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An analytical investigation of critical factors to prioritize coalfields for Underground Coal Gasification – Bangladesh case

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ABSTRACT

In recent decades, many countries have shown a growing interest in Underground Coal Gasification (UCG) as a potential clean and environmental-friendly means of harnessing coal energy for power generation, and production of hydrogen, diesel fuel, etc. While Bangladesh may have good UCG potential that can be utilized to alleviate the country's current energy scarcity, this avenue has remained completely untapped up to now. In this work, the possibility of UCG implementation in five (05) indigenous discovered coalfields of the country was evaluated for the first time by using the preference selection index (PSI) method. This novel technique was considered to prioritize coalfields for gauging UCG potential. The PSI method is chosen over numerous traditional multi-criteria decision-making (MCDM) techniques, because it selects the best alternative from given alternatives without deciding the relative importance between attributes. The study indicated Jamalganj coalfield as the most suitable for implementing the UCG technique with a 93.6% potential. The second priority is Khalaspir coalfield with around 70.0% prospect and the other three coalfields – Dighipara (64.7%), Barapukuria (63.5%), and Phulbari (58.3%) may have UCG suitability in decreasing order of preference. The deduction is expected to assist the cogitation of energy-sector researchers and facilitate the decision-making of relevant authorities, policy makers, planners, and entrepreneurs.

1. Introduction

Large coal reserves (around 3.3 billion tons) were discovered in five coalfields of Bangladesh (Barapukuria, Phulbari, Dighipara, Khalaspir and Jamalganj) during the time between 1962 and 1995 [1,2]. Unfortunately those failed to serve energy demand of the country promptly through conventional mining techniques (i.e., underground or opencast) [2,3]. Nevertheless, the demand of solid fuel (coal) has been significantly increased in recent years to support national economic development. Therefore, the imminent necessity is largely being met through imported sources as much as around 90% for operating coal-based thermoelectric power stations, thousands of brick kilns and other industrial units. In fiscal year 2019–20 and 2020–21, among the total supply of 7.6 and 7.5 million tons of coal nationwide, imported volume was 6.8 and 6.8 million tons respectively [4]. The import dependency is projected between ~77% and ~90% in between 2030 and 2041 [5]. While energy security is one of the most pressing issues worldwide, such dependency

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is a grave concern for the nation. This may be crucial time for pursuing technical advances and environmental data collection to conduct research to prioritize suitable approach for exploiting immediately the indigenous coal fuel for electricity generation to meet current power shortage, ensure uninterrupted industrial production, and secure national energy policy. It is worth noting that geological complexity [6], hydrogeological conditions of the coal basins, absence of favorable depth for conventional coal mining method, eco-environmental issues [7], mine development consequences and costs, public and miners' health safety [8], etc. have motivated unconventional coal exploitation technique such as Underground coal gasification (UCG) as the suitable alternative option [9–11].

In the wake of global warming concern, UCG can be a viable clean coal technology as this does not bring the coal to surface, thus there is no coal handling, or washing, or transportation, no ash problem, and no mine workings in the underground [12,13]. UCG is an industrial method of harnessing energy from apparently un-mineable coal (too deep, or low grade, or very thin) through thermo-chemical process which converts coal into a high quality yet low-cost synthesis gas or liquid fuel through partial oxidation [14]. It involves drilling of injection and production wells from surface to the target coal seam followed by creating a highly permeable channel between those two wells (Fig. 1) to develop a flow-path within the coal seam. The product gas (containing H_2, CO and CO_2 with minor quantities of CH_4, higher hydrocarbons, and traces of tars and pollutants) can be used as a feedstock for chemical products like hydrogen, methanol, ammonia, fertilizers, and synthetic natural gas, or to produce electricity [12,13,15]. UCG modelling such as, Computational fluid dynamics (CFD) model, etc. For exhibiting the potential, is evolved as an extraordinary opportunity which not only help to better understand UCG operations based on underlying physicochemical processes, but also facilitate better designing and optimization of the whole operation [16]. For example, Saik and Berdnyk identified the issues with laboratory studies on the coal gasification process and developed a numerical heat transfer modelling related to UCG [17]. UCG potential of a coalfield depends on a wide range of attributes, or criteria to be evaluated first and must be specified. Several researchers took initiatives to establish universal UCG site-specific requirements [12,13,18–23]. For example, Perkins listed the siting factors as "*Guidelines for site selection*" [18]. Mastalerz et al. [19] pointed them as "*Desired geologic and hydrologic characteristics for UCG*" based on [20]. Shafirovich and Varma termed these as "*Criteria for UCG Site Selection*" [21]. G. R. Couch also mentioned them as "*UCG site selection criteria*" [22]. Burton et al. addressed these site-specific attributes as "*Minimal requirements for UCG siting and operation*" [13]. Nonetheless, since large-scale UCG production is yet to be conducted, the factors for a potential UCG site selection only act as recommendations and cannot be taken as strict criteria. The study intends to evaluate these site selection parameters to ascertain the UCG potential of the coal deposits of Bangladesh.

