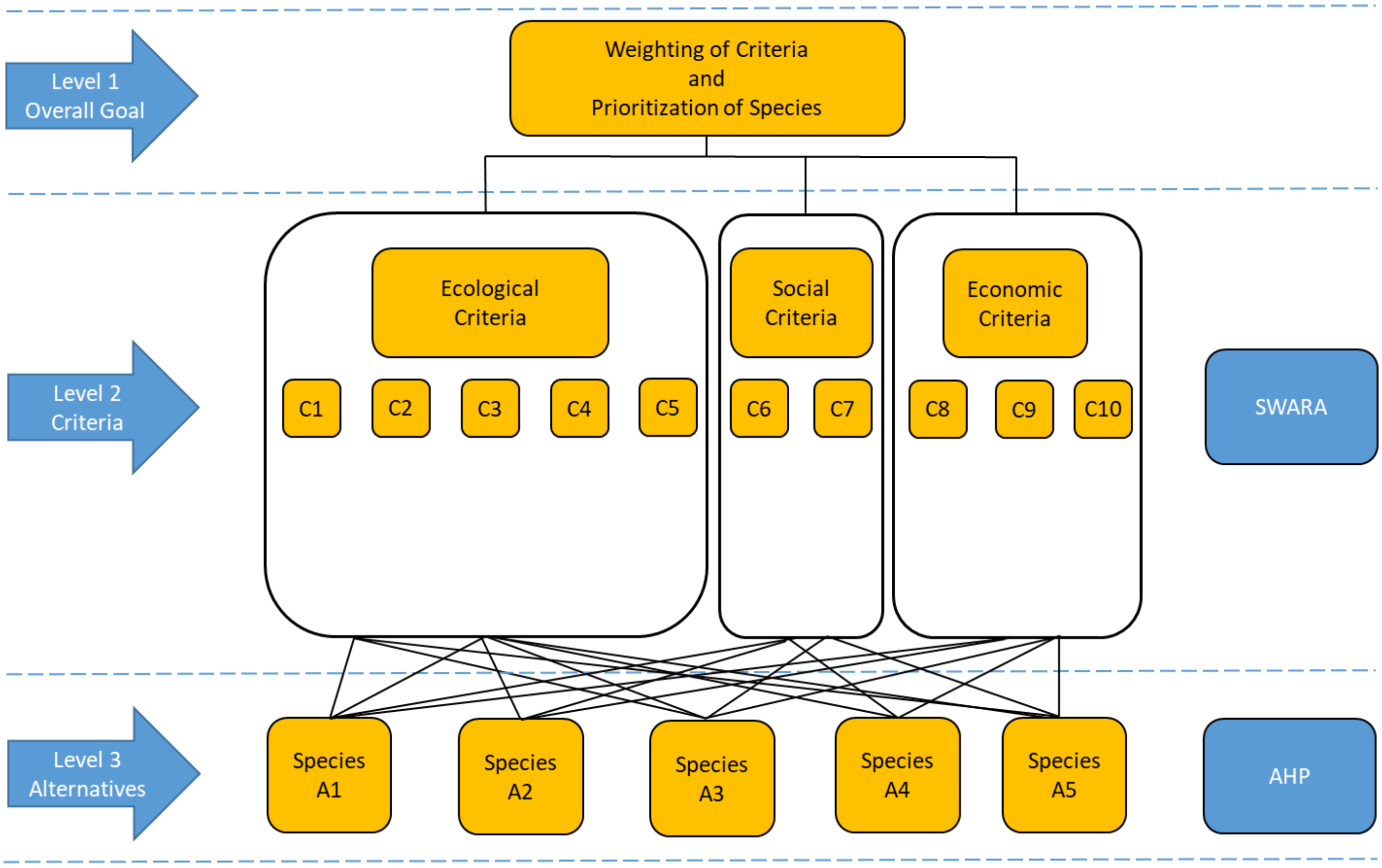

Figure 2. Hierarchical structure of WPA.

2.5. A Hybrid SWARA-AHP Method Integrated into WPA Framework

DMs select the best alternative under many criteria. MCDM techniques have been developed using iterative numerical techniques to assist the DM [57]. Evaluation criteria often try to achieve conflicting objectives simultaneously.

The problem is solved with an integrated SWARA-AHP hybrid approach developed on the WPA framework. SWARA was preferred for weighting the criteria, and the AHP was preferred for prioritizing the species. In this context, the SWARA-AHP hybrid approach was preferred for its short-time results and simplicity of calculations. With a sample application realized in this way, the study is different from other studies and has a unique structure.

On the other hand, many hybrid methods, such as SWARA-TOPSIS, SWARA-VIKOR, SWARA-COPRAS, SWARA-PROMETHEE, and SWARA-MOORA, are suitable to be used together [58–60].

A group decision-making procedure was designed to integrate the SWARA-AHP hybrid approach (Figure 3). In the goal-oriented calculations, ranking, weighting, and prioritization processes were carried out in a hierarchical order. In the analyses, group decisions were combined using the geometric mean approach, which is an accepted technique in the relevant field. In addition, expert opinions could be obtained consistently due to the ease of data evaluation [61].

