Physicochem. Probl. Miner. Process., 60(5), 2024, 193741

http://www.journalssystem.com/ppmp

Physicochemical Problems of Mineral Processing

ISSN 1643-1049

Investigation of the effects of coal properties, environmental conditions, and costs on coal drying method selection using multi-criteria decision-making method (AHP)

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Abstract: In this study, coal properties and environmental characteristics were investigated, and the most suitable coal drying method was determined for four different regions (Armutcuk, Afsin, Can, and Soma) where Türkiye's significant coal reserves are located, using the AHP method (Analytical Hierarchy Process). Installation and operating cost, drying rate, environmental risk, and land area parameters were used as selection criteria in the AHP method. After analyzing the physical and chemical properties of coals from four different regions, changes in moisture content and drying costs were calculated according to various drying methods (rotary, microwave, solar, and air). The results indicated that the solar energy data of the regions were determined to be 1315, 1610, 1400, and 1444 kWh/m^2-year for Armutcuk, Afsin, Can, and Soma, respectively. Accordingly, solar energy drying systems are expected to be preferred in regions with high solar energy. However, with the effect of other selection criteria, it was determined that although the Can region receives less solar energy than the Soma region, the microwave drying method should be used for the coal of the Soma region, and the solar energy drying method should be used for the coal of Can region. Microwave and solar energy methods should be preferred for drying the coals of the Armutcuk and Afsin regions, respectively. As in many sectors, multi-criteria decision-making methods are necessary for optimum equipment/method selection in the mining sector. In conclusion, this study showed that the AHP method can be used when appropriate criteria are thoroughly determined.

Keywords: coal, drying, AHP, solar energy, microwave

1. Introduction

It is inevitable to reduce the moisture content of coal to increase coal quality, however, the cost of coal-drying processes is quite high for industries. There are four different drying methods most commonly used in coal production (rotary, microwave, solar, and air), and their drying efficiency varies according to the physical and chemical properties of the coal and the environmental characteristics of the production location (solar energy, climate changes, sufficient space, etc.). For this reason, choosing the most appropriate drying method for coal and production region characteristics is necessary to minimize costs and energy use. When selecting a coal drying method, only moisture content is generally considered.

The most accessible and economical fossil fuel in the world is lignite coal. However, the moisture content of lignite coal, which varies between 25-60%, directly affects its functionality and quality (Tahmasebi et al., 2011). Meanwhile, there are some difficulties, especially in grinding, separation, and classification processes for high-moisture coals. Additionally, the moisture content of coals is an

DOI: 10.37190/ppmp/193741

essential parameter in technological applications to obtain high-efficiency and quality products. The moisture limitations imposed by coal evaluation processes such as combustion, briquetting, coking, gasification, low-temperature carbonization, and liquefaction are different from each other. Dewatering of coal, in economic terms, is as essential as de-ashing coal. Reducing moisture by 10% benefits approximately $3 per ton (Seehra et al., 2007).

Various coal-drying technologies have been developed for coal dewatering. These technologies may use hot air, combustion gases, or superheated steam as the drying medium. When superheated steam is used as the drying medium, high temperature and high vapor pressure are created within the materials during the drying process, thus promoting moisture transfer through the materials. In traditional drying systems, heat flow is from the particle surface to the particle center, and moisture mass flow is from the particle to the surface. Commonly used conventional drying systems are rotary dryers, hot air fluidized bed dryers, superheated steam fluidized bed dryers (SFB), vibrating fluidized bed dryers, shaft dryers, and pneumatic dryers (Tahmasebi et al., 2011). Classical dewatering/drying equipment (filter press, vacuum disc filter, rotary dryer etc.) can remove moisture from coal, especially before it is fed to a thermal power plant. Classical dewatering/drying equipment meets the energy they consume with either electrical energy, the primary energy type, or fossil fuels. This increases the cost and negative environmental impacts. For this reason, devices that use renewable energy sources should be preferred over classical mechanical dewatering/drying devices. Renewable energy technologies offer an excellent opportunity to reduce greenhouse gas emissions and global warming by replacing traditional energy sources. Optimum use of these resources minimizes environmental impacts, produces minimal secondary waste, and is sustainable according to current and future economic and societal needs (Pikon and Mujumdar, 2006; Demir, 2016; Guo et al. al., 2022). In the solar energy drying system, drying is carried out in a particular volume, considering external air temperature, relative humidity, air circulation, and solar radiation. These dryers can be used alone or with fossil fuel systems. Although solar energy technologies vary widely in terms of method, material, and technological level, they can be divided into two main groups: photovoltaic and solar thermal technologies (Kalogirou, 2014). Among solar energy systems, parabolic concentrator systems are more advantageous than other solar energy systems in terms of cost and ease of manufacturing (Demir, 2016; Liu et al., 2017).

Many coal properties affect coal drying efficiency, and, therefore, the choice of drying method. In particular, coal's natural moisture (Standish et al., 1988; Binner et al., 2014), surface area, thermal conductivity coefficient, and void ratio are among these features (Seehra et al., 2007; Tahmasebi et al., 2011). In addition, land adequacy and costs are effective parameters in choosing the coal drying method. If the solar energy drying method is preferred, the production area's solar energy potential is also essential (Demir, 2016). These parameters must be evaluated to determine the most appropriate coal drying method to minimize costs and environmental damage. For this reason, determining the coal drying method in industrial applications is a multiple-attribute decision-making (MADM) problem. There are many multi-criteria decision-making methods in the literature. Fuzzy multiple attribute decision-making (FMADM), analytic hierarchy process (AHP), TOPSIS, Fuzzy TOPSIS (FT), PROMETHEE, and Fuzzy Analytic Hierarchy Process (FAHP) are the most used of these methods. FMADM, AHP, and TOPSIS can be understood and applied more quickly than other methods. Decision-makers can easily learn and use these methods to solve problems (Yavuz, 2015). In this context, the use of multi-criteria decision-making methods in mining has been studied in many areas and is given in Table 1.

