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RESEARCH

An Integrated Framework for Prioritizing Sustainability Indicators for the Mining Sector with a Multicriteria Decision-Making Technique

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Abstract

Sustainable development challenges are nowhere more relevant than in the natural resource sectors, most importantly coal mining, due to environmental and societal challenges, which are a known fact. A plethora of frameworks and indicators for assessing sustainable development are available in the literature. The GRI (Global Reporting Initiative) is one such instrument that is predominantly adopted by various sectors. However, the large number of GRI indicators often draws concern about the accuracy of measurements and management of the variables. The present study aims to prioritize the 78 GRI indicators for the mining sector on four attributes—practicality, relevance, reliability, and importance—to enhance the accuracy of measurements. A survey-based methodology in line with the Delphi method and the multicriteria decision-making methods (MCDM) TOPSIS, MOORA, and SAW combined with criteria weight calculation by the entropy method is applied to rank the GRI indicators. The study enables the prioritization of 78 indicators into 20 indicators based on stakeholder perception using a perceptual map and ranks them through the application of MCDM. Second, the larger Spearman's rank correlation coefficient of TOPSIS with MOORA and SAW shows better agreement between these three MCDM methods. The study demonstrates the usefulness of the MCDM methods either individually or in combination as a tool to support the decision-making process for prioritizing the indicators, assessing sustainability at coal mine sites, and benchmarking between adjacent mine sites.

Keywords Sustainability coal mine · Entropy weight · MCDM · GRI indicators

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1 Introduction

Affordable and reliable energy is critical to development worldwide. Coal is India's most plentiful and vital energy source. Over half of the country's energy needs are met by coal, which is predicted to account for 76% of the total capacity for thermal power. (Online document Coal India Ltd., website) It is expected that coal will play a large role in India's energy security as a result of the country's growing population, burgeoning economy, and desire to improve living standards. However, the impacts of coal mining operations pose risks to the environment and people surrounding the operating area, which have been widely documented in academic research [1–5]. Opencast mining has a negative impact on groundwater quality as well as flow regime [6]. Water pollution is mostly caused by runoff or discharge from mining activities, including extraction, processing, tiling, and disposal facilities, as well as repair and service facilities. An acid mine is a by-product of drainage, mining, and processing activities, and it is also another form of water pollution during active mining and after mine closure. Landslides, topography, erosion, and soil pollution are all caused by contamination or runoff from wastewater or leaching from tiling ponds, landfills, and treatment and repair workshops. Air quality is affected by emissions of particulate matter (PM10 and PM2.5) from dust during various mining operations [7–10]. There has been evidence of nearby populations being exposed to cancer-causing coal products such as silica dust and organic chemicals [11, 12]. In the coal mining area, there is a high mortality rate from heart, respiratory, and kidney diseases, as studied by Hendrix [13] and Werner et al. [14]. Coal mining is one of the most important sources of anthropogenic methane emissions [15–17]. The degradation of land and changes in its use pattern as a result of mining activities are forcing communities to move away from traditional economic activities such as agriculture, livestock, and fishing. In addition, occupational health and safety issues and adverse effects on vulnerable groups have increased the pressure on mining companies to integrate fundamentals of sustainability to better manage their social impact despite being the largest provider of energy and employment. Coal mining does not easily fit the definition of sustainability because it usually deals with a finite resource located in environmentally sensitive areas, leading to climate change risks. Although many studies, frameworks, and approaches are available in the literature for discussions on the definition, application, and implementation of sustainable development, scholarly arguments indicate that defining sustainable development in the context of different stages of coal mining remains a major challenge [18–22]. Even within the same units of study and context, the ongoing debate over mining sustainability reveals a lack of agreement on how to define mining sustainability [23, 24]. As a result, for the mining industry, creating an integration of sustainability concepts at the strategic level with sector-specific frameworks is crucial.

In response to the growing demands of society for accountability, there are Indian companies issuing sustainability reports. The GRI (Global Reporting Initiative) has been approved by a majority as a mechanism for disseminating sustainability reports (online sustainability reports). GRI rules were initially published in 2000. Their mission is to help businesses prepare sustainability reports that address social, environmental, and economic challenges. In 2016, the GRI went beyond making proposals to establish the first global standards for sustainability reporting known as "GRI standards." The standard is broad, including important aspects such as organizational, management, economic, environmental, social, human rights, community, and product responsibility. The GRI has produced 78 indicators for the mining industry in the environmental, social, and economic domains. The environmental category has 11 subcategories, with a total of 33 indicators. There are three subcategories and 36 indicators in the social category and four subcategories and nine indicators in the economic category. Sustainability Reports based on GRI offers two benefits: assessing a company's triple bottom line (economic, environmental, and social factors) and informing shareholders about sustainability efforts made and progress thereupon [25, 26].