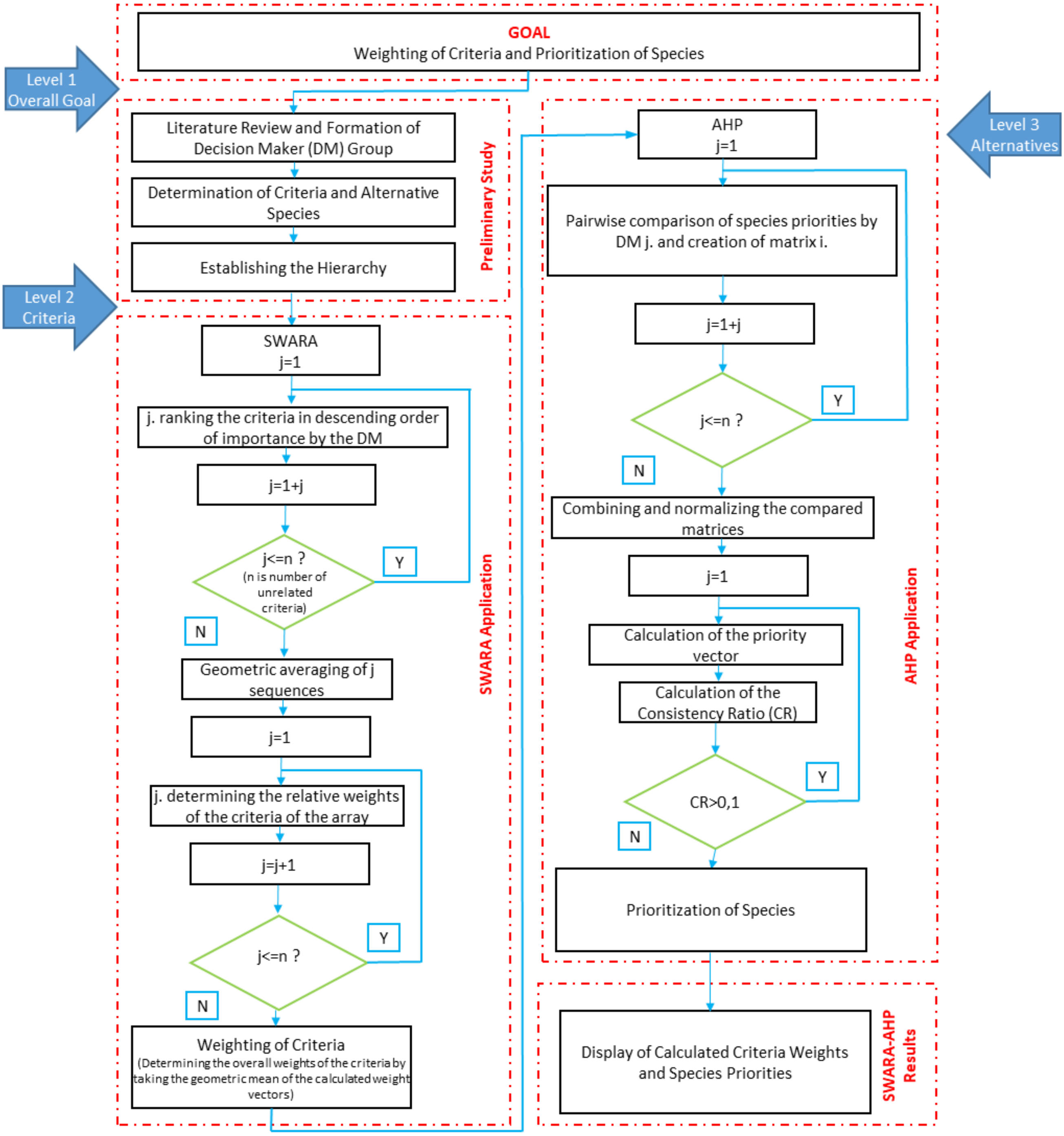

Figure 3. WPA framework of proposed SWARA-AHP-integrated MCDM methodology.

In the SWARA-AHP hybrid approach, the criteria required for the evaluations were brought together with the help of the literature review and expert opinions. In this research, ten DMs were involved in the decision-making for mine site afforestation. Hybrid approaches that utilize more than one expert opinion are not uncommon for group applications of MCDM. In fact, these hybrid applications enhance the quality of the study. On the other hand, hybrid approaches improve the quality of the findings by capturing as many opposing views as possible. The individual opinions of the experts are handled according to the group decision-making rules, and the solution method of the hybrid approach is used. In the SWARA-AHP hybrid approach, expert judgments are combined by taking the geometric mean of the data.

The AHP and SWARA methods used in the study are briefly introduced theoretically in this section, and the application processes are explained.

2.5.1. SWARA Method

The stepwise weight assessment ratio analysis (SWARA) method is one of the MCDM methods introduced into the literature by Keršuliene, Zavadskas, and Turskis in 2010. In the SWARA method, the criteria of alternatives are ranked from the most important to the least important [62]. First, the DM ranks the criteria in descending order of importance. In the case of multiple DMs, each DM ranks the criteria in descending order of importance.

Accordingly, there are as many criteria rankings as the number of DMs. In group decision-making, the overall ranking is determined by taking the geometric mean of the criteria rankings determined by the DMs. Based on the overall ranking, the DMs compare the criteria with the previous criterion starting from criterion 2. Each DM performs the comparison of the criteria in the overall ranking individually. The weights of the criteria are determined according to the SWARA method after the comparison of the DMs. As a result, the number of DMs results in priority vectors showing the weights of the criteria. The final overall priority values are obtained by taking the geometric mean of the priority value of each criterion [61–64].

The SWARA method was preferred because it supports group decision-making, has given good results in past applications, is easy to use, and gives DMs more opportunities to set priorities.

The analysis steps of the SWARA method are listed below [63]:

Step 1: Each DM prioritizes the criteria according to their importance. The most important criterion is usually given a score of 1.00 points, while the other criteria are given scores in multiples of 0.05 points. In a model with lth DM and n criteria, the priority assigned to criterion j by DM k is denoted as p_j^k, where $j = 1, 2, \ldots, n; k = 1, 2, \ldots, l$.

Step 2: The individual evaluations of all DMs are combined according to the geometric mean given in relation (1). Here, $\overline{p_j}$ denotes the combined relative importance score for each criterion.

$$\overline{p_j} = \left(\prod_{k=1}^{l} p_j^k \right)^{\frac{1}{l}}, \ \forall j. \tag{1}$$

Step 3: All criteria are ranked in descending order according to their relative importance scores. Then, starting with the second criterion, the relative importance (comparative importance) of the following criteria is calculated as the value of criterion j relative to the previous criterion $(j-1)$, denoted as s_j. According to this order, the comparative importance values of the geometric means are shown in Equation (2).

$$s_j = \overline{p}_{j-1} - \overline{p}_j, \ j = 2, \ldots n. \tag{2}$$

Step 4: The coefficients of each criterion are obtained by pairwise comparison and denoted as c_j. This coefficient indicates how important criterion $j+1$ is relative to criterion j. The c_j values are calculated, as in Equation (3):

$$c_j = \begin{cases} 1, \ j = 1; \\ s_j + 1, \ j = 2, \ldots n. \end{cases} \tag{3}$$