However, there is a lack of research work on the assessment of UCG potential of five discovered national coalfields. UCG prospect of Jamalganj coalfield has been studied only by two groups of researchers with limited scope of study. Sajjad et al. [3] presented a review work considering the hydrology and geology of coal bearing region of the country. Second group suggested theoretical UCG feasibility based on techno-economic assessment of combined UCG-fertilizer-CO_2 storage/usage [25,26]. It is noted that a feasibility study for the extraction of coal bed methane (CBM) was carried out and deduced that CBM production is not economically feasible due to extreme gas under-saturation in Jamalganj [27]. Hence, the study is set to assess UCG potential based on site-specific characteristics of the individual coalfields using *Multi-criteria decision-making* (MCDM) technique, which can serve as the preliminary justification of venturing UCG in the country.

Decisions regarding energy resources development play a vital role towards the advancement of civilization. Therefore, decision

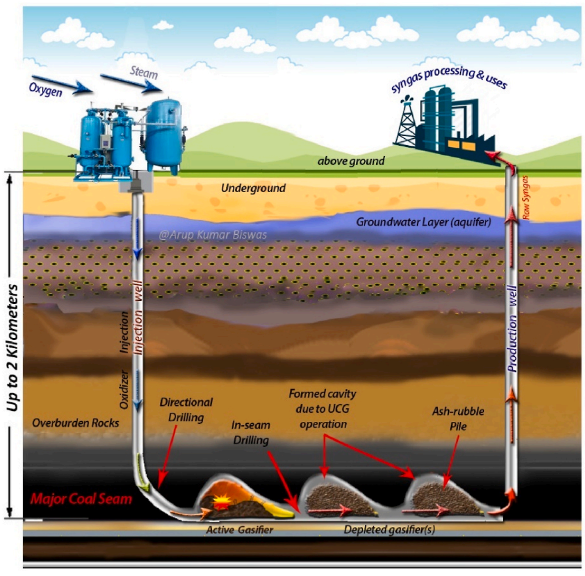

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Fig. 1. Schematic of Underground Coal Gasification; adapted from [24].

makers (DM) must make appropriate decisions based on concrete guidelines, especially if there are many conflicting criteria likely to affect the choice of alternatives. MCDM methods can be very instrumental in providing such solutions. Hence, MCDM methods have been used widely for diverse objectives (e.g., resource management and planning, resource allocation, policy-making, etc.) in energy sector [28,29]. Several researchers grouped various decision-making processes comprehensively by employing diverse methods and tools, as well as discrete objectives [30–36]. Kaya et al. [29] and Siksnelyte et al. [37] reviewed use of popular MCDM techniques to solve different issues of energy sector (energy policy/project selection, site selection, impact analysis, regional/national planning, etc.). The most familiar methods are *Analytic hierarchy process* (AHP) [38,39], *Analytic network process* (ANP) [40], *Technique for order of preference by similarity to ideal solution* (TOPSIS) [41,42], Multicriteria optimization and compromise solution (VIKOR) [43], *Elimination and choice transcribing reality* (ELECTRE) [44], *Preference ranking organization method for enrichment of evaluations* (PROMETHEE) [45], *Decision Making Trial and Evaluation Laboratory* (DEMATEL) [46], *Data envelopment analysis* (DEA) [47], etc. Different studies of energy technologies, sustainable energy planning and selection of technologies in Poland, Iran, Malaysia, Thailand and Northern Cyprus were conducted using AHP [48–52]. Zaman et al. [53] used AHP method for assessing socio-economic-environmental aspects of coal-based power generation in Bangladesh. Çelikbilek and Tüysüz [54] have established a grey-based multi-criteria decision model integrating DEMATEL, ANP, and VIKOR methods for impact assessment of renewable energy resources on sustainable development. However, there are some notable setbacks of these popular methods. The AHP makes the premise that all attributes are independent, which might be an impractical postulation to deal with real problems [55]. A group of researchers examined the problems of ranking the alternatives using TOPSIS and deduced that the ideal solution may not be the considered best alternative [43,56]. Moreover, these methods are often adopted to examine specific alternatives and select the optimal choice based on relative preferences (e.g., weights) of multiple criteria (attributes). Most of the MCDM techniques are predominantly of subjective nature, which are not capable of serving the aim of the study. A comprehensive solution may be attained by employing Preference Selection Index (PSI) method. The method achieves the results based on statistical concept with minimum and simple calculations, but without the necessity of determining weights of attributes [57,58]. Attri and Grover [59] compared PSI with AHP, ANP, TOPSIS, VIKOR, DEA, PROMETHEE, etc. They concluded that PSI outweighs other methods in terms of computational time, simplicity of statistical concept, required mathematical skills, introduction of extra parameters. These advantages have favored the