As seen in Table 1, multi-criteria decision-making methods have been used in many mining areas, but there is no study on drying method selection. In addition, the most used decision-making method is AHP, which was used in this study due to its ease of use and flexible results. Accordingly, AHP determined the most suitable method for drying coals with different properties produced from four regions: rotary dryers, microwave dryers, solar energy, and air-drying methods. Operating costs, the land area, drying speeds, environmental risks, and installation costs were determined as selection criteria. All drying devices used in the study were designed on a laboratory scale, and a parabolic trough-type dryer, which can be made suitable for industrial use, was used for drying with solar energy. As in many sectors, the mining industry requires the application of multi-criteria decision-making methods for optimum equipment/method selection. For this reason, this study was conducted to determine the optimum method for coal drying using the AHP method.

Table 1. Use of multi-criteria decision-making methods in mining

Problem	**Method**	**References**
Underground mining method selection problem	AHP	Gupta and Kumar, 2012
Underground mining method selection problem	AHP and FMADM	Yavuz, 2015
Green supply chain management	AHP	Shen et al., 2015
Select suitable plant species for reclamation	FAHP	Ebrahimabadi, 2016
Slope stability analysis of open-pit mine	AHP	Lou et al., 2016
Prevent occupational health risks in mining	AHP	Bao et al., 2017b
Mine occupational health and safety management	FAHP	Bao et al., 2017a
The decision to outsource coal mining	FAHP	Modak et al., 2017
Analysis of supply chain for mining equipment companies	AHP	Chand et al., 2018
Groundwater vulnerability assessment in coal mining	AHP	Karan et al., 2018
Groundwater potential zones in coal mining	AHP	Kumar and Krishna, 2018
Human factors analysis of significant coal mine accidents	AHP	Liu et al., 2018
Sensitivity analysis for risk assessment in mining projects	AHP	Banda, 2019
Assessing environmental conflicts in the titan mining	FAHP and TOPSIS	Dao et al., 2019
Bulldozers are available in the open-pit lignite mine.	AHP	Djenadic et al., 2019
Analysis of coal mine occupational disease hazard	AHP	Cheng et al., 2021
Mining method optimization	AHP and TOPSIS	Guo et al., 2021
Optimization model for sustainable transportation in mining	AHP	Gupta et al., 2021
The risk management of natural hazards in surface mining	FAHP	Spanidis et al., 2021
Identifying security factors influencing coal mineworkers	AHP	Chen et al., 2022
Selection of the safety risk analysis technique for mining	AHP	Hazrathosseini, 2022
Green mining strategy selection	FAHP	Wu et al., 2022
Selection of abandoned underground mines for energy storage	AHP	De la Flor et al., 2023
Global cooperation in asteroid mining	AHP and TOPSIS	Fan et al., 2023
Safety risk assessment and management of open-pit mining	AHP	Li et al., 2023
Evaluation of green mine construction in coal mining	AHP	Liu et al., 2023
Selection of optimum mine planning for open-pit mines	AHP and TOPSIS	Ozdemir, 2023
Sustainable transformation of surface coal mines	AHP	Spanidis et al., 2023
Evaluation of coal mine safety risk	AHP and TOPSIS	Su et al., 2023
Risk analysis in surface mines	AHP and FT	Sherin and Raza, 2024

2. Materials and methods

2.1. Materials

The samples used in this study were obtained from the regions where Türkiye's significant coal deposits (Zonguldak-Armutcuk (AR), Kahramanmaras-Afsin (AF), Canakkale-Can (CN), and Manisa-Soma (SM)). The type and moisture content of coals in these regions differ from each other. There is also solar energy potential, land use constraints, and environmental differences on a regional basis. Therefore, choosing which type of drying method during coal production in these regions requires multi-criteria decision-making. Moisture, ash, and volatile matter analyses in coal samples' original, air-dry, and dry bases were performed according to ISO 1171, 562, 589, and ASTM D 2013 standards. Additionally, C, H, N, and S contents and calorific values were determined using Leco 628CHN, Leco 628S, and Leco AC 500 devices, respectively (ASTM D 5373, D 4239, D 5142, and D 5865). Accordingly, the proximate and ultimate analysis results of the materials on an original, air-dry, and dry basis are presented in Table 2. The particle size distribution determined using laboratory sieves is shown in Fig. 1.