Step 5: The adjusted weights (s'_j) are calculated for all criteria in Equation (4):

$$s'_j = \begin{cases} 1, j = 1; \\ \dfrac{s'_{j-1}}{c_j}, j = 2, \ldots n. \end{cases} \tag{4}$$

Step 6: The final criteria weights (w_i) are calculated in Equation (5):

$$w_i = \frac{s'_j}{\sum_{j=1}^{n} s'_j},\ j = 1, 2, \ldots n. \tag{5}$$

2.5.2. AHP Method

The analytic hierarchy process (AHP) is one of the most widely used MCDM techniques in identifying, weighting, and prioritizing the types of criteria. This method, developed by Saaty [65], solves many problems, such as equipment selection in mining, mine site selection, post-mining land use type selection, and species selection in afforestation [25]. This interactive method allows the DM or group of DMs to express their preferences and discuss the results. In general, the AHP is based on the principle of decomposition, a series of "pair-wise comparisons", i.e., comparing criteria and alternatives against each other. It is based on the principle of synthesizing and prioritizing preferences. This method is also used to assign priorities to criteria and sub-criteria [66,67].

In the AHP, DMs evaluate their judgments about criteria and alternatives by considering qualitative and quantitative elements together. In addition, this method is frequently used to solve complex decision problems by considering multiple criteria. The AHP examines the components of complex problems in a hierarchical structure, and qualitative and quantitative information can be evaluated together in the analysis. The scores obtained at each level of the hierarchy are combined to reach a conclusion. The AHP reaches the result by multiplying the weight scores in the hierarchy [68].

The stages of AHP analysis are stated below in order:

Step 1: A hierarchical structure is created. Thus, DMs can easily compare criteria and alternatives. At the top of the hierarchical structure is the purpose of the model;

Step 2: DMs compare the criteria through pairwise comparisons. "Pairwise comparison matrices" are used in comparisons. In these matrices, the values on the prime diagonal are one. The relative importance of n and the superiority of each objective in terms of criteria are determined according to the importance scale consisting of numerical values between 1 and 9 in pairwise comparisons through judgments [68];

Step 3: The weights of the values in the benchmark matrix are determined. Each element of the matrix is divided by the sum of its column. Thus, vectors belonging to the columns are formed, and the column vectors are combined to form a normalized comparison matrix. The arithmetic mean of the row elements of the normalized matrix is taken. The column vector defined as the eigenvector is obtained, and a $(n \times n)$ pairwise comparison matrix is formed in Equation (6) [69].

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{6}$$
$$a_{iz} = \frac{1}{a_{iz}}, aii = 1, z = 1, 2, \ldots, n$$

Here, a_{iz} expresses the preference level of attribute i over attribute z and vice versa. The comparison matrix is then normalized by dividing each column of the pairwise comparison matrix by the sum of the entries of the corresponding column. The relative weight of attribute i results from the eigenvalue λ_I in this matrix. The resulting relative weight vector is multiplied by the element weight coefficients at higher levels to reach the hierarchy apex. The global weight vector W of the attributes is the result according to Equation (7).

$$W = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \tag{7}$$

The DM team considers Saaty's importance scale (Table 2) in pairwise comparisons. The pairwise comparison matrix is obtained by calculating the weighted geometric scores of the DMs in Equation (8).

$$a_{iz}^{g} = \prod_{x=1}^{X} (a_{iz}^{x})^{wx} \quad (8)$$

Table 2. Importance scale in AHP [67].

Intensity of Importance	Description
1	Equal Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Extreme Importance
2, 4, 6, 8	Intermediate Values

In Equation (8), the term a_{iz}^{g} represents the collective assessment of DMs on the relative importance of attributes i and z. The term a_{iz}^{x} represents x's DM's assessment of the relative importance of attributes i and z. The terms w_x and x represent the normalized weight and the number of DMs by DMx, respectively;

Step 4: The consistency ratio and consistency indicator of the criteria whose eigenvectors are created are calculated. The consistency ratio (CR) is calculated, as in Equations (9) and (10). The consistency ratio is an indicator of whether the comparisons made by DMs about the criteria are consistent. The consistency ratio should be less than 0.1. If it is higher, the calculations should be checked by re-evaluating the pairwise comparisons [70]. The CR value is obtained by calculating the largest eigenvector (λ_{max}) of the matrix in Formula (9).

$$\lambda_{max} = \frac{\sum_{i=1}^{n} \frac{d_i}{w_i}}{n} \quad (9)$$

The Randomness Index (RI) is used to calculate the consistency indicator (CR). The RI is the value needed to calculate the consistency ratio. Table 3 shows the RI values, which consist of fixed numbers and are determined according to the value of n [68]. The CR value is calculated according to Equation (10).

$$CR = \frac{\lambda_{max} - n}{(n-1) \cdot RI} \quad (10)$$

Table 3. Randomness Index (RI).

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

3. Results

3.1. Weighting of Criteria

In the study, SWARA was calculated according to the steps (steps 1–6) specified in the relevant method. In this context, the opinions of ten decision-making experts (DMs) were considered within the scope of SWARA. The combined relative importance scores for each criterion were calculated using individual evaluations. The SWARA calculations are given in Tables A4–A6 and Figure 4. This section is divided into subheadings. It should provide a concise and precise description of the experimental results and their interpretation, as well as the experimental conclusions that can be drawn.