Although GRI standards are recognized worldwide, they have a major drawback: instead of analyzing and reporting consistent performance at a site or mining site, mining companies are tasked with examining themselves and reporting on overall performance. Corporate reporting rather than reports on particular projects such as mining facilities might lead to confusion among shareholders based on the GRI guidelines. The studies of Böhling et al. [27], Fonseca et al. [28], Jeskins et al. [29], and Que et al. [30] are some examples of recent research in this field. GRI reports being voluntary, this flexibility gives companies the choice of which result indicators to disclose. A study by Boiral [31], Boiral and Henry [32] revealed that up to 90% of important adverse events were not disclosed in the sustainability reports of 23 corporations in the energy and mining industries, although they achieved A or A + application status in third-party assessment. Coal India Limited (CIL), a government-owned coal mine corporation in India, functioning in 84 mining areas with a total of 352 mines both open cast and underground, annually publishes sustainability reports highlighting the implementation of the GRI. However, few of its subsidiaries incorporate all 78 GRI indicators in it, and the reports lack representation of all 352 mining sites.

It is evident from the literature that in terms of measurement and management, a large number of key (core) sustainability indicators are often of concern. For target consumers, especially decision-makers and the general public, a large number of different indicators can be confusing [33]. It is also advocated that these indicators be easily comprehensible, with no complexity and a limited number for easy management [34]. Indicators should be adapted to their intended audience and preferably selected in tandem with them. A small number of 10–15 indicators that represent the most significant trends are generally considered by stakeholders such as decision-makers and the general public [35].

This study aims to explore the basic research question "How well do the 78 GRI standard indicators of the mining sector fulfill the requirement of mine site-specific sustainability using the Delphi method in the first stage and then prioritizing the reduced number of indicators using multicriteria decision-making (MCDM) techniques to obtain a manageable set that quantifies sustainability performance for individual coal mine sites.

To our knowledge, no studies have yet been conducted on the prioritizing of sustainability indicators of the mining sector using stakeholder participation and the MCDM approach. Nevertheless, Sitorus et al. [36] presented the application of MCDM methods in mining and mineral processing and even more specifically in mining technology, equipment, and site selection.

The present study intends to answer the basic research question mentioned above and thereby fill a gap in the literature and contribute in the following manner:

1. It provides a ranking of sustainability indicators by the multicriteria decision-making (MCDM) method and further classification by stakeholder perception mapping to obtain a prioritized set of indicators.
2. It will contribute to the literature on the comparability of MCDM methods.
3. Based on what was discovered within the limited scope of our research, there are no studies of the kind we conducted with stakeholder participation in the Indian coal mine on sustainability.

The remainder of this paper presents the following: Section 2 discusses the methodology adopted. Section 3 details the summary of findings including a discussion, Section 4 contains validation and sensitivity analysis, and Section 5 highlights limitations and future research along with conclusions.

2 Methodology

2.1 Delphi Method

The study utilized expert interviews and questionnaire surveys in two stages in line with the Delphi technique [37], which creates a structure for dealing with a complex problem effectively. The two stages of the study were conducted between 2017 and 2019.

For the first stage, which was a pilot study, expert interviews were chosen as the primary method to explore how 78 GRI sustainability indicators for the mining sector are viewed by the intended user in the Indian coal mining sector to fulfill the requirement of mine site-specific sustainability. The methodology adopted aims to focus on the understanding of the terms, their application, and the achievement of the intended goal within the regulatory framework of sustainable development in India, rather than on statistical generalization. The interviewees were selected based on their subject expertise and a minimum of 8 years of work experience in the subject matter. The sample size started with 30 individuals who were contacted for the discussion out of which 17 agreed to discuss the subject. The target population was mostly government officials involved in policy-making, and others were working in consulting firms who were directly involved in the development of the sustainability reports for industries (Table 1).

The interviews were semi-structured, and the interviewees had the freedom to elaborate on their views. GRI indicators for the mining sector were also provided for them to rate on the basis of importance with “yes” and “no” scales. The basis of the questionnaire was repeatable and systematic.