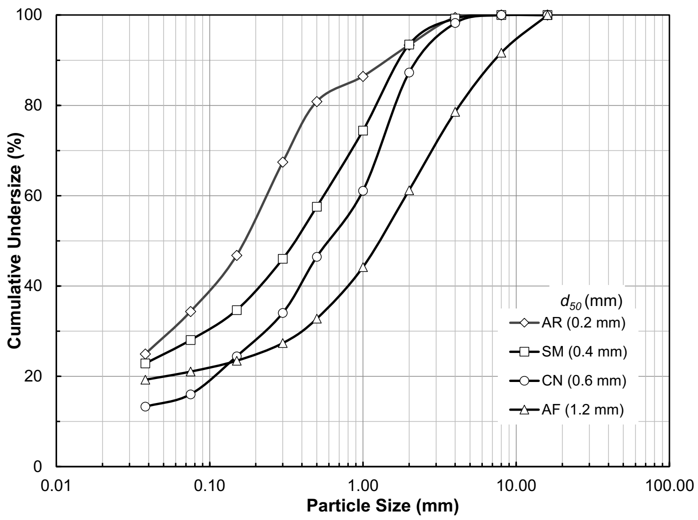

Fig. 1. Results for particle size distributions of coal samples

Table 2. The proximate and ultimate analysis results of the coals

		Proximate Analysis (%)				Elemental Analysis (%)				Calorific Value (Kcal/Kg)	
Region	Basis*	Moisture	Ash	Volatile Matter	Fixed Carbon	C	H	N	S	Low	High
AR	AsR	7.80	44.18	13.43	34.59	37.27	2.58	0.63	0.96	3311	3453
	AD	2.10	46.91	14.26	36.73	39.57	2.74	0.67	1.02	3506	3666
	D	-	47.92	14.57	37.52	40.42	2.80	0.68	1.04	3627	3745
AF	AsR	54.30	12.53	16.77	16.40	21.68	1.57	0.49	1.82	1662	1877
	AD	36.50	17.41	23.30	22.79	30.12	2.18	0.68	2.53	2386	2608
	D	-	27.42	36.70	35.89	47.44	3.44	1.07	3.98	3863	4107
CN	AsR	19.40	35.28	22.27	23.05	27.39	2.28	0.54	5.69	2436	2600
	AD	13.60	37.82	23.87	24.71	29.36	2.44	0.58	6.10	2637	2787
	D	-	43.77	27.63	28.60	33.98	2.83	0.67	7.06	3065	3226
SM	AsR	16.10	30.88	24.51	28.51	35.69	2.78	0.68	0.80	2986	3157
	AD	7.70	33.97	26.96	31.36	39.26	3.06	0.75	0.88	3288	3473
	D	-	36.81	29.21	33.98	42.54	3.31	0.81	0.95	3617	3762

*AsR: Original (As Received), D: Dry, AD: Air-Dry

The maturation process of coals from peat to anthracite is called charring; in this process, volatile and moisture content decreases, and carbon content increases. For this reason, coals with low volatile matter and moisture content and high carbon content are called high-grade coals (Keshavarz et al., 2018). As can be seen from Table 2, AR coals have the highest degree of charring. These coals have the lowest moisture (7.80%), volatile matter (13.43%) contents, and the highest carbon content (34.59%). According to ASTM D388-05 and proximate analysis results of coals, AR, AF, CN, and SM coals are classified as bituminous with medium carbonization, lignite, sub-bituminous, and high-volatile bituminous coal, respectively. Since the differences in coals will directly affect the drying times, they will also affect when choosing the appropriate drying method for the region.

2.2. Methods

The drying method (rotary dryer, microwave dryer, solar energy, and natural drying) was chosen using AHP to dry coals with different properties obtained from four regions in this study. AHP is a decision-making method based on multi-criteria analysis, widely developed in industry, production, finance, business, and project management. The method is a simple and easy problem-solving tool that does not require complex or costly software. AHP is an Eigenvalue approach for pairwise comparison of components based on attributes and alternatives. A pairwise comparison matrix n×n is created, where n is the number of items to compare. After hierarchy structuring, a pairwise comparison matrix is created for each level, where a nominal discrete scale from one to nine is used for evaluation. Then, the Maximum Eigenvalue value and Consistency Index (*CI*) are calculated (Eqs. 1 and 2). The *CR* must be calculated to determine whether the resulting *CI* is acceptable (Eq. 3). Generally, a *CR* value of 0.10 or lower is considered acceptable. If the maximum Eigen value, *CI*, and *CR* are satisfactory, the decision is taken according to these values; otherwise, the process is repeated until these values reach the desired range (Saaty, 1990; Saaty, 2016).

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^{n} \left\{ \frac{\sum_{j=1}^{n} a_{ij} * w_j}{w_i} \right\} \tag{1}$$

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{2}$$

$$CR = \frac{CI}{RI} \tag{3}$$

where λ_{max} is the maximal or principal Eigenvalue, n is the matrix size, a_{ij} is an element of the matrix, w_j and w_i are the j^{th} and i^{th} elements of Eigenvalues, respectively, and RI is random indices.

To compare different drying methods, drying experiments with a rotary dryer, a microwave dryer, an air dryer, and a solar energy were carried out (Fig. 2). Due to the size of the rotary dryer devices used in enterprises, a device working with the same drying principle was used to represent the rotary dryer to carry out experimental studies on a laboratory scale. In the microwave dryer drying experiments, a laboratory-type device with a power of 1.15 kW was used. For drying with solar energy, a parabolic corrugated type dryer suitable for industrial use was designed (Demir, 2016) (Fig. 2).