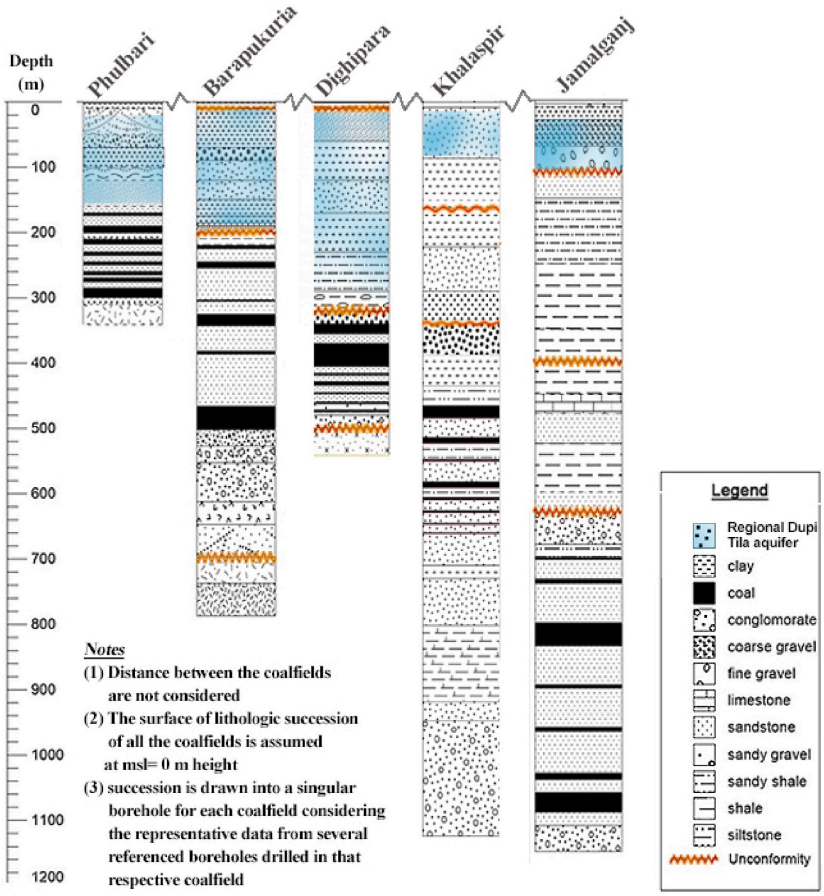

Fig. 2. - Generalized subsurface lithologic succession of the coalfields showing the coal intersections along with the significant hydrogeological layer.

method to be used in different fields (e.g., material selection, optimal design parameters, vehicle/fuel selection, etc.) [60–66].

As the coalfields needed to be assessed across various criteria, applying PSI method could be the reliable as well as efficient scientific approach. Therefore, the overarching objective or the aim of the study is to prioritize UCG suitability of the coalfields in the country through multi-criteria analysis (PSI) of the governing factors. To attain the objectives, few notable tasks were conducted – information of essential physical factors which maneuver UCG process and limiting values as well as relevant data of the coalfields of Bangladesh were numerically analyzed using PSI method, which subsequently determined the preferential order of target coalfields for UCG implementation. The findings could aid energy researchers, decision-makers, planners, and entrepreneurs in making informed decisions regarding UCG implementation in the country.

1.1. Geology of coal basin and coal characteristics of Bangladesh

Five Permian (Gondwana) coal basins were discovered in the subsurface of north-west region of the country (please refer to the supplementary document for Fig. S1) within the southern slope of the Rangpur Saddle of the Stable shelf area [67]. The deposits are present on top of the Precambrian Basement Complex. All exploitable thick to thin coal layers/seams of the country have been encountered in shallow to deeper depth. The coal basins were formed before the Gondwana supercontinent breakup in the depressions of the Basement during geologic past. Currently, the intracratonic fault-bounded, half-graben basins are bounded in the north by Himalayan Foredeep, south by Bogra Stable Shelf, east by Shillong Massif and in the west by Precambrian Indian Shield [68,69]. While four Gondwana basins are situated in NNW-SSE extended intra-tectonic basins in Rangpur saddle, Jamalganj coal area lies in the Bogra slope of the stable platform zone. Structural, stratigraphic, and depositional history of these basins are somewhat similar. The Permian rocks generally overlain by Precambrian basement complex and underlain either by Tertiary or Cretaceous sediments (Table S1 in the supplementary document). The sedimentary sequences are composed of light to dark grey, fine to very coarse grained, sub-angular to sub-rounded feldspathic sandstones, dark grey carbonaceous shale and sandstones, variegated conglomerates and thick coal seams [70–72]. A generalized stratigraphic succession of the north-western part of Bangladesh (Fig. 2 and Table S1) is appended to the supplementary document. The coal deposits are intersected in between 118 *m* and 1158 *m* depth and aggregated thickness varies from 38 *m* to 64 *m*. The coal is characterized by low sulfur, low ash, high carbon content, and high volatile C to A type bituminous coal (Please see Table S2 in the supplementary document) [1,72–75].