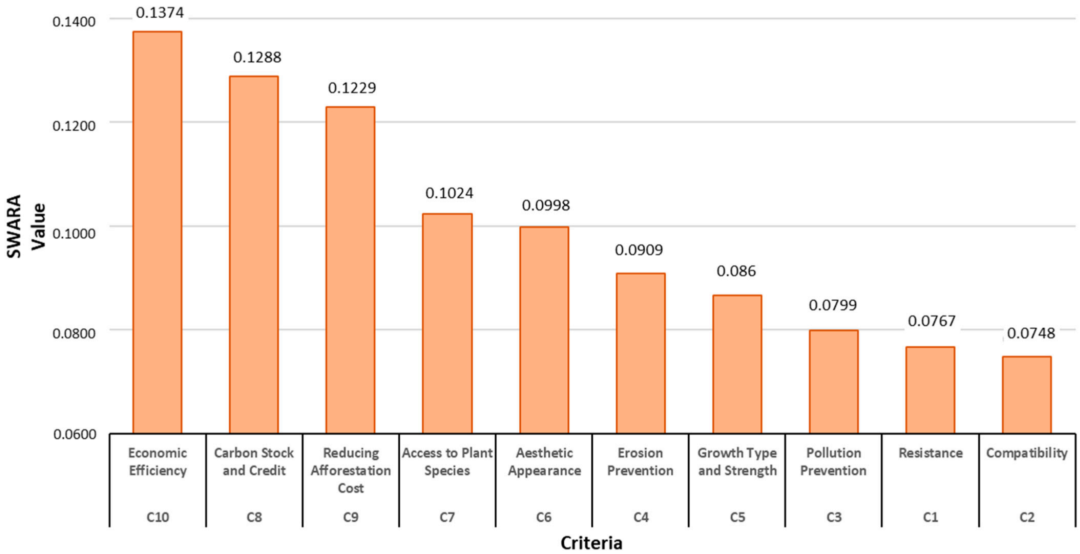

Figure 4. Global weights of criteria calculated by SWARA method.

3.2. Prioritization of Species

The AHP was calculated according to the steps (steps 1–4) specified in the relevant method (see Tables A7 and A8). Within the scope of the AHP, pairwise comparison opinions from ten DMs were considered. In this way, the priority values of the alternatives for each tree species were determined.

3.3. SWARA-AHP Results

Within the scope of the study, the SWARA and AHP results were combined under one roof. According to the results of the SWARA-AHP hybrid approach, A1 alternative was selected as the most suitable tree species for rehabilitation plantations since it received the highest priority value (Table 4). The ranking order is A1: *Robinia pseudoacacia* L. (0456) > A2: *Alnus glutinosa* subsp. *glutinosa* (0248) > A3: *Populus nigra* subsp. *nigra* (0146) > A4: *Salix alba* L. (0103) > A5: *Quercus robur* subs. *robur* (0048) (Figure 5).

Table 4. Summary representation of SWARA × AHP calculations.

	SWARA Results										
Criteria (c)	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	
	0.0767	0.0748	0.0799	0.0909	0.0866	0.1024	0.0998	0.1288	0.1229	0.1374	
Alternative	AHP Results										
A1	0.424	0.505	0.431	0.505	0.459	0.487	0.450	0.427	0.425	0.425	
A2	0.243	0.207	0.243	0.234	0.289	0.275	0.240	0.247	0.260	0.260	
A3	0.180	0.134	0.160	0.115	0.083	0.087	0.158	0.185	0.180	0.180	
A4	0.110	0.105	0.120	0.093	0.123	0.104	0.083	0.095	0.093	0.093	
A5	0.042	0.050	0.045	0.052	0.046	0.047	0.068	0.045	0.042	0.042	
	SWARA × AHP Results										
C / A	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	wi
A1	0.058	0.065	0.053	0.052	0.046	0.044	0.039	0.034	0.033	0.032	0.456
A2	0.033	0.027	0.030	0.024	0.029	0.025	0.021	0.020	0.020	0.019	0.248
A3	0.025	0.017	0.020	0.012	0.008	0.008	0.014	0.015	0.014	0.013	0.146
A4	0.015	0.013	0.015	0.009	0.012	0.009	0.007	0.008	0.007	0.007	0.103
A5	0.006	0.006	0.006	0.005	0.005	0.004	0.006	0.004	0.003	0.003	0.048

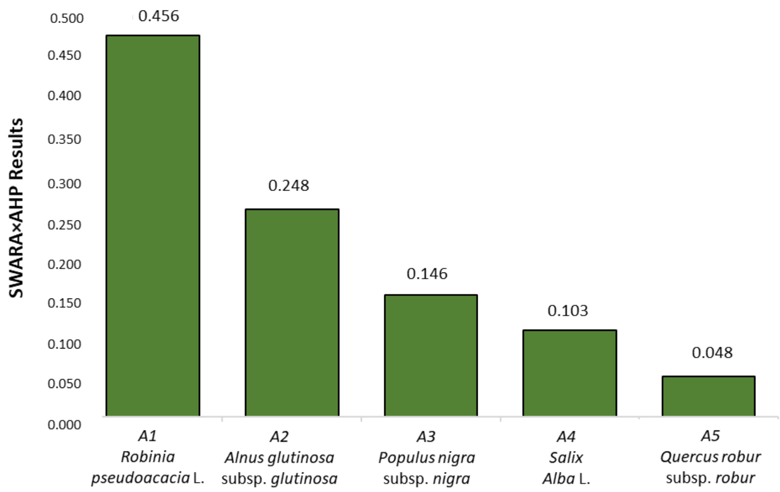

Figure 5. Prioritization of plant species.

4. Discussion

The main objective of this research was to select suitable plant species for mine reclamation. However, the author also endeavored to implement a robust MCDM approach, specifically SWARA-AHP, in selecting the plant types as an additional objective of this work.

4.1. Criteria and Sub-Criteria

In this context, 10 criteria under three criteria groups were ranked and weighted by SWARA. The criteria with the highest degree of importance in rehabilitation afforestation for DMs were included in the "economic criteria" group and constituted the first three places in the overall ranking (C10: 0.1374, C8: 0.1288, and C9: 0.1229). It is stated in many studies [71–73] that economic criteria have an important place in mine rehabilitation feasibility studies. For this reason, plants that are intended to reduce afforestation costs should be preferred when selecting plant species in rehabilitation afforestation. On the other hand, productivity should also be adopted as a principle in plant species selection. This will contribute to the sustainability of rehabilitation projects. Effective projects will also encourage the efficient use of resources. The carbon sequestration capacity of plant species in rehabilitation afforestation should be another important criterion to be considered in afforestation investments. Afforestation with species with high carbon sequestration capacity will effectively combat climate change and reduce carbon emissions.

Studies involving species contributing significantly to the aesthetic value in afforestation areas will enhance visual appeal. On the other hand, ease of access to the selected plant species is another factor affecting the success of afforestation. For this reason, the cultural kit will provide practicality to the decision-maker in the process of initiating and maintaining afforestation projects.