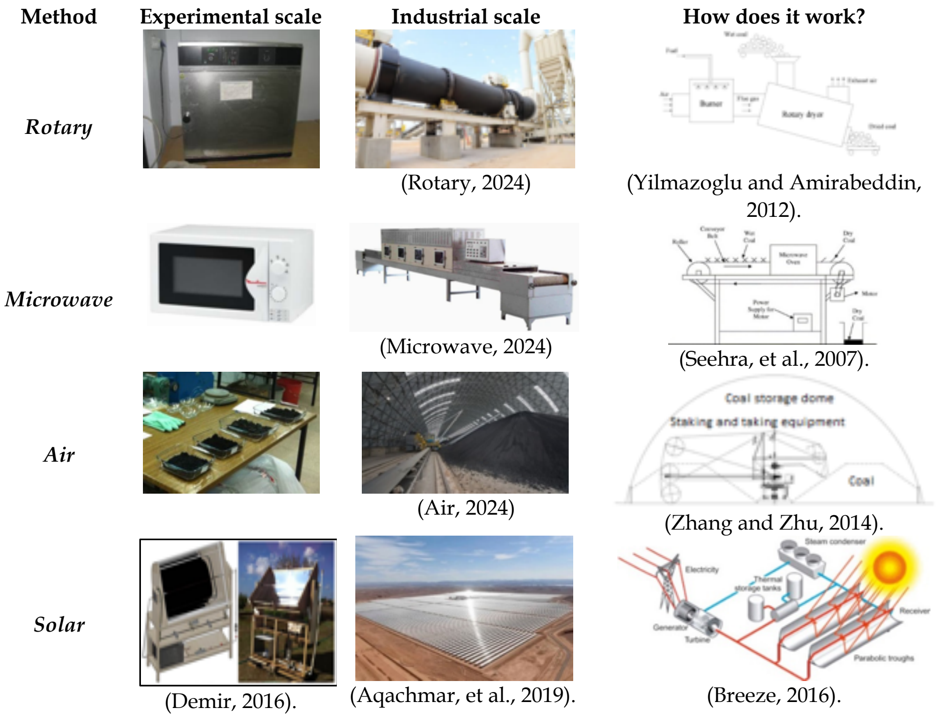

Fig. 2. Dryers used in the experimental studies

In Türkiye, which is one of the suitable countries in terms of solar energy, the average annual sunshine duration is 2741 hours (total of 7.5 hours per day), and the average total radiation intensity is 1527 kWh/m²-year (total of 4.18 kWh/m² per day). (GEPA, 2016). China, which has ~40% of the world's installed capacity, has an average annual sunshine duration of ~2000 hours (Zhang et al., 2022; Chadly et al., 2024). The solar energy and sunshine duration of the Zonguldak-Armutcuk (AR), Kahramanmaras-Afsin (AF), Canakkale-Can (CN), and Manisa-Soma (SM) regions are given in Table 3 (GEPA, 2016).

Table 3. Solar energy and sunshine duration in the regions (GEPA, 2016)

Region	Annual Sunshine (h)	Longest Sunshine (h)	Daily Sunshine (h)	Annual Total Radiation Intensity (kWh/m²)	Daily Solar Radiation Intensity (DSR) (kWh/m²)
AR	2403	10.73	6.58	1315	3.60
AF	2883	12.13	7.90	1610	4.41
CN	2749	11.85	7.53	1400	3.84
SM	2791	11.96	7.65	1444	3.96

As seen in Table 3, the most extended sunshine periods are 10.73, 12.13, 11.85, and 11.96 hours for Armutcuk, Afsin, Can, and Soma regions, respectively, annual sunshine durations are 2403, 2883, 2749, and 2791 hours, and total radiation intensities are 1315, 1610, 1400 and 1444 kWh/m^2-year, respectively. These values are above the world average (GEPA, 2016). Based on the selection criteria for the AHP method, operating costs, land area, drying rates, environmental risks, and installation costs of drying methods were considered. These criteria vary depending on the coal properties and conditions of the production region. Coal drying plants in Türkiye are established with capacities of 20-250 t/h, depending on the size of the coal mine capacity. For this reason, considering the average capacity of 100 t/h, the parameters affecting the drying method selection were calculated and determined. To compare the experiments carried out at the laboratory scale with the industrial scale, the costs were calculated by increasing the capacity according to the 0.6 rule (Mishra and Klimpel, 1987).

Operating cost calculations considered the energy required for drying and the energy consumed by the auxiliary tools/devices used. During the rotary and microwave drying experiments, the energy consumed by the devices was measured with an energy meter. Operating cost calculations were made using the energy consumption data obtained. In the air-drying operating cost, the energy consumption of the electrical equipment (spreader, mixer, collector, conveyor, etc.) used during the material's laying, turning, and collecting is considered. In drying with a solar dryer, the energy costs required for the electrical parts of the device used (circulation pump and conveyor belt) were considered. It is stated that the electricity production cost per MW of parabolic trough-type equipment in solar energy systems is ~5 million € (Kalogirou, 2014). In the area calculations of drying methods, catalog data for rotary dryers and microwave dryers were used. The required area for air-drying at 100 t/h was calculated using the 1 g/cm^2 rate specified in the drying standards. For the solar dryer, the area covered by parabolic troughs was used. As additional structures, combusters in rotary dryers, belts in microwave dryers, auxiliary equipment in air-drying, and drying chambers and belts in solar drying are considered. While an area of 15 - 20 decares is needed for a one MW power plant based on photovoltaic (PV) technology, an area of 35 decares is required for parabolic trough-type solar energy systems (Yilmazoglu and Amirabeddin, 2012; Kalogirou, 2014; Demir, 2016). For drying speeds, another critical parameter in dryer selection, calculations were made based on 5% moisture loss rates. In selecting drying methods, environmental risks that may occur during operation (greenhouse gas emissions, CO_2 emissions, etc.) were considered together with the ecological values of the region where the dryer is planned to be installed. Fossil fuels such as powder coals with low calorific value, fuel oil, or natural gas provide energy to rotary dryers used in coal drying (Jangam et al., 2011). For this reason, their emissions to the environment are higher compared to other drying methods. Since direct electrical energy is used in microwave drying, the emission rates released into the environment during operation are lower than in rotary dryers. Emissions from electrical equipment used during air-drying, laying, turning, and collecting the material were considered. Drying with solar energy is the most environmentally friendly method since very few emission devices are used (Hand, 2000; Pikon and Mujumdar, 2006; Yilmazoglu and Amirabeddin, 2012; Demir, 2016).

3. Results and discussion

In the experiments, four different drying methods evaluated within the scope of the study were applied. The amount of 1 g/cm^2 material specified in coal moisture standards was used in the drying experiments carried out in the rotary, microwave, air, and with a solar dryer. The drying rate values of different methods determined according to the test results are shown in Fig. 3a-d.