In the second stage, a group of professionals with working experience in mining sectors was considered an expert group for further rating of indicators under three

Table 1 Profile and code of the interviewee group in the first stage of the survey

Interviewee group (First stage)	Code	No. of participant
Policy decision maker for coal sector	GC	3
Policy decision maker for environment, forest, and climate change sector	GE	5
Consulting firms working on sustainability	CF	9

pillars of the sustainability assessment framework developed by the GRI: environmental, social, and economic impacts. In this stage, 60 professionals were provided with the questionnaire, of which 40 responded. The sample size in the study is justified in the literature as the Delphi panel sample size ranged from three to eighty [38, p3].

Delphi's first stage suggested revising the rating scale to emphasize comprehensibility, data accessibility, fit for purpose, measurement, and data usability.

Adopting the methodology developed by Feng and Joung [39] as cited by Popovic et al. [40], the rating of each of the indicators was performed based on the four attributes defined below:

(i) Relevance: Is the indicator suitable for assessment from multidimensional standpoints, e.g., environmental, social and economic and technical, for the local coal mine? This attribute's assessment will reveal the logical relationship between the GRI indicators and the respondent's operating area.
(ii) Practicality: How practical is the indicator for quantitative/qualitative measurement? Ratings on this attribute will shed light on ease of measurability of the GRI indicators with respect to the working area of the respondent.
(iii) Reliability: Does the indicator provide trusted and useful information that is understandable by those who are not experts? Is such information readily accessible? Ratings on this attribute will shed light on ease of data accessibility and trustworthiness of measured data in accordance with the GRI indicators with respect to the working area of the respondent.
(iv) Importance: How important is the indicator in addressing site-specific sustainability and its progress (trend) at the local level in the focal work area? Ratings on this attribute will shed light on the decision-making aspect of the GRI indicators even when measurability is directly or indirectly low from the perspective of the working area of the respondent.

The rating scale for attributes' relevance, reliability, and practicality is given as "low, medium, high, and no opinion."

The response to the questionnaire survey was changed to low = 1, medium = 2, and high = 3 according to the 3-point Likert scale, and the scale option "no opinion" was also provided in case the respondent had no idea about a particular indicator in the context of his working area. A three-point scale was selected for the respondents to generate the simplest and easiest response. Owing to the large number of GRI indicators in the questionnaire survey, the "importance" attribute is rated using a slightly different scale (1–9) to have a broader view of how one indicator dominates another under the "importance" attribute. Instead of cardinal data, the study employs a questionnaire survey with ordinal data (low, medium, and high) having assigned numerical values 1, 2, and 3 for the attributes practicality, relevance, and reliability to rate the 78 GRI Sustainability Indicators. For the TOPSIS application, this approach was taken in order to make it easier, more convenient, and quicker for the participants to fill out the questionnaire. Some of the earlier studies on TOPSIS application have adopted this approach [41–52].

2.2 Reliability of Scale

To determine the reliability of the scale, an appropriate statistical method, Cronbach's alpha coefficient (α), or McDonald's omega coefficient (ω), is used. Reliability coefficients can vary from 0 to 1.

The mathematical expression for Cronbach's alpha coefficient (α) is as follows:

$$\alpha = \left(\frac{k}{k-1}\right)\left(1 - \frac{\sum_{1=1}^{k}\sigma_{yi}^2}{\sigma_x^2}\right) \tag{1}$$

where k is the number of items/factors, σ_{yi}^2 refers to the variance associated with item i, and σ_x^2 refers to the sum of item variance.

The McDonald Omega coefficient (ω) is calculated as the ratio of variation owing to a common property (i.e., factor) to overall variance.

$$\omega = \frac{\left(\sum_{i=1}^{k}\lambda_i\right)^2}{\left(\sum_{i=1}^{k}\lambda_i\right)^2 + \sum_{i=1}^{k}\delta_{ii}} \tag{2}$$

where λ_i is the standardized factor loading, and δ_{ii} is the standardized error variance (i.e., $\delta_{ii} = 1 - \lambda_i^2$).

2.3 Multicriteria Decision-Making Approach (MCDM)

MCDM methods are the most widely used and well-known technique for ranking a group of alternatives. Stojčić et al. [53] reviewed and reported through online journal databases that more than four thousand articles in the field of science and technology covering sectors such as construction, supply chain management, transport and logistics, and energy make use of MCDM approaches. The basic procedure for MCDM methods requires three steps [54]:

(i) Identifying decision problems, defining goals to be obtained, analyzing and selecting alternatives that will be evaluated against a set of criteria, and identifying decision-makers.