2. Methodology

A mixed-design matrix (Fig. 3) is applied for the study to identify and assess factors relevant to implement UCG in Bangladesh.

2.1. Selection of important factors

The UCG operational prerequisites i.e., attributes/factors, distinguished in different trials, were identified by studying the worldwide published literature relating to UCG deployment (Table 1).

Table 1 lists the preferable UCG site characteristics, which are required in the site design and risk reduction, or management strategies.

2.2. Limiting value of the governing factors for a feasible UCG

Threshold limits of essential factors for UCG site selection, determined by different researchers, vary widely. In some cases, those were localized experiences from trials around the world. These data, as tabulated in Table 1, facilitated deduction of a recommended limit (threshold value) of the decision factors for UCG implementation (Table 2).

2.3. Collection of relevant data for Bangladesh coalfields

Different attributes of coalfields in the country for considering UCG potential have been collected partly from published literature while some are from government's archive. The collected data are listed in Table 3. More information is available in the supplementary

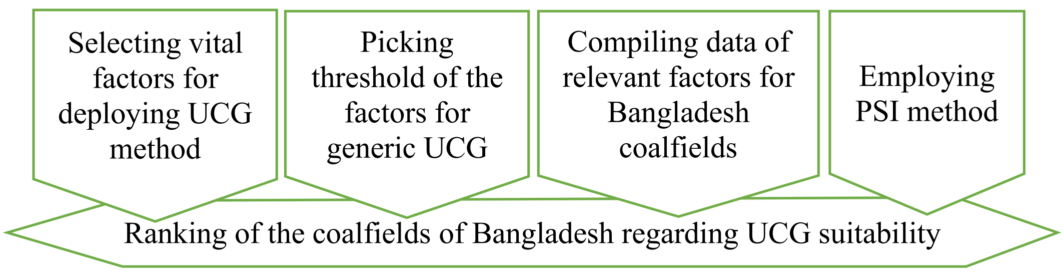

Fig. 3. Flowchart of the research approach.

Table 1
Important factors for a preferable UCG site.

Factor	Consideration	Cited
Thickness of seam	Thinner seams (<2 *m*), more heat loss; Thicker seams, fewer wells, cost reduced.	[12,18,76,77]
Burial depth	As deeper, as minimum pressure is required for the process and surface impacts decrease	[12,18,76,78]
Closeness to aquifers	No aquifer in the vicinity; Possibility of connecting with overlying aquifer becomes low.	[18,79–81]
Thickness of consolidated overburden	To support cavity span, minimize subsidence; low permeable for controlled water influx and gas containment.	[18,22,78]
Scale of deposit	To ensure the resource volume is substantial to justify the proposed project capacity towards a reasonable life-span	[18,22]
Reservoir pressure	Higher is better for gasification efficiency and downstream processing	[12,18]
Coal rank	Coals of all ranks can be gasified. Yet, the lower the rank the better. Also, low swelling is preferred.	[12,18]
Ash content (air dried)	Impact profitability; above 50% ash shows a marked decline in product gas quality.	[12,18,82]
Discontinuities	Low/no faulting/parting simplifies layout and operation; also, to avoid product gas loss or contaminant transport to surrounding strata.	[12,18,22]
Seam dipping	<20° Optimal for most techniques; >50° Limited to SDB techniques	[12,18,76]

Table 2
Threshold of the deciding factors for suitable UCG siting.

Factor	Recommended limit
Thickness of seam	>2 *m* preferred
Burial depth	>200 *m* preferred
Closeness to aquifers	No potable aquifer within 25 times the seam height
Overburden thickness	Compacted, very thick (>40 *m*), essentially impervious
Scale of deposit	>100 Mt preferred
Reservoir pressure	High (>20 bar)
Coal rank	≤bituminous, low FSI (Free Swelling Index)
Ash content	<40%
Discontinuity	Free from any major discontinuities
Seam dipping	Not steeply, <20°

Mt = Million tons.

document, Table S2.

2.4. Deploying PSI technique

To assess across multiple criteria without determining the relative importance between attributes based on the objective type of methodology, PSI method is applied in this study. The procedural stages of this method are as follows –

Stage 1: Defining objective.

The overall objective is to find out all alternatives (here, five coalfields) and the attributes (here, ten most important factors/physical parameters of a coalfield) relevant to assess suitability of the UCG application in Bangladesh.

Stage 2: Forming decision matrix.

In the decision matrix, information regarding alternative and attributes are grouped. The "alternatives" (m) are shown in rows and the "attributes" (n) are in columns. If the data is qualitative, then it is converted into quantitative. For example, in Table 4, the coal rank qualitative data is converted into quantitative sequential numbers following the principle that higher the number, better the quality. Finally, an m _ n decision matrix is formed as below.

$$\begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{pmatrix} \tag{1}$$

Where, x_{ij} is the performance of alternatives ($i = 1,2,3, \ldots,n$) examined against criteria/attributes ($j = 1,2,3, \ldots, m$).

Stage 3: Normalizing the attribute data.