The plant species selected for good afforestation should help reduce soil and water pollution. In particular, plants that can contribute to reducing problems such as industrial pollution should be preferred. Plant species should be selected with root systems and soil retention properties that help prevent or reduce soil erosion. This improves soil fertility and reduces the effects of environmental erosion. The growth rate, size, and overall robustness of the selected plant species are important for the success of the rehabilitation process. The rehabilitation process can be accelerated by choosing fast-growing, strong, and durable plants.

In the selection of plant species in rehabilitation plantations, it is important to prefer species that are resistant to plant diseases and pests. This ensures the healthy and sustainable development of plant populations and can reduce maintenance costs. The selected plant species should be compatible with the climate, soil, and other environmental conditions of the rehabilitation area. Regional compatibility is critical to ensure successful plant growth and ecosystem stability. The compatibility and interactions of plant species with other species in the rehabilitation area should be considered. Adaptation should be encouraged, and negative interactions should be avoided. Thus, ecosystem balance can be maintained.

In fact, the criteria groups considered in this publication and all the criteria under them have an important place in mine rehabilitation afforestation. However, in rehabilitation investments and feasibility studies, economic criteria have an important place in making afforestation decisions. Likewise, rehabilitation works for mines mean the closure of a mining operation. Such activities are considered a cost element rather than a return for the enterprise. For this reason, rehabilitation costs should be included in feasibility reports at the stage of deciding to mine a site, that is, at the very beginning of the project. In this way, it will be possible to return mines that have completed their economic life back to nature.

4.2. Alternatives

For the plant species considered, it should be noted that the selection of suitable plant species for mine reclamation is closely related to edaphic and topographic factors as well as climatic conditions. Among soil properties, saturation moisture, organic matter, limestone, and the C/N ratio greatly influence the distribution and selection criteria of plants. Furthermore, the relationship of plants with environmental factors was the basis for the selection of plant species [74]. Plant species were selected based on the mentioned criteria. The identification of plant species adapted to the environmental conditions in a particular area will also provide guidance for the remediation and regeneration of similar mine sites. In this context, the selected species will be adapted to the mining conditions in the Gürgenpınar–Topluca region and will be suitable for the regeneration of the mine.

In the SWARA-AHP hybrid approach, analyses were carried out with ten DMs to determine the weights of the criteria and determine the priorities of the species. In the Gürgenpınar–Topluca area, *Robinia pseudoacacia* L. was found to be the most suitable species for mine site rehabilitation afforestation, with 0.502 in line with the regional conditions and criteria. On the other hand, the results of the study show that *Alnus glutinosa* subsp. *glutinosa* with 0.288 and *Populus nigra* subsp. *nigra* with 0.210 were also suitable for afforestation.

In mine rehabilitation afforestation, it is important to select suitable plant species and determine the afforestation criteria to be used in the selection process. *Robinia pseudo-acacia* L. is considered an important plant because it is the most common plant in the region. It was considered an alternative plant in terms of erosion prevention in the rehabilitation plan, especially due to its suitability to the conditions of the site. This species may also have some advantages, such as its C/N ratio and carbon accumulation. *Alnus glutinosa* subsp. *glutinosa* is highly compatible with the climatic conditions of the Western Black Sea region, and this species is also important for aesthetic value and carbon sequestration. *Populus nigra* subsp. *nigra* is very good at wastewater absorption and is considered to have a high potential for Gürgenpınar–Topluca mine rehabilitation. Likewise, the chance of afforestation success and carbon accumulation in rehabilitation works to be carried out with these species is high, and the afforestation costs are low compared to other species. Furthermore, it is difficult to ignore the selection of preferences due to the role that plant presence plays in the rehabilitation of the mine; for this reason, only existing species were considered in the assessments.

A study conducted by Ebrahimabadi (2016) [73] in the Chadormaloo iron mine of Iran identified key criteria for plant species selection in mine reclamation, including landscape characteristics, resistance to pests and diseases, growth consistency and method, availability, economic viability, soil protection, water storage, and pollution prevention. Four alternatives—*Artemisia sieberi*, *Zygophyllum*, *Salsola yazdiana*, and *Halophytes types*—were assessed in the Chadormaloo iron ore mine. Subsequently, utilizing the fuzzy AHP approach, Artemisia sieberi was determined as the optimal plant species for mine rehabilitation. Furthermore, Ebrahimabadi et al. (2018) [75] conducted a comparative analysis of the PROMETHEE and fuzzy TOPSIS methods for selecting the most suitable plant species to reclaim the Sarcheshmeh copper mine. Six vegetation types, such as pistachio, wild almond, ephedra, astragalus, salsola, and tamarix, were considered and adapted to the mine's conditions. The PROMETHEE and fuzzy TOPSIS methods were then employed to assess these alternatives based on seven criteria, including appearance, resistance to pests and diseases, growth characteristics, accessibility, economic feasibility, soil-water conservation, and pollution control. As a result, wild almond was identified as the optimal choice according to both methods. These findings highlight the robustness of the MCDM approaches in selecting appropriate plant species for mine rehabilitation efforts.

4.3. Comparison to Other MCDM and Group Decision-Making Studies

Within the scope of the study, the SWARA-AHP hybrid approach, which is a robust MCDM approach, was applied and the opinions of DMs, i.e., experts, were analyzed. SWARA-AHP is a suitable method for selecting criteria, plant species, or other multi-criteria in decision-making problems.

In fact, both criteria and tree species can be prioritized using the AHP only. However, since 10 criteria are considered in this survey, it is not easy to compare the criteria one by one with the others using the AHP. In comparisons of seven or more criteria, the AHP consistency rates are often not among the desired levels. Therefore, in problems with more than seven variables, the AHP alone is insufficient as a solution [67]. In such problems, the ranking method should be preferred instead of comparison in criteria weighting. For this purpose, many methods, such as SWARA, TOPSIS, and VIKOR, are used together with the AHP [60].

SWARA has been successfully applied to the solution of many MCDM problems. SWARA is used in various fields due to its suitability for experts to work together and its simple application [61–63,76–81]. For this reason, SWARA is also defined as an expert-oriented method in the literature [81]. The number of comparisons required in SWARA is significantly lower compared to other methods. In the data obtained through questionnaires, the consistent responses of the participants make the SWARA method more successful. In the SWARA method, participants evaluate the criteria freely, without employing any scale [82].