(ii) Applying the MCDM method suitable to the defined objective by normalizing and weighting the alternatives and criteria chosen.
(iii) Evaluating the relative performance of the alternative with respect to the chosen criteria and finally ranking the alternatives based on the overall weighted score. The higher the ranking is, the more preferable the alternative.

Technique for order preferences by similarity to ideal solutions (TOPSIS), simple additive weighting (SAW), multi-objective optimization based on ratio analysis (MOORA), preference ranking organization method for enrichment evaluations (PROMETHEE), elimination et choix traduisant la realite´ (ELECTRE), vlsekriterijumska optimizacija i kompromisno resenje (VIKOR), and multi-attribute utility theory (MAUT) are some of the most frequently applied methodologies in MCDM problems.

A diagram with the workflow describing the research methodology is given in Fig. 1.

The MCDM approach—TOPSIS [55–57]—is used and justified in the present study due to its easy adaptability. MOORA [58, 59] and SAW [60] are applied to the results of TOPSIS as validation methods. The normalization method of TOPSIS is also used in MOORA and SAW to maintain uniformity.

Weight is a numerical number that shows the relative relevance of the criteria used to assess options in all of these multicriteria decision models. The entropy approach is used to determine the weights [61, 62].

A diagrammatic approach known as "perceptual mapping" is used to show how stakeholders perceive their decision with respect to the mean and standard deviation (SD). It is a pictorial representation of data to classify them into four quadrants by shifting its axis from the origin to a specified point. The four quadrants are labeled high mean high SD, high mean low SD, low mean high SD, and low mean low SD, by relocating their axis away from the origin to its average mean and average SD.

For successful optimization, the rankings from the three selected MCDM approaches along with stakeholder perception mapping are compared.

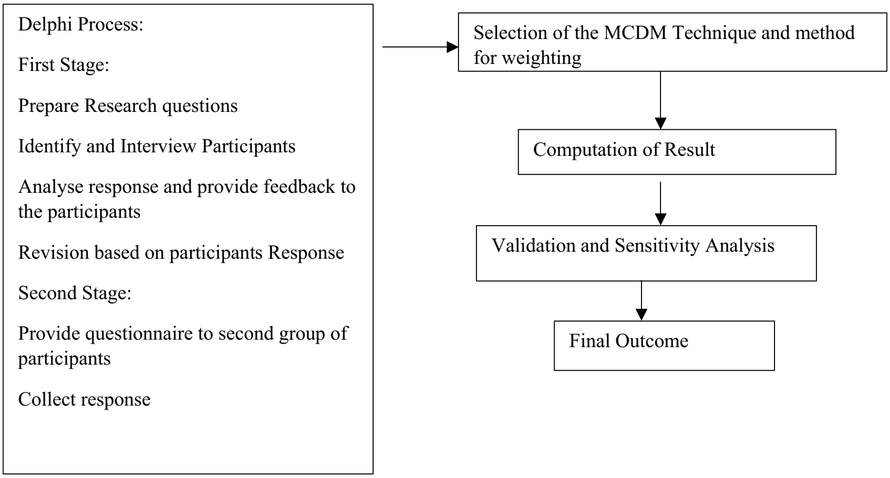

Fig. 1 Research design

Expressions for the determination of weight and MCDM methodologies are summarized as follows:

(I) Entropy method for the determination of weights [58]

$$\text{Matrix normalization } p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \; i = 1, \ldots \text{m}; j = 1 \ldots n \tag{3}$$

$$\text{Output entropy } E_j = \frac{\sum_{i=1}^{m} p_{ij}\, ln\left(p_{ij}\right)}{ln(m)} \; j = 1, \ldots .n \tag{4}$$

$$\text{Weight entropy } w_j = \frac{1 - E_j}{\sum_{i=1}^{n}\left(1 - E_j\right)} \; j = 1, \ldots n \tag{5}$$

(II) TOPSIS method [63]

The TOPSIS approach is broken down into the following steps:

$$\text{Normalized decision matrix} \quad n_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r_{ij}^2}} \tag{6}$$

$$\text{Weighted normalized decision matrix} \quad v_{ij} = w_{ij} r_{ij} \tag{7}$$

The positive and negative ideal solutions are as follows:

$$v_j^+ = \left\{v_{1,}^+, v_2^+, \ldots \ldots, v_n^+\right\} = \left\{max_j\left(v_{ij}\right)\right\} \tag{8}$$

$$v_j^- = \left\{v_1^-, v_2^-, \ldots \ldots ., v_n^-\right\} = \left\{min_j\left(v_{ij}\right)\right\} \tag{9}$$

The distance between each criterion and the positive and negative ideals is calculated as follows:

$$D_i^+ = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^+\right)^2} \tag{10}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^-\right)^2} \tag{11}$$

Relative closeness to the ideal solution is reflected as

$$C_i = \frac{D_i^-}{D_i^- + D_i^+} \tag{12}$$

The order of preference is ranked.