Attribute data of different measuring units are transformed into a dimensionless compatible unit through normalization. The obtained values are called normalized values in terms of binary form, i.e., 0 and 1. Normalization of the matrix takes place in two aspects [57,59] – "beneficial" and "non-beneficial". When the attributes are expected to be larger to impact the activity positively, those are treated as beneficial. Therefore, the larger the value the better and the attribute data can be normalized as:

$$N_{ij} = \frac{x_{ij}}{x_j^{\max}} \tag{2}$$

Table 3
- Important attributes (factors in consideration) of the coalfields.

Factor	Jamalganj	Barapukuria	Khalaspir	Dighipara	Phulbari
Depth (m) of the thickest seam	Seam III; 660–977 *m*	Seam VI; 118–450 *m*	Seam I; 285–318 *m*	Seam II; 348.5–382.3 *m*	Seam II; 140–250 *m*
Thickness (m) of the thickest seam	Seam III; 8–47 *m*	Seam VI; 21.6–42.3 *m*	Seam I; Mean 16.95 *m*	Seam II; 36.6 *m*	Seam II; 10.59 *m*
Ash content	7–16% (seam I-IV); 23–28% (seam V-VII)	12.4%	21.80%	5.70–28.80% (mean 15%)	12%
Coal rank	Seams I–V: HV-B; seams VI-VII: HV-A bit.	HV-B	MV bituminous low sulfur coal	Ranging from HV-B to MV bit. coal	HV-B
Discontinuity	*E*-W trending boundary fault in the north and another 2 minor faults in the south	37 faults were found with 1–3 *m* throw; Fracture intensity from 7 to 10 per meter	7 normal faults sub-parallel to NW-SE; >50 *m* max. vertical displacements	A NW-SE trending major fault marking the northern limit of the basin	A *N*–S trending bounding fault marking the eastern limit of the basin
Groundwater layer in the vicinity	No aquifer in the vicinity; safer distance (~600 *m*) from overlying Dupi Tila aquifer.	Active aquifer is unconformably overlying	Minor groundwater source in the vicinity; 2nd aquifer with lower hydraulic conductivity	Coal beds are overlain by Dupi Tila aquifer, major GW source	Regional aquifer Dupi Tila on top
Overburden/Roof materials (preferably Impervious)	150–200 *m* cover of hard, compacted, impervious Gondwana sandstone	140 *m* thick Permian Gondwana sandstone (aquifer) in hydraulic continuity with the seam VI	184 *m* Gy mudstone, sandstone and pebble interbeds of Surma group, lower permeability	>300 *m* of poorly consolidated water-bearing sandy layer forming Dupi Tila aquifer	unconformably overlain by loosely consolidated Upper Tertiary Dupi Tila sandy formation
Hydraulic head	108 bar	–	–	–	–
Seam dipping	5°–15°	12° (seam VI)	–	13.4° (seam-II)	–
Reserve (Million Ton)	1053	390	685	865	572
Cited	[1,83–85]	[73,86]	[72,87]	[75,88]	[88,89]

Table 4
Conversion of decision factors into attributes.

Factor(s)	Thickness of coal seam (m)	Depth of coal (m)	Aquifer distance (m)	Thickness of consolidated overburden (m)	Deposit size (million tons)	Reservoir pressure (bar)	Rank (Lig. = 1, HV-B = 2, MV-B = 3, An. = 4)	Ash content (%)	Discontinuity	Dip angle of coal seam (°)
Attributes	$_j$**1**	$_j$**2**	$_j$**3**	$_j$**4**	$_j$**5**	$_j$**6**	$_j$**7**	$_j$**8**	$_j$**9**	$_j$**10**
	Beneficial attributes						**Non-beneficial attributes**			

Note: Lig. = Lignite; HV-B = High Volatile Bituminous coal; MV-B = Medium Volatile Bituminous coal; An. = Anthracite.

But if lower value is desirable, it is considered as a non-beneficial attribute, in which case, the smaller the value the better, and the performance of the original attribute can be normalized as:

$$N_{ij} = \frac{x_j^{\min}}{x_{ij}} \tag{3}$$

Where N_{ij} is the value of normalized attribute.

Stage 4: Determining the mean value of normalized attribute data.

The mean of normalized value $\overline{N}_j$ of attribute j is calculated as:

$$\overline{N}_j = \frac{1}{n}\sum_{i=1}^{n} N_{ij} \tag{4}$$

Stage 5: Measuring preference variation value.

At this stage, the task is to compute the preference of attributes depending upon the value derived from the 3rd and 4th stage.

$$\delta_j = \sum_{i=1}^{n}\left(N_{ij} - \overline{N}_j\right)^2 \tag{5}$$

Stage 6: Finding the deviation in preference value.