4.4. Limitations of the Study and Future Improvements

The SWARA-AHP approach stands as a suitable tool for the selection of plant species or addressing other multi-criteria decision-making challenges. Nonetheless, this approach presents certain constraints and drawbacks, as elucidated below.

In this approach, the DM is only asked to make a judgment based on the criteria specified in this context. At this point, the DM is required to indicate the relative importance of one criterion over another or to prefer one alternative to another. However, when the number of alternatives and criteria increases, the pairwise comparison process becomes cumbersome, and the risk of inconsistency arises. For this reason, instead of using a single method, such as the AHP, there is a need for hybrid approaches where more than one method is considered together. Researchers or mine site managers should create an appropriate hybrid approach according to the nature of the problem they have. In this context, many methods, such as COPRAS, PROMETHEE, and MOORA, which are among the methods of MCDM, are suitable to be used together with both SWARA and the AHP.

5. Conclusions

Multi-criteria decision-making (MCDM) approaches, especially hybrid methods such as SWARA-AHP, are considered appropriate methods for species selection for post-mining afforestation. This approach has contributed to making the right decisions in a rational decision-making process. MCDM effectively reflects the experience of DMs.

As previously mentioned, criteria weighting and species prioritization for rehabilitation afforestation were performed to determine the environmental, social, and economic use possibilities of post-mining sites. Establishing a decision-supported WPA framework is important for the adoption of an analytical method with the following benefits:

- DMs' opinions and preferences are taken into account in identifying plant species that can be used in rehabilitation afforestation. The attributes of DMs' preferences are integrated into the MCDM approach;
- The mathematical operations on the WPA framework are designed in a hierarchical order to understand various and contradictory attributes. This facilitates a more comprehensive and accurate decision-making process in criteria prioritization and plant species selection;
- Results for post-mining afforestation are presented to all stakeholders through an understandable algorithm. The data are accessible, and analyses and calculations can be audited.

In post-mining afforestation, it is important to determine appropriate criteria to reduce environmental impacts and select appropriate plant species for mining areas. In this context, the Bartın region, which includes important mining areas of Turkey, was selected as a case study. The Gürgenpınar–Topluca mine site was analyzed to determine the compatibility of local plants with the soil, water, and climatic conditions. In this paper, the forest was selected as the post-mining land use type for rehabilitation afforestation, and criteria and candidate tree species were identified for this purpose. The SWARA-AHP hybrid approach is suitable for weighting criteria and prioritizing plant species. Through this approach, criteria, such as resistance compatibility, pollution prevention, erosion prevention, growth type and strength, aesthetic appearance, access to plant species, carbon stock and credit, reducing afforestation cost, and economic efficiency, can be effectively ranked and weighted under the group of ecological, social, and economic criteria.

The analyses show that economic criteria play an important role in rehabilitation investments and feasibility studies. This is because post-mining afforestation is considered a cost rather than a return for the enterprises in the Gürgenpınar–Topluca mining region. The results demonstrate that economic criteria are important in the decision-making process. In the Gürgenpınar–Topluca mining area, prioritizing species with low afforestation costs and high productivity and carbon sequestration potential can be adopted as a strategy for sustainable land management and successful forest establishment. This strategy contributes to the efforts to combat climate change and reduce carbon emissions. For successful forest restoration in the region, environmental, economic, and social uses of the post-mining land use type should be considered. Based on these criteria, the best candidates for revegetation were prioritized as follows: *Robinia pseudoacacia* L., *Alnus glutinosa* subsp. *glutinosa*, *Populus nigra* subsp. *nigra, Salix alba L.*, and *Quercus robur subs. robur*.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

WPA	Analysis of weighting criteria and prioritization of species
MCDM	Multiple-criteria decision-making
AHP	Analytic hierarchy process

SWARA	Stepwise weight assessment ratio analysis
CR	Consistency ratio
DMs	Decision-makers

Appendix A

Table A1. Information about DMs.

Education Level	Specializations	Experience	Department
PhD	Forestry	25 years	Planning
PhD	Forestry	20 years	Pollution and Resistance
PhD	Forestry	21 years	Water
PhD	Forestry	18 years	Aesthetics
PhD	Forestry	15 years	Carbon
PhD	Environmental	28 years	Erosion
MSc	Environmental	15 years	Afforestation
MSc	Soil	16 years	Solid Waste
BSc	Civil	30 years	Planning
BSc	Civil	30 years	Planning

Table A2. Assessment criteria.

Criteria Group	Label	Criterion	Description
Ecological	C1	Resistance	Plants fight both diseases and insect pests in nature. In rehabilitation plantations, species that do not cause direct and indirect losses and are resistant to diseases and insects should be preferred.
	C2	Compatibility	In rehabilitation, compatibility with the region and other species is important in species selection. Plants with high adaptability make good use of nutrients, water, heat, and light in the environment. They develop protection against drought, parasites, or extreme temperature changes.
	C3	Pollution Prevention	Mining waste is one of the most undesirable pollutants for the environment. Each plant has the ability to eliminate different pollutants at different levels. For this reason, afforestation should be undertaken with plants that have a high potential to eliminate pollution.
	C4	Erosion Prevention	Rehabilitation sites should be afforested with species that have high wind resistance and water and soil retention capacity, as well as fast and well-growing species. In this way, the risk of soil, water, and wind erosion can be reduced.
	C5	Growth Type and Strength	In afforestation, the growth type and strength of the plant are important for its attachment to the soil, its growth, and its continuity in the field.
Social	C6	Aesthetic Appearance	Aesthetic appearance forms the basis of human beings' view of nature. Prioritizing species with high aesthetic value in rehabilitation has a positive effect on the appearance of the site and human psychology [83].
	C7	Access to Plant Species	In rehabilitation works, access to and procurement of plant species to be planted on the site is important. In afforestation, saplings that are easy to procure and adapt to local conditions should be selected from regional nurseries.
Economic	C8	Carbon Stock and Credit	Carbon stock refers to the process that prevents the release of carbon into the atmosphere over a certain period of time [84]. Prioritizing species with a high carbon storage capacity in afforestation is important for reducing the amount of carbon dioxide in the atmosphere and for the enterprise to receive carbon credits. This will also contribute to the prevention of global warming [85].
	C9	Reducing Afforestation Cost	In rehabilitation feasibility studies, many cost items, such as surveys, land preparation, fencing, and planting, should be well defined. Methods with low-cost items and species suitable for these methods reduce the cost of afforestation. Likewise, candidate species for afforestation should not only be ecologically and technically healthy but also socially acceptable and economically cost-effective.
	C10	Economic Efficiency	Economic efficiency is an important criterion affecting costs and investment decisions. In mining investments, the economic return of the ore to be obtained and the damage to nature should be analyzed well. In fact, the cost of reclamation works to be carried out on lands devastated after mining should be included in investment calculations in the initial feasibility studies. Likewise, the tree species to be used in rehabilitation afforestation is an important variable in calculating economic efficiency.