The following expressions of MOORA and SAW are used for validation purposes:

(III) MOORA method [58]

$$\text{Normalized decision matrix } X_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{13}$$

$$\text{Weighted normalized decision matrix } W_{ij} = w_j \times X_{ij} \tag{14}$$

w_j is the weight of the jth criterion

$$\text{Priorities}\left(Q_i\right) = \sum_{j=1}^{n} W_{ij} \tag{15}$$

Ranking of preferences: The maximum value of Q_i is ranked first and so on.

(IV) SAW method

$$\text{Normalized decision matrix} \quad n_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r_{ij}^2}} \tag{16}$$

Select the best option using Eq. (17)

$$A_i = \sum_{j=1}^{m} w_j r_{ij} \tag{17}$$

where A_i is a performance value of the i^{th} alternative; w_j denotes the weights of the j^{ih} criterion; and r_{ij} is the normalized value of the i^{th} alternative with respect to the j^{ih} criterion.

2.4 Correlation of the MCDM Methods

Analysis of Spearman correlations may further establish the comparability of rankings derived by the various approaches of MCDM. No effort is made to establish one variable as dependent and the other as independent; rather, it is interpreted as an association among the MCDM approaches utilized in the study.

3 Results and Discussion

3.1 First Stage (Expert Interview)

The study explores the basic research question "How well do the GRI standard indicators of the mining sector fulfill the requirement of mine site-specific sustainability."

We base our discussion on five main criteria:

1. To what extent is sustainability effectively incorporated into the current practice of environmental assessment in the Indian coal mining sector.
2. The current state of implementation of sustainability during operation.
3. A system to monitor and system to report sustainability.
4. A system to show progress/trend among coal mines.
5. Usefulness of global/national sustainable development assessment procedures for the performance assessment of local sustainable development.

Most of the interviewees who are directly involved in policy-making on sustainable development and GRI reporting and auditing stated that sustainable development is a major term in reference to mining projects in India to obtain environmental clearance (GC-2, GC-3, GE-1, GE-2, GE-4, CF-1, CF-2, CF-4, CF-5). The GRI standard is robust in guiding mining organizations to publish reports that provide relevant information about their contributions to sustainability (GC-1, GC-2 GE-4, CF-1, CF-4, CF-5, CF-6, CF-7, CF-9). However, the majority of interviewees agreed that "definition and interpretation of sustainable development/sustainability is biased by the organization" (GE-2, GE-4, GE-5, CF-1, CF-2, CF-3, GC-3) and "applicability to every stage of the project is difficult" (GC-1, GC-2, CF-6). Some respondents cited the voluntary nature of sustainability reporting as a barrier to adopting the standard in letter and spirit (GE-2, CF-1, CF-4, CF-5). A GRI reporting consultant (CF-8) suggested that "The current project scenario necessitates the development of methods to mitigate a variety of effects. Without a complete image of the project's output on multiple measures, the ability to provide a true picture of the project's impacts as a whole would be jeopardized."

Policy decision-makers have shown concern about monitoring and reporting systems for sustainability based on GRI standards, as "less focus on the quantitative aspect of GRI indicators is of concern. Most of the indicators require either a qualitative datum and sometimes a combination of qualitative and quantitative data" (GE-1, GE-3, CF-4, GE-5, GE-6). One GRI consultant (CF-7) revealed another problem associated with measuring sustainability: the "measuring scales are not identical for an indicator among two sustainability reports; rather, they are mixed." Furthermore, on the question of whether post-monitoring of the mining project shows progress/trend, the opinion of policy decision-makers is that "overemphasis on positive statements undermine the problematic issues of an organization." Regarding the usefulness of global/national sustainable development assessment procedures for local sustainable development performance assessment, participants from consulting firms (CF-1, CF-2, CF-7, CF-8, CF-9) viewed "less involvement of the operational workforce in discussion while working on sustainability issues for their work area" as a concern, while the majority of policy decision-makers stated that "challenges, such as climate change, poverty alleviation, biodiversity, energy access, etc., currently are very less incorporated in terms of geographic locations for meaningful sustainable progress" (GC-2, GE-1, GE-2, GE-3, GE-4, GE-5).