Here, deviation (λ_j) in preference value (δ_j) is measured as follows.

$$\lambda_j = 1 - \delta_j \tag{6}$$

Stage 7: Calculate overall preference value (φ_j)

Then the overall preference (φ_j) is determined, and a form of attribute's weight is estimated using following equation:

$$\varphi_j = \frac{\lambda_j}{\sum_{j=1}^{m} \lambda_j} \tag{7}$$

The sum of overall preference value ought to be one, i.e. $\sum_{j=1}^{m} \varphi_j = 1$.

Stage 8: Obtain preference selection index (P_i)

Finally, the P_i is obtained for each alternative,

$$P_i = \sum_{j=1}^{m} N_{ij} \times \varphi_j \tag{8}$$

Subsequently based on these PSI values, the alternatives are ranked at the last stage.

Stage 9: Ranking of the alternatives.

The alternatives are ranked in ascending or descending order depending on their PSI values. The alternative with the highest PSI value is ranked one as the best alternative, and subsequently others are ranked in decreasing order of preference.

3. Results

3.1. Decision model attributes

The shortlisted decision factors listed in Table 2 are outlined as attributes $_{j}\mathbf{1}$ to $_{j}\mathbf{10}$. According to the definition of "beneficial" and "non-beneficial" attributes (described in the *Stage 3: Normalizing the attribute data* section), thickness/depth of the target coal seams, proximity of aquifer, extent of consolidated overburden, resource reserves and hydrostatic pressure in the coal-bearing sequence are considered as beneficial, whereas, coal rank, ash content, number of discontinuities and seam dipping angle are desired to be the lowest possible values for a successful UCG deployment and are attributed to non-beneficial.

3.2. Decision model alternatives

Five discovered coalfields in Bangladesh are outlined (Table 5) as alternatives, $_{i}\mathbf{1}$ to $_{i}\mathbf{5}$.

3.3. Decision matrix

The different attributes vis-à-vis the governing factors for considering UCG potential of the coalfields (as alternatives) are tabulated (Table 6) to form a decision matrix using Equation (1).

3.4. Normalized value of attributes

The attribute data are normalized applying Equation (2) (for "beneficial") and Equation (3) (for "non-beneficial"). Representation of normalized value of attributes depict the overall comparison among the alternatives (coalfields of Bangladesh in this case) as shown in Fig. 4.

This kind of correlation merely can identify the best and/or worst -case scenario. Whereas a ranking of the alternatives has interoperability to assess different attributes in a coordinated manner.

At this stage $\overline{N}_j$ is calculated using Equation (4) which is the mean of normalized value of attribute j as in Table 7.

Then δ_j is calculated (Table 8) exercising Equation (5), where δ_j is the preference variation value of attribute j.

Thereafter, Deviation (λ_j) in preference value (δ_j) is calculated as in Table 9 employing equation (6).

Then the overall preference (φ_j) is determined (Table 10) from equation (7), and this estimates a form of attribute's weight.

3.5. PSI (P_i)

In this stage, P_i is determined using equation (8) and the preference of the alternatives based on the individual factor can be compared as shown in Fig. 5.

In the final step, the cumulative strength (PSI values) of different factors facilitates the ranking of alternatives (Table 11).

A step-by-step calculation is presented in the supplementary document (Table S3).

Table 5

- Conversion of the coalfields into alternatives.

Coalfield	Phulbari	Barapukuria	Dighipara	Khalaspir	Jamalganj
Alternatives	$_{i}\mathbf{1}$	$_{i}\mathbf{2}$	$_{i}\mathbf{3}$	$_{i}\mathbf{4}$	$_{i}\mathbf{5}$

Table 6
Quantitative data organization for the decision matrix.

		Attributes (Factors for UCG site preference)									
		$_j1$	$_j2$	$_j3$	$_j4$	$_j5$	$_j6$	$_j7$	$_j8$	$_j9$	$_j10$
Alternatives (coalfield)	$_i1$	11	150	0	20	572	50	2	12	1	13
	$_i2$	30	250	0	100	390	60	2	12.4	37	12
	$_i3$	36	348	0	40	865	68	3	15	1	13.4
	$_i4$	17	300	184	184	685	70	3	10	7	10
	$_i5$	46	850	250	250	1053	108	2	15	3	10

Note: Please refer to Table 3 for data details.

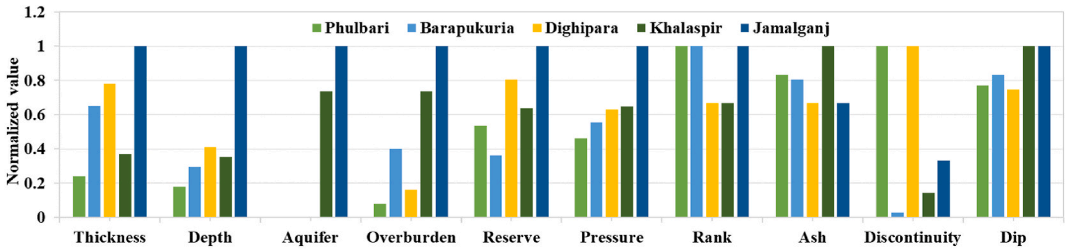

Fig. 4. Comparison of normalized values of different attributes of different coalfields.