Table A3. Species suitable for rehabilitation afforestation in the study area and Delphi score.

	Species	Delphi Score Mean	Included in WPA Framework
1	A1—*Robinia pseudoacacia* L.	4.35	Yes
2	A2—*Alnus glutinosa* subsp. *glutinosa*	4.20	Yes
3	A3—*Populus nigra* subsp. *nigra*	3.82	Yes
4	A4—*Quercus robur* subsp. *robur*	3.22	Yes
5	A5—*Salix alba* L.	3.22	Yes
6	*Pinus pinea*	2.65	No
7	*Pseudotsuga menziesii*	2.64	No
8	*Acer negundo*	2.60	No
9	*Acer campestre*	2.56	No
10	*Ailanthus altissima*	2.54	No
11	*Carpinus betulus*	2.50	No
12	*Gleditsia triacanthos*	2.48	No
13	*Juglans regia*	2.42	No
14	*Pinus nigra*	2.41	No
15	*Ulmus minör*	2.40	No

Table A4. Evaluations of DMs for criteria and merged relative importance SWARA scores.

Criteria	Individual Evaluations of DMs p_j^k										Merged Relative Importance Score $\overline{p}_j$
	DM_1	DM_2	DM_3	DM_4	DM_5	DM_6	DM_7	DM_8	DM_9	DM_{10}	
C_1	0.40	0.15	0.20	0.50	0.60	0.35	0.20	0.25	0.50	0.60	0.337013
C_2	0.50	0.20	0.30	0.20	0.40	0.45	0.25	0.30	0.20	0.40	0.302801
C_3	0.60	0.25	0.50	0.35	0.25	0.55	0.30	0.35	0.35	0.25	0.356503
C_4	0.65	0.40	0.40	0.40	0.75	0.70	0.55	0.55	0.40	0.75	0.536673
C_5	0.35	0.50	0.65	0.25	0.65	0.40	0.40	0.65	0.25	0.65	0.446138
C_6	0.80	0.65	0.60	0.55	0.55	0.80	0.45	0.60	0.55	0.55	0.601182
C_7	0.95	0.45	0.55	0.65	0.50	1.00	0.65	0.55	0.65	0.50	0.623497
C_8	1.00	0.70	1.00	0.90	0.80	0.95	0.70	1.00	0.95	0.95	0.887299
C_9	0.70	1.00	0.80	0.80	0.85	0.75	0.95	0.90	0.70	0.90	0.829290
C_{10}	0.90	0.90	0.90	1.00	1.00	0.85	0.90	0.95	1.00	1.00	0.938450

Table A5. Calculation of final criteria weights using the SWARA method.

Criteria	Merged Relative Importance Score (Ordered) $\overline{p}_j$	Comparative Importance s_j	Coefficient Value c_j	Corrected Weight Value s'_j	Final Weight Value w_j	Rank
C_{10}	0.938450	-	1.000000	1.000000	0.1365	1
C_8	0.887299	0.051151	1.051151	0.951338	0.1298	2
C_9	0.829290	0.058009	1.058009	0.899178	0.1227	3
C_7	0.623497	0.205793	1.205793	0.745714	0.1018	4
C_6	0.601182	0.022315	1.022315	0.729437	0.0995	5
C_4	0.536673	0.064509	1.064509	0.685234	0.0935	6
C_5	0.446138	0.090535	1.090535	0.628346	0.0857	7
C_3	0.356503	0.089635	1.089635	0.576657	0.0787	8
C_1	0.337013	0.019490	1.019490	0.565633	0.0772	9
C_2	0.302801	0.034211	1.034211	0.546922	0.0746	10

Table A6. Summary representation of SWARA calculations.

Criteria	SWARA Results									
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
	0.0772	0.0746	0.0787	0.0935	0.0857	0.0995	0.101898	0.1298	0.1227	0.1365

Table A7. Weight values of tree species found by AHP calculations.