3.1. Rotary drying

The drying process with a rotary dryer takes place from the outside to the inside via thermal conduction. In the first stage of drying coals with a rotary dryer, the coal surface is heated and surface moisture is removed. Afterwards, the inner parts of the coal continue to heat up and the body moisture begins to be removed. Thermal conduction capacities of coals, the amount and type of moisture content (such as surface moisture, and hygroscopic moisture) are effective on the drying rate (Pikon and Mujumdar, 2006). In rotary dryers with the same ambient temperature (105°C), coals' surface moisture removal rates are close to each other. Experiments have shown that CN coals have a relatively faster drying rate than other regions.

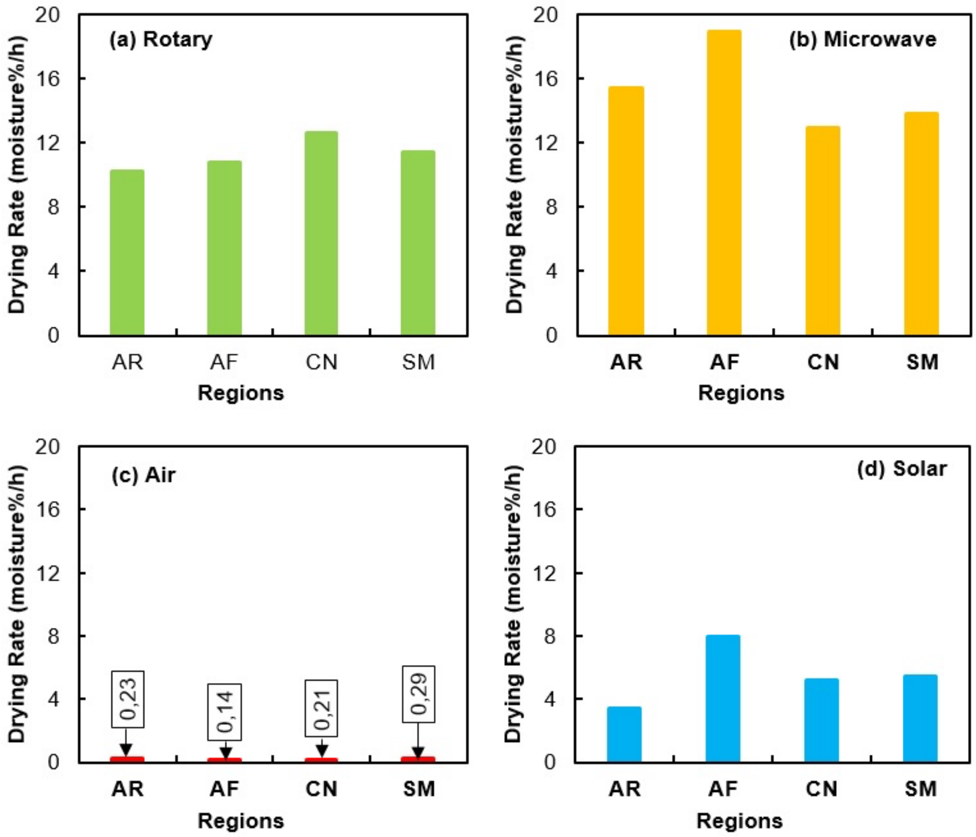

Fig. 3. Drying rate results for (a) the rotary (b) microwave (c) air, and (d) solar methods

As seen from Fig. 3a, the initial moisture of coals from AR, CN, and SM regions were 7.8%, 19.4%, and 16.1%, respectively, and it was determined that they reached the dry base within 2 h with the rotary dryer. In addition, the coal sample from the AF region, with an initial moisture of 54.3%, reached the dry base in ~4 h. The drying rate values of rotary dryer coals were measured as 10.2, 10.8, 12.6, and 11.4 moisture%/h for AR, AF, CN, and SM, respectively. The original coal bed moisture content can be up to 70%, but the moisture in the coal does not exist as pure water. Heteroatoms in coal form soluble functional groups such as carboxylates and amines. Inorganics such as sodium (Na^{+}), calcium (Ca^{2+}), and magnesium (Mg^{2+}) ions can bind to the carboxylate ($-COO^{-}$) and exist as salts in coal moisture (Binner et al., 2014). Therefore, during the coal drying process, there are different moisture losses and calorific values simultaneously as can be seen in Fig. 3a.

3.2. Microwave drying

In microwave dryers, the drying process occurs from inside to outside. In the first stage of drying coals with a microwave dryer, the water in the coal begins to be heated and removed (Pickles, et al., 2014).

For this reason, in the drying experiments conducted with microwave dryers, it was observed that AF coals with the highest hygroscopic moisture reached a higher drying speed than coals from other regions (Fig. 3b).

The drying rate values of coals for the microwave dryer were measured as 15.38, 18.89, 12.93, and 13.85 moisture%/h for AR, AF, CN, and SM, respectively. In a study conducted by Binner et al. (2014), the dielectric properties of many coals during heating and cooling were measured, and it was stated that coal moisture determines their microwave heating properties. A significant decrease in dielectric properties between 80°C and 180°C results from moisture loss. Additionally, this study stated that the drying rates of lignite using 650 W microwave heating were faster than traditional thermal drying at 80°C (Standish et al., 1988; Binner et al., 2014). Since moisture may remain in the thin capillaries of bituminous coals, it is impossible to remove it using microwaves (Seehra et al., 2007). In another study conducted by Tahmasebi et al. (2011), the effects of particle size, output power, coal sample weight, and ash yield were determined when three lignite coals were dried in a 1300 W microwave oven. As expected, increasing the output power and decreasing the sample size causes the drying rate to increase.