The Delphi technique helped to define the attributes and response scale for the second stage of the questionnaire survey to arrive at a holistic view of sustainable development in the coal mining sector.

3.2 Second Stage of Survey

3.2.1 Reliability of Opinions of Participants

The 78 indicators of GRI mining sector indicators representing the environmental, social, and economic pillars of sustainable development were used on the questionnaire for the participants to rate them on four attributes. Data analysis was conducted with Microsoft Excel 2016 version and Statistical software Jamovi version 1.6.23.

To validate the reliability of the questionnaire, Cronbach's alpha coefficient was computed. The obtained overall Cronbach's alpha coefficient value (Table 2) for the aspects evaluated was $\alpha > 0.70$ and very proximate to 1. The Cronbach's α was further compared with McDonald's ω (Table 2), which in all cases was greater than Cronbach's α, demonstrating a high degree of internal consistency and reliability.

3.2.2 Ranking of GRI Indicators

As mentioned earlier, the responses of participants on the questionnaire were analyzed in the decision matrix for the purpose of MCDM methods, and weight computation was obtained from the mean response of participants for each indicator of sustainability on four attributes.

The entropy weight was computed and is presented in Table 3.

The attribute "practicality" was given a higher weight (0.411) for social (LPDW) indicators. For social (prod res) indicators and economic indicators, the attribute "relevance" was given a higher weight (0.380, 0.285). The attribute "reliability" was given a higher weight (0.305) for social (society) indicators. The environmental indicators were given a higher weight (0.361) for the attribute "importance."

The TOPSIS method is considered the fundamental method for selecting the best-ranked indicators.

The ranking of each indicator was obtained utilizing the mathematical expressions shown in Eqs. (6) and (7).

Table 4 presents the TOPSIS ranking of the environmental sustainability indicators. The top five TOPSIS rankings include environmental protection expenditures and investments (EN 30), water withdrawal by source (EN 7), water discharge by quality and destination (EN 21), NOx, SOx, and other significant air emissions (EN20), and total weight of waste by type and disposal method (EN 22). These are perceived as most significant by the respondents.

Greenhouse gas emissions, consumption, and reduction within and outside the organization (EN 14, EN 15, EN 16, and EN 17) ranked in the middle, suggesting that these are seen as significant, but respondents were not confident that they could be measured with the current methods available.

Table 2 Overall Cronbach's α and McDonald's ω

Category	Relevance		Practicality		Reliability		Importance	
	Cronbach's α	McDonald's ω	Cronbach's α	McDonald's ω	Cronbach's α	McDonald's ω	Cronbach's α	McDonald's ω
Environmental pillar	0.868	0.893	0.888	0.887	0.901	0.908	0.917	0.933
Social pillar_Labor practices and decent work	0.961	0.969	0.961	0.969	0.866	0.879	0.959	0.965
Social pillar_Society	0.762	0.795	0.961	0.969	0.866	0.879	0.959	0.965
Social pillar_Product responsibility	0.624	0.746	0.71	0.821	0.829	0.867	0.844	0.863
Economic pillar	0.728	0.813	0.629	0.687	0.57	0.626	0.876	0.892

Table 3 Weight factor (W_j) of criteria by entropy method

Criteria	Practicality	Relevance	Reliability	Importance
Env indicators	0.221	0.193	0.226	0.361
Social (LPDW) indicators	0.411	0.153	0.27	0.165
Social (society) indicators	0.242	0.204	0.305	0.249
Social (prod res) indicators	0.152	0.38	0.144	0.324
Economic indicators	0.267	0.285	0.244	0.204

Biodiversity indicators (EN 10, EN 11, EN 12, EN 14) ranked at the bottom could be interpreted as operations outside the eco-sensitive area.

The subcategory of labor practices and decent work in social sustainability indicators (Table 5) ranks rates of injury, occupational diseases, lost days, and absenteeism and total number of work-related fatalities, by region and by gender (SL 6) first, emphasizing the need to monitor and report workplace-related safety in mining operations.