Table 7
- Mean value of normalized data calculation.

	$_j1$	$_j2$	$_j3$	$_j4$	$_j5$	$_j6$	$_j7$	$_j8$	$_j9$	$_j10$
$\overline{N}_j$	0.609	0.447	0.347	0.475	0.677	0.659	0.867	0.795	0.501	0.870

Table 8
- Preference variation value (δ_j) calculation.

	$_j1$	$_j2$	$_j3$	$_j4$	$_j5$	$_j6$	$_j7$	$_j8$	$_j9$	$_j10$
δ_j	0.379	0.413	0.939	0.605	0.238	0.166	0.133	0.077	0.879	0.061

Table 9
- Deviation (λ_j) calculation.

λ_j	0.621	0.587	0.061	0.395	0.762	0.834	0.867	0.923	0.121	0.939

Table 10
- Overall preference value (φ_j) calculation.

	$_j1$	$_j2$	$_j3$	$_j4$	$_j5$	$_j6$	$_j7$	$_j8$	$_j9$	$_j10$
φ_j	0.102	0.096	0.010	0.065	0.125	0.136	0.142	0.151	0.020	0.154

4. Discussion

The PSI method is used in this study to delineate the UCG potential of the coalfields of the country by screening the suitability factors for UCG implementation. According to their burial depths, all the coalfields except Phulbari (prospective Seam II lying at shallow depth) would pass for UCG requirements. Thicknesses of the main considerable seams in all the coalfields are positive (>10 *m*). Ash contents (air dried basis) of all the coalfields are favorable (<40%) for UCG application. Although the rank of coal is less important, the coal types with high volatiles (lower ranks) are still preferable for UCG. From that perspective, Khalaspir and Dighipara coalfields, having medium volatile coal, are higher ranked than the other 3 fields, thereby less promising for UCG trial.

Noteworthy, the biggest hindrance of coal resources development in the country is the regional groundwater layer - Dupi Tila formation, which is lying immediately on top of the coal seam at places like Phulbari, Barapukuria, or Dighipara (Fig. 2). In this context, Jamalganj basin offers great advantages, as there is considerable overburden (around 200 *m*) of sufficiently impermeable

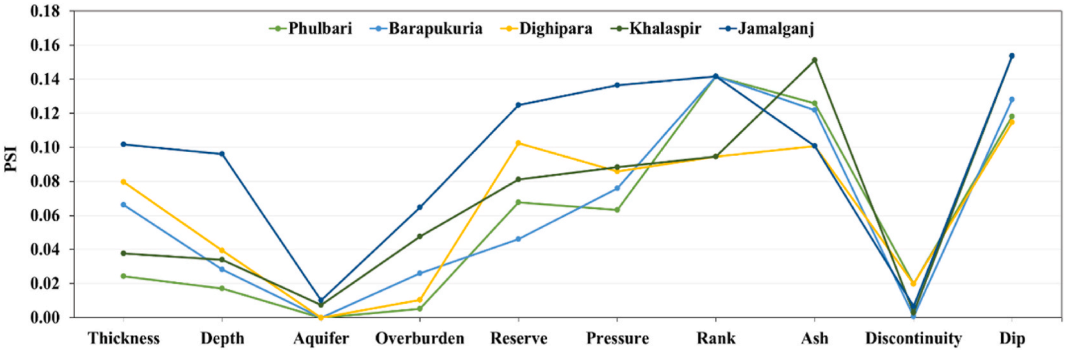

Fig. 5. Preference of the alternatives (coalfields) comparing different attributes (factors).

Table 11
Ranking of the selected coalfields in terms of suitability for UCG application according to the PSI method.

Alternatives	Coalfields	PSI (P_i)	Ranking
$_i$**1**	Phulbari	0.583	**5**
$_i$**2**	Barapukuria	0.635	**4**
$_i$**3**	Dighipara	0.647	**3**
$_i$**4**	Khalaspir	0.698	**2**
$_i$**5**	Jamalganj	0.936	**1**

strata.

Regarding the presence of faults and fractures, Barapukuria, Dighipara and Phulbari exhibit somewhat precarious conditions as the overburden is usually a loosely consolidated sandy type and either itself a Dupi Tila (major regional aquifer) or in hydraulic continuity with Dupi Tila. In Khalaspir, though there is a considerable number of discontinuities (7 normal faults), the overburden which itself is the 2nd aquifer with lower hydraulic conductivity, makes a barrier between the coal seam and the Dupi Tila aquifer. In contrast, the Jamalganj coal beds have a considerable distance (over 600 *m* in places) between the major aquifer and the coal seams and a robust overburden (150–200 *m* cover of hard, compacted, impervious Gondwana sandstone) and can be an ideal candidate for UCG. The sandstone over the roof of the coal seams is effectively impermeable, being highly compacted and cemented, especially because of kaolinitic cement presence. This formation will create an active shield on top of the coal seams and keep in check any de-pressuring (dewatering) issues. Unlike Barapukuria, the chances of water influx would be less. The hard rock would also offer less chances of roof collapse during mining.