3.3. Air drying

The air-drying speed of coals is relatively low compared to other drying methods. In air drying experiments conducted at the same ambient temperature (20°C), it was observed that SM coals had a relatively higher drying rate than coals from other regions (Fig. 3c). The drying speed values for air-drying were measured as 0.23, 0.14, 0.21, and 0.29 moisture%/h for AR, AF, CN, and SM, respectively.

3.4. Solar drying

In a parabolic trough-type dryer that uses solar energy, the region's solar energy directly affects the heat created in the drying chamber (Demir, 2016). In the drying experiments carried out by taking into account the average solar energy data for each region within the scope of the study, it was observed that the drying speeds of AF coals were higher than the coals of other regions due to the higher average solar energy of the AF region compared to other regions (Fig. 3d).

According to the test results of four different coal samples, the solar drying system has a higher drying rate than the air-drying method, at values of 3.17%, 7.86%, 3.23%, and 5.15% for AR, AF, CN, and SM, respectively. As seen in Fig. 3d, since the AF region has the highest daily solar radiation intensity (DSR), the drying rate with solar energy was higher than in other regions. The drying rate with solar energy in the AF region was almost equal to that of the rotary dryer. The AR region has the lowest drying rate because it has the lowest average solar energy. The drying speed values for solar drying, these values were measured as 3.40, 8.00, 5.24, and 5.44 for AR, AF, CN, and SM, respectively.

3.5. Drying method by regions

Regional drying rates of coal samples according to the drying method are given in Fig.4. When Fig. 4 is examined, it is seen that the microwave drying method provides the fastest results for coals in all regions. Similarly, the rotary drying method is in the 2nd place, solar drying is in the 3rd place and air drying is in the last place. Even though the order is the same, coals may show different drying behavior in different methods due to the difference in their structures. As can be seen in Fig. 4(b), there is an approximately 2-fold speed difference (18.89%/h - 10.80%/h) between the microwave method and the rotary drying method due to the high inherent moisture of AF coals. As in Fig. 4(c), this difference is very low in CN coals (12.93%/h - 12.60%/h). Moreover, if the drying method was chosen based on only one parameter, the microwave drying method would be the most suitable. However, for choosing the most appropriate drying method, the AHP method was used to see how the result would change when other parameters were taken into account. Additionally, all parameters (calculated and measured) affecting the choice of drying method are given in Table 4.

To start solving the problem with the AHP method, the problem is structured in a hierarchy of different levels consisting of objectives, criteria, and alternatives. After the hierarchy was structured, a pairwise comparison matrix for each level was created for four regions (Table 5).

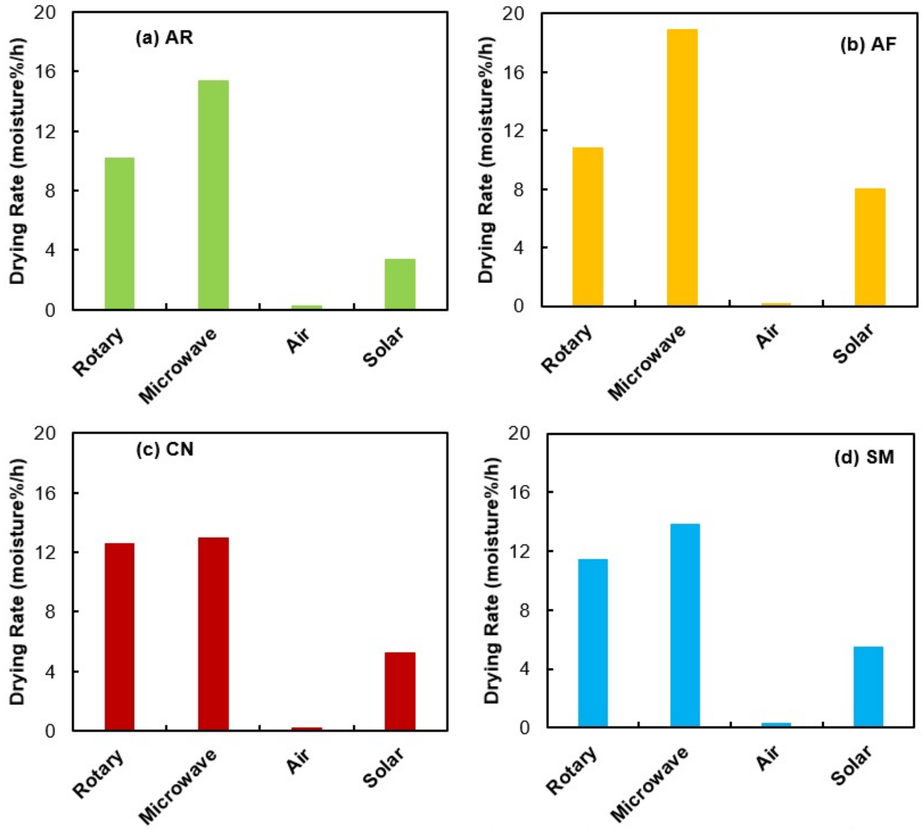

Fig. 4. Drying rate results for (a) AR (b) AF (c) CN, and (d) SM

Table 4. Values of selection criteria (calculated and measured)