Alternative	Ranking Values Obtained					Normalized Value of Decision Matrix					Weight
C1	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	S1
A1	1.000	3.000	7.000	3.000	5.000	0.498	0.634	0.525	0.246	0.217	0.424
A2	0.333	1.000	5.000	3.000	5.000	0.166	0.211	0.375	0.246	0.217	0.243
A3	0.143	0.200	1.000	5.000	7.000	0.071	0.042	0.075	0.410	0.304	0.180
A4	0.333	0.333	0.200	1.000	5.000	0.166	0.070	0.015	0.082	0.217	0.110
A5	0.200	0.200	0.143	0.200	1.000	0.100	0.042	0.011	0.016	0.043	0.042
CR < 0.05	2.010	4.733	13.343	12.200	23.000	1.000	1.000	1.000	1.000	1.000	1.000
C2	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	S2
A1	1.000	7.000	7.000	3.000	5.000	0.550	0.789	0.600	0.290	0.294	0.505
A2	0.143	1.000	3.000	3.000	5.000	0.079	0.113	0.257	0.290	0.294	0.207
A3	0.143	0.333	1.000	3.000	3.000	0.079	0.038	0.086	0.290	0.176	0.134
A4	0.333	0.333	0.333	1.000	3.000	0.183	0.038	0.029	0.097	0.176	0.105
A5	0.200	0.200	0.333	0.333	1000	0.110	0.023	0.029	0.032	0.059	0.050
CR < 0.05	1.819	8.867	11.667	10.333	17.000	1.000	1.000	1.000	1.000	1.000	1.000
C3	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	S3
A1	1.000	3.000	5.000	3.000	5.000	0.484	0.616	0.524	0.294	0.238	0.431
A2	0.333	1000	3.000	3.000	5.000	0.161	0.205	0.315	0.294	0.238	0.243
A3	0.200	0.333	1.000	3.000	5.000	0.097	0.068	0.105	0.294	0.238	0.160
A4	0.333	0.333	0.333	1.000	5.000	0.161	0.068	0.035	0.098	0.238	0.120
A5	0.200	0.200	0.200	0.200	1.000	0.097	0.041	0.021	0.020	0.048	0.045
CR < 0.05	2.067	4.867	9.533	10.200	21.000	1.000	1.000	1.000	1.000	1.000	1.000
C4	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	S4
A1	1.000	5.000	7.000	5.000	5.000	0.574	0.734	0.574	0.349	0.294	0.505
A2	0.200	1.000	3.000	7.000	3.000	0.115	0.147	0.246	0.488	0.176	0.234
A3	0.143	0.333	1.000	1.000	5.000	0.082	0.049	0.082	0.070	0.294	0.115
A4	0.200	0.143	1.000	1.000	3.000	0.115	0.021	0.082	0.070	0.176	0.093
A5	0.200	0.333	0.200	0.333	1.000	0.115	0.049	0.016	0.023	0.059	0.052
CR < 0.05	1.743	6.810	12.200	14.333	17.000	1.000	1.000	1.000	1.000	1.000	1.000
C5	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	S5
A1	1.000	5.000	7.000	3.000	5.000	0.533	0.764	0.488	0.246	0.263	0.459
A2	0.200	1.000	5.000	7.000	5.000	0.107	0.153	0.349	0.574	0.263	0.289
A3	0.143	0.200	1.000	1.000	3.000	0.076	0.031	0.070	0.082	0.158	0.083
A4	0.333	0.143	1.000	1.000	5.000	0.178	0.022	0.070	0.082	0.263	0.123
A5	0.200	0.200	0.333	0.200	1.000	0.107	0.031	0.023	0.016	0.053	0.046
CR < 0.05	1.876	6.543	14.333	12.200	19.000	1.000	1.000	1.000	1.000	1.000	1.000
C6	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	S6
A1	1.000	7.000	7.000	3.000	5.000	0.550	0.812	0.568	0.243	0.263	0.487
A2	0.143	1.000	3.000	7.000	7.000	0.079	0.116	0.243	0.568	0.368	0.275
A3	0.143	0.333	1.000	1.000	3.000	0.079	0.039	0.081	0.081	0.158	0.087
A4	0.333	0.143	1.000	1.000	3.000	0.183	0.017	0.081	0.081	0.158	0.104
A5	0.200	0.143	0.333	0.333	1.000	0.110	0.017	0.027	0.027	0.053	0.047
CR < 0.05	1.819	8.619	12.333	12.333	19.000	1.000	1.000	1.000	1.000	1.000	1.000
C7	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	S7
A1	1.000	7.000	5.000	5.000	3.000	0.533	0.807	0.436	0.246	0.231	0.450
A2	0.143	1.000	5.000	7.000	3.000	0.076	0.115	0.436	0.344	0.231	0.240
A3	0.200	0.200	1.000	7.000	3.000	0.107	0.023	0.087	0.344	0.231	0.158
A4	0.200	0.143	0.143	1.000	3.000	0.107	0.016	0.012	0.049	0.231	0.083
A5	0.333	0.333	0.333	0.333	1.000	0.178	0.038	0.029	0.016	0.077	0.068
CR < 0.05	1.876	8.676	11.476	20.333	13.000	1.000	1.000	1.000	1.000	1.000	1.000
C8	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	S8
A1	1.000	3.000	7.000	3.000	5.000	0.498	0.634	0.525	0.243	0.238	0.427
A2	0.333	1.000	5.000	3.000	5.000	0.166	0.211	0.375	0.243	0.238	0.247
A3	0.143	0.200	1.000	5.000	7.000	0.071	0.042	0.075	0.405	0.333	0.185
A4	0.333	0.333	0.200	1.000	3.000	0.166	0.070	0.015	0.081	0.143	0.095
A5	0.200	0.200	0.143	0.333	1.000	0.100	0.042	0.011	0.027	0.048	0.045
CR < 0.05	2.010	4.733	13.343	12.333	21.000	1.000	1.000	1.000	1.000	1.000	1.000
C9	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	S9
A1	1.000	3.000	7.000	3.000	5.000	0.498	0.642	0.525	0.243	0.217	0.425
A2	0.333	1.000	5.000	3.000	7.000	0.166	0.214	0.375	0.243	0.304	0.260
A3	0.143	0.200	1.000	5.000	7.000	0.071	0.043	0.075	0.405	0.304	0.180
A4	0.333	0.333	0.200	1.000	3.000	0.166	0.071	0.015	0.081	0.130	0.093
A5	0.200	0.143	0.143	0.333	1.000	0.100	0.031	0.011	0.027	0.043	0.042
CR < 0.05	2.010	4.676	13.343	12.333	23.000	1.000	1.000	1.000	1.000	1.000	1.000
C10	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	S10
A1	1.000	3.000	7.000	3.000	5.000	0.498	0.642	0.525	0.243	0.217	0.425
A2	0.333	1.000	5.000	3.000	7.000	0.166	0.214	0.375	0.243	0.304	0.260
A3	0.143	0.200	1.000	5.000	7.000	0.071	0.043	0.075	0.405	0.304	0.180
A4	0.333	0.333	0.200	1000	3.000	0.166	0.071	0.015	0.081	0.130	0.093
A5	0.200	0.143	0.143	0.333	1000	0.100	0.031	0.011	0.027	0.043	0.042
CR < 0.05	2.010	4.676	13.343	12.333	23.000	1.000	1.000	1.000	1.000	1.000	1.000

Table A8. Summary representation of AHP calculations.

Alternative	AHP Results									
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
A1	0.424	0.505	0.431	0.505	0.459	0.487	0.450	0.427	0.425	0.425
A2	0.243	0.207	0.243	0.234	0.289	0.275	0.240	0.247	0.260	0.260
A3	0.180	0.134	0.160	0.115	0.083	0.087	0.158	0.185	0.180	0.180
A4	0.110	0.105	0.120	0.093	0.123	0.104	0.083	0.095	0.093	0.093
A5	0.042	0.050	0.045	0.052	0.046	0.047	0.068	0.045	0.042	0.042

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