Based on the above considerations, Jamalganj is likely to have the best potential for UCG pilot runs. The high-volatile (HV–B type) bituminous coal at a favorable depth of occurrence, lucrative thickness of the coal seam, low ash content, manageable discontinuities, safe distance from regional groundwater reservoir, seemingly bear the promise of a rewarding UCG exploitation opportunity.

PSI method not only finds the order of preference for the alternative options based on the available attributes/factors, but also facilitates the relative strength of the decision (Fig. 6). This study deduces that Jamalganj coalfield has 93.6% potential to site a UCG venture, whereas Khalaspir as the second candidate has 69.8% and other three coalfields have below 65% UCG potential. Phulbari is the lowest potential coalfield with 58.3% in the PSI ranking chart.

4.1. Environmental and safety concerns

One of the biggest environmental and safety concerns associated with UCG implementation is that this could lead to groundwater contamination in the vicinity, if not implemented properly [9,10,90]. Hence, exploiting coal through UCG method in the prioritized coalfields can be catastrophic for the north-western region of Bangladesh. Especially, the low priority coalfields derived from the analysis – Phulbari, Barapukuria and Dighipara, may bear the risks due to the presence of coal seams immediately beneath the groundwater reservoir. On the contrary, Jamalganj coal deposits stand by the advantageous side in this context, as there is considerable overburden (around 200 *m*) of sufficiently impermeable strata (Fig. 2 and Table S2). Moreover, if the UCG technique is adopted, there is no need for any surface/subsurface installations/work, reducing occupational health safety environment (OHSE) risk, eco-environmental risk, etc. significantly.

5. Conclusion

In this study, integration of multi-factors to determine the UCG potential of the five discovered coalfields of Bangladesh was assessed following the PSI method. The method ranked the coalfields (i.e., alternatives) by analyzing the prevailing site characteristics (i.e., attributes) which were considered as key factors in this study - thickness of coal seam, burial depth, hydraulic head, ash content,

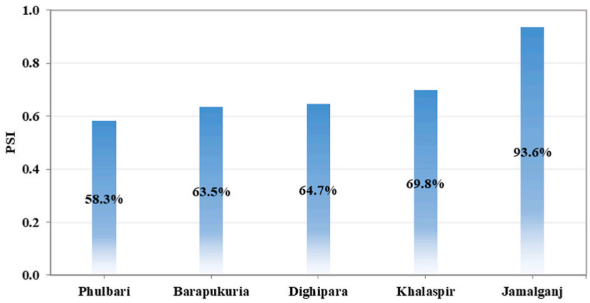

Fig. 6. Relative strength of the alternatives enumerated by the PSI method.

coal rank, discontinuities, proximity to aquifers, roof composition, seam dipping, and reserve. The PSI analysis indicated Jamalganj coalfield as the most suitable one (93.6% potential) for venturing UCG application while Khalaspir (69.8%), Dighipara (64.7%), Barapukuria (63.5%) and Phulbari (58.3%) were rated less potential in preferential order. In terms of the UCG prospects, two coalfields - Jamalganj and secondly Khalaspir have got all the essential factors as positive. Other three coalfields - Dighipara, Barapukuria and Phulbari, may bear the risks of groundwater contamination due to the presence of coal seams immediately beneath the aquifer. The study can perform as the preliminary work towards evaluating the feasibility of unconventional coal mining techniques i.e., UCG as an alternative to the disputable traditional coal mining methods. The method is capable to scale the influence of different factors affecting UCG success. The approach of the study can be readily implemented in other coal regions of the world for seeking the primary assessment on UCG potential considering different variables/factors suitable for that regional geological context. The shortcomings of the current research evolve from selecting the key attributes for a suitable UCG implementation, which might not be functional singularly or in combination in different aspects. Any conceptual uncertainty regarding the geotechnical issues to UCG might incur an incorrect decision affecting the overall outcome of the research. Therefore, most widely experimented site-specific characteristics have been selected and analyzed for arriving at a comprehensive decision to select the best alternative coalfield for UCG implementation. The use of MCDM technique in the assessment of UCG potential is a relatively new approach both regionally and globally and PSI method has been introduced for the first time in this field of study. A reappraisal of the recorded output of PSI method in this study may be complemented by an extended Grey Relational Analysis (GRA) method, which also follows objective method of enumeration. Further research directions from national perspective may include delineation of syngas properties of coals, simulation of gasifier and inherent processes by CFD modelling, fixation of operating parameters through piloting, hydrogeological and geotechnical investigation to eliminate any environmental and safety concerns associated with UCG implementation, etc. This is high time for pursuing technical advancement along with environmental data collection necessary for evaluating this technology while the window of opportunity opens in the wake of UCG research projects around the world.

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Author contribution statement

Arup Kumar Biswas: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Md. Rafiqul Islam: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data. Md. Ahosan Habib: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e18416.

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