Drying Method	Cost			Area		Drying Rate (Moisture%/h)	Envr. Risk
	Capital ($)	Installation ($)	Operating ($/t)	Types of Equipment (m²)	Auxiliary Equipment (m²)		
AR							
Rotary	2613507	3542478	1.59	2362.5	709	10.20	4
Microwave	248351	275946	0.23	1687.5	338	15.38	3
Air	1500000	1650000	0.01	15000.0	1500	0.23	2
Solar	14445000	17334000	0.01	46596.8	2330	3.40	1
AF							
Rotary	2613507	3542478	1.59	2362.5	709	10.80	4
Microwave	248351	275946	0.23	1687.5	338	18.89	3
Air	1500000	1650000	0.01	15000.0	1500	0.14	2
Solar	32400000	38880000	0.01	104516.1	5226	8.00	1
CN							
Rotary	2613507	3542478	1.59	2362.5	709	12.60	4
Microwave	248351	275946	0.23	1687.5	338	12.93	3
Air	1500000	1650000	0.01	15000.0	1500	0.21	2
Solar	19905000	23886000	0.01	64209.7	3210	5.24	1
SM							
Rotary	2613507	3542478	1.59	2362.5	709	11.40	4
Microwave	248351	275946	0.23	1687.5	338	13.85	3
Air	1500000	1650000	0.01	15000.0	1500	0.29	2
Solar	19110000	22932000	0.01	61645.2	3082	5.44	1

Table 5. Pairwise comparison matrix of main criteria and normalized weight

Main Criteria	Region	Operating Cost	Area	Drying Rate	Environmental Risk	Capital Cost	Normalized Weight
Operating Cost	AR	0.20	0.19	0.20	0.22	0.22	0.21
	AF	0.24	0.25	0.19	0.33	0.33	0.27
	CN	0.14	0.11	0.22	0.13	0.22	0.17
	SM	0.24	0.25	0.19	0.33	0.33	0.27
Land Area	AR	0.40	0.38	0.40	0.33	0.33	0.37
	AF	0.03	0.03	0.04	0.02	0.02	0.03
	CN	0.29	0.22	0.22	0.20	0.22	0.23
	SM	0.03	0.03	0.04	0.02	0.02	0.03
Drying rate	AR	0.2	0.19	0.20	0.22	0.22	0.21
	AF	0.48	0.28	0.38	0.33	0.33	0.36
	CN	0.07	0.11	0.11	0.13	0.11	0.11
	SM	0.48	0.28	0.38	0.33	0.33	0.36
Environmental Risk	AR	0.10	0.13	0.10	0.11	0.11	0.11
	AF	0.12	0.22	0.19	0.16	0.16	0.17
	CN	0.43	0.44	0.33	0.40	0.33	0.39
	SM	0.12	0.22	0.19	0.16	0.16	0.17
Capital Cost	AR	0.10	0.13	0.10	0.11	0.11	0.11
	AF	0.12	0.22	0.19	0.16	0.16	0.17
	CN	0.07	0.11	0.11	0.13	0.11	0.11
	SM	0.12	0.22	0.19	0.16	0.16	0.17

All the main criteria affecting the choice of drying method were compared with each other, and the pairwise comparison matrix given in Table 5 was obtained. While creating this matrix, conditions in different regions were considered, and the importance levels of the criteria were determined accordingly. Since there are restrictions in the land area selection criteria in the Armutcuk (AR) region, the land area was the most critical factor in the selection of criteria in this region. As seen in Table 5, the normalized value of the land area is the highest, with 0.37. The normalized value ranking for this region is land area, drying rate, operating cost, environmental risk, and initial investment cost. Coal produced in AF and SM regions is regularly fed to the thermal power plant. Therefore, these regions' drying rate selection criterion was the most critical parameter with a normalized value of 0.36. This is followed by operating cost, environmental risk, installation cost, and land area selection criteria. The most critical parameter for the CN region is the environmental risk parameter, with a normalized value of 0.39. This region is precious in terms of tourism and agriculture. Therefore, environmental risk and land area selection criteria are the most important. The normalized value ranking for this region is Environmental risk, land area, operating cost, installation cost, and drying rate. In the next step, a pairwise comparison of the alternatives was made according to each sub-criteria. After comparing the main criteria, the same process was applied to all subgroup criteria, and the result of the calculations and the comparison matrices in Table 6 were obtained.

In the next step, the overall rating of each alternative is calculated by summing the relative priority of each criterion multiplied by the relative priority of the alternative, considering the relevant criteria. The final matrix results are given in Table 7. Since comparisons are based on subjective evaluation, CR values were calculated using Eq. (3) to ensure selection accuracy. The results showed that the maximum Eigenvalues (λ_{max}) were close to the size of the corresponding matrices, and the CR values for all matrices were less than 0.1. This shows that the results are consistent.

As can be seen from Fig. 5, which was created using the final matrix in Table 7. According to the results in Fig. 5(a), the most suitable drying method for the Armutcuk (AR) region is the microwave method, with a value of 0.39. Since there is not enough space in this region and the amount of annual solar energy is low, drying with solar energy should not be preferred. As an alternative to the microwave method, the rotary dryer method with a value of 0.22 can be preferred for this region. In the

Table 6. Comparison matrices

Region	Drying Method	Operating Cost	Area	Drying Rate	Environmental Risk	Capital Cost
AR	Rotary	0.04	0.35	0.31	0.06	0.18
	Microwave	0.10	0.52	0.51	0.09	0.48
	Air	0.36	0.09	0.04	0.43	0.30
	Solar	0.50	0.04	0.14	0.43	0.05
AF	Rotary	0.04	0.35	0.26	0.06	0.18
	Microwave	0.10	0.52	0.44	0.09	0.48
	Air	0.36	0.09	0.04	0.43	0.30
	Solar	0.50	0.04	0.26	0.43	0.05
CN	Rotary	0.04	0.35	0.37	0.06	0.18
	Microwave	0.10	0.52	0.37	0.09	0.48
	Air	0.36	0.09	0.04	0.43	0.30
	Solar	0.50	0.04	0.22	0.43	0.05
SM	Rotary	0.04	0.35	0,30	0.06	0.18
	Microwave	0.10	0.52	0,47	0.09	0.48
	Air	0.36	0.09	0,04	0.43	0.30
	Solar	0.50	0.04	0,19	0.43	0.05