Ranks 2, 3, 4, and 13 indicate interesting outcomes, as respondents perceive inclusive participation in health and safety meetings as essential but place less emphasis on training employees' gender-wise (SL 9).

Skill management (SL 10) and equal remuneration (SL 13) find bottom-order ranking.

Minimum notice periods regarding operational change (SL 4) at rank 16 is a surprising observation as it is related to avoiding risks in the mining operation.

Local community engagement, impact assessments, development programs and political contributions (SS1, SS 2, and SS 6) are ranked in the top 3 under social (society) sustainability indicators (Table 6), suggesting that respondents consider it important to have transparent monitoring of the commitments to local communities in and around mining operations.

Formal grievance mechanisms and risk assessment for corruption in operations (SL 4 and SL 5) at the 4th and 5th rank reflect respondents' view that there should be a foundation for responding early to concerns with the mining company and resolving community conflict.

In Table 7 below, the top-ranking assessment of significant product and service categories having health and safety impacts (SP 1) and provisions for penalties on violations of regulations and codes (SP 2) suggests that respondents are concerned about human wellbeing and are advocates for penalties if violations by the mining organization occur. The customer satisfaction survey (SP 9), ranking last in order, reflects its limited to no effect on sustainability.

In the economic sustainability category (Table 8), the top-ranking indicator, direct economic value generated and distributed (EC 1), reinforces its role in sustainability. Another interesting insight is that the middle-order rankings of infrastructure investment (EC 7) and procurement from local suppliers (EC 9) show heterogeneous opinions with the important attached to social indicators.

Table 4 TOPSIS ranking GRI environmental sustainability indicators

Indicator description	Ind. code	Rank	Indicator description	Ind.Code	Rank
Total environmental protection expenditures and investments by type	EN 30	1	Energy indirect greenhouse gas (GHG) emissions (scope 2) gross energy indirect (scope 2) GHG emissions in metric tons of CO2 equivalent, independent of any GHG trades, such as purchases, sales, or transfers of offsets or allowances	EN 15	18
Total water withdrawal by source	EN 7	2	Identity, size, protected status, and biodiversity value of water bodies and related habitats significantly affected by the organization's discharges of water and runoff	EN 25	19
Total water discharge by quality and destination	EN 21	3	Other indirect greenhouse gas (GHG) emissions (scope 3) gross other indirect (scope 3) GHG emissions in metric tons of CO2 equivalent, excluding indirect emissions from the generation of purchased or acquired electricity, heating, cooling, and steam consumed by the organization	EN 16	20
NOx, SOx, and other significant air emissions	EN 20	4	Reduction in energy consumption	EN 5	21
Total weight of waste by type and disposal method	EN 22	5	Percentage of products sold and their packaging materials that are reclaimed by category	EN 27	22
Monetary value of significant fines and total number of nonmonetary sanctions for noncompliance with environmental laws and regulations	EN 28	6	Emissions of ozone-depleting substances (ODS)	EN 19	23
Percentage and total volume of water recycled and reused	EN 9	7	Energy intensity	EN 4	24
Number of grievances about environmental impacts filed, addressed, and resolved through formal grievance mechanisms	EN 33	8	Materials used by weight or volume	EN 1	25
Water sources significantly affected by withdrawal of water	EN 8	9	Percentage of new suppliers that were screened using environmental criteria	EN 31	26
Weight of transported, imported, exported, or treated hazardous waste under the terms of The Basel Convention2 Annex I, II, III, and VIII, and percentage of transported waste shipped internationally	EN 24	10	Reductions in energy requirements of products and services	EN 6	27
Extent of impact mitigation of environmental impacts of products and services	EN 26	11	Habitats protected or restored	EN 12	28

Table 4 (continued)

Indicator description	Ind. code	Rank	Indicator description	Ind.Code	Rank
Significant environmental impacts of transporting products and other goods and materials for the organization's operations, and transporting members of the workforce	EN 29	12	Operational sites owned, leased, managed in, or adjacent to, protected areas and areas of high biodiversity value outside protected areas	EN 10	29
Greenhouse gas (GHG) emissions intensity	EN 17	13	Energy consumption outside of the organization	EN 3	30
Direct greenhouse gas (GHG) emissions (scope 1) GHG emissions in metric tons of CO2 equivalent, independent of any GHG trades, such as purchases, sales, or transfers of offsets or allowances. biogenic CO2 emissions in metric tons of CO2 equivalent separately from the gross direct (scope 1) GHG emissions	EN 14	14	Total number of IUCN red list species and national conservation list species with habitats in areas affected by operations, by level of extinction risk	EN 13	31
Total number and volume of significant spills	EN 23	15	Percentage of materials used that are recycled input materials	EN 2	32
Reduction of greenhouse gas (GHG) emissions	EN 18	16	Description of significant impacts of activities, products, and services on biodiversity in protected areas and areas of high biodiversity value outside protected areas	EN 11	33
Significant actual and potential negative environmental impacts in the supply chain and actions taken	EN 32	17			

Table 5 TOPSIS ranking GRI social (labor practices and decent work) sustainability indicators

Ind description	Ind. code	Rank
Type of injury and rates of injury, occupational diseases, lost days, and absenteeism and total number of work-related fatalities, by region and by gender	SL 6	1
Percentage of total workforce represented in formal joint management–worker health and safety committees that help monitor and advise on occupational health and safety programs	SL 5	2
Health and safety topics covered in formal agreements with trade unions	SL 8	3
Number of grievances about labor practices filed, addressed, and resolved through formal grievance mechanisms	SL 16	4
Workers with high incidence or high risk of diseases related to their occupation	SL 7	5
Benefits provided to full-time employees that are not provided to temporary or part-time employees, by significant locations of operation	SL 2	6
Significant actual and potential negative impacts for labor practices in the supply chain and actions taken	SL 15	7
Total number and rates of new employee hires and employee turnover by age group, gender, and region	SL 1	8
Composition of governance bodies and breakdown of employees per employee category according to gender, age group, minority group membership, and other indicators of diversity	SL 12	9
Programs for skills management and lifelong learning that support the continued employability of employees and assist them in managing career endings	SL 10	10
Return to work and retention rates after parental leave, by gender	SL 3	11
Ratio of basic salary and remuneration of women to men by employee category, by significant locations of operation	SL 13	12
Average hours of training per year per employee by gender, and by employee category	SL 9	13
Percentage of new suppliers that were screened using labor practices criteria	SL 14	14
Percentage of employees receiving regular performance and career development reviews, by gender and by employee category	SL 11	15
Minimum notice periods regarding operational changes, including whether these are specified in collective agreements	SL 4	16

Table 6 TOPSIS ranking GRI social (society) sustainability indicators

Indicator description	Ind. code	Rank
Percentage of operations with implemented local community engagement, impact assessments, and development programs	SS 1	1
Operations with significant actual and potential negative impacts on local communities	SS 2	2
Total value of political contributions by country and recipient/beneficiary	SS 6	3
Number of grievances about impact on society filed, addressed, and resolved through formal grievance mechanisms	SS 11	4
Total number and percentage of operations assessed for risks related to corruption and the significant risks identified	SS 3	5
Communication and training on anticorruption policies and procedures	SS 4	6
Monetary value of significant fines and total number of nonmonetary sanctions for noncompliance with laws and regulations	SS 8	7
Total number of legal actions for anticompetitive behavior, anti-trust, and monopoly practices and their outcomes	SS 7	8
Confirmed incidents of corruption and actions taken	SS 5	9
Significant actual and potential negative impacts on society in the supply chain and actions taken	SS 10	10
Percentage of new suppliers that were screened using criteria for impacts on society	SS 9	11

Table 7 TOPSIS ranking GRI social (product responsibility) sustainability indicators

Indicator description	Ind. code	Rank
Percentage of significant product and service categories for which health and safety impacts are assessed for improvement	SP 1	1
Monetary value of significant fines for noncompliance with laws and regulations concerning the provision and use of products and services	SP 9	2
Total number of incidents of noncompliance with regulations and voluntary codes concerning marketing communications, including advertising, promotion, and sponsorship, by type of outcomes	SP 7	3
Sale of banned or disputed products	SP 6	4
Total number of incidents of noncompliance with regulations and voluntary codes concerning the health and safety impacts of products and services during their life cycle, by type of outcomes	SP 2	5
Type of product and service information required by the organization's procedures for product and service information and labeling, and percentage of significant product and service categories subject to such information requirements	SP 3	6
Total number of substantiated complaints regarding breaches of customer privacy and losses of customer data	SP 8	7
Total number of incidents of noncompliance with regulations and voluntary codes concerning product and service information and labeling, by type of outcomes	SP 4	8
Results of surveys measuring customer satisfaction	SP 5	9

Table 8 TOPSIS ranking GRI economic sustainability indicators

Indicator description	Ind. code	Rank