Table 7. Final matrix

Drying Method	AR Region	AF Region	CN Region	SM Region
Rotary	0.22	0.16	0.17	0.17
Microwave	0.39	0.30	0.26	0.31
Air	0.19	0.23	0.28	0.23
Solar	0.20	0.31	0.29	0.29

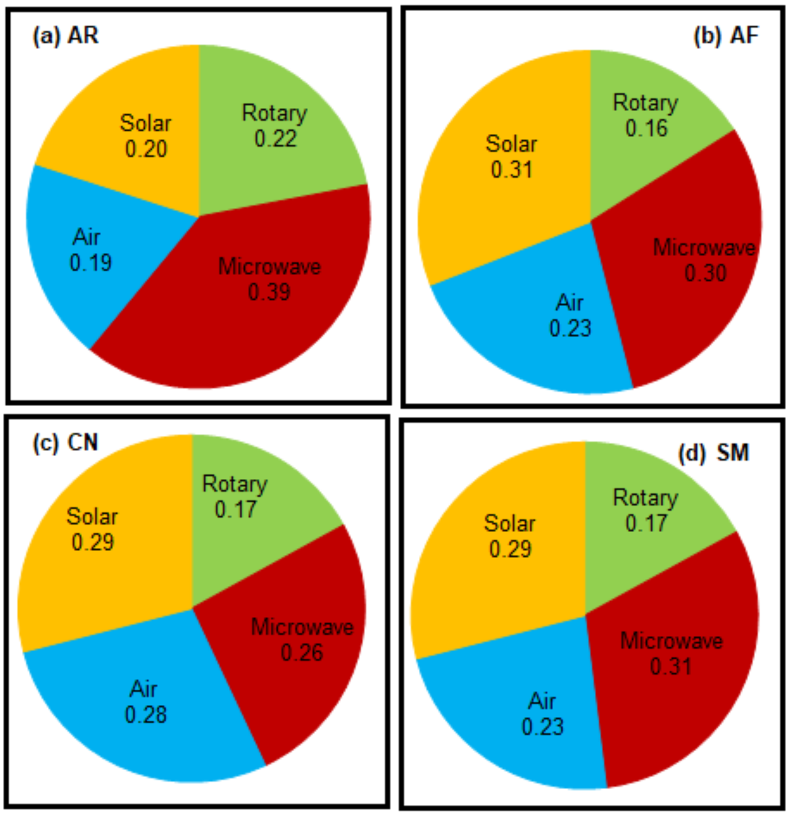

Fig. 5. Final comparison results for (a) AR (b) AF (c) CN, and (d) SM

Afsin (AF) region, the solar drying method is the most suitable compared to other methods, with a value of 0.31. The microwave method with a value of 0.29 is suitable as an alternative to this method (Fig. 5(b)). Thermal power plants in this region are essential for drying speed. Despite the advantages of the microwave method in terms of drying speed, the solar drying method should be preferred due to this region's high solar radiation value. For the Can (CN) region, the solar energy method is most suitable, with a value of 0.29. This method is followed by air-drying with a value of 0.28 (Fig. 5(c)). Since this region is very suitable for tourism and agriculture, this region is susceptible to environmental risks. Therefore, the solar energy drying method should be preferred for this region. For production in the Soma (SM) region, the microwave drying method with a value of 0.31 should be preferred. As an alternative to this method, the solar drying method with a value of 0.29 can be preferred (Fig. 5(d)). The presence of a thermal power plant in this region, like the AF region, highlights the drying rate parameter. Therefore, the microwave method is more suitable for this region.

4. Conclusions

Determining the most suitable method for drying coal fed to thermal power plants with a single parameter is impossible. Installation cost, operating cost, land use, environmental risks, and drying speed are practical when choosing the drying method applied to coal. Accordingly, in this study, the most suitable coal drying method for four different regions (Armutcuk (AR), Afsin (AF), Can (CN), and Soma (SM)) was determined by the AHP method. The most suitable drying methods determined for the regions in the study are listed below:

The microwave method is the most suitable drying method for the AR region. Solar energy drying should not be preferred for production in this region because no large areas can be used for drying due to the rugged land structure, and the amount of solar radiation in the region is insufficient. As an alternative to the microwave method, the rotary dryer method can be preferred for this region.

In the AF region, the solar drying method is the most suitable. The microwave method can be used as an alternative to this method. Thermal power plants in this region are essential for drying speed. Despite the advantages of the microwave method in terms of drying speed, the high solar radiation value in this region and the large flat areas make the solar drying method preferable.

The solar energy method is most suitable for the CN region. This method is followed by air-drying. Since the CN region is very suitable for tourism and agriculture, this region is susceptible to environmental risks. Considering the environmental risks of rotary and microwave dryers, they are not suitable methods as they may damage the historical and natural structures of the CN region. Therefore, the solar energy drying method should be preferred for this region.

The microwave drying method should be preferred for production in the SM region. The solar drying method can be preferred as an alternative to this method. The presence of a thermal power plant in this region, like the AF region, highlights the drying rate parameter. Therefore, the microwave method is more suitable for this region. As in many sectors, equipment/method selection in the mining sector requires multi-criteria decision-making. In this case, it has been seen that the AHP method can be used to select the optimum equipment/method by determining the appropriate criteria.

Acknowledgments

This study, project number 38086, was funded by the Scientific Research Projects Coordination Unit of Istanbul University-Cerrahpasa. The authors thank the Executive Secretariat of Scientific Research Projects of Istanbul University-Cerrahpasa.

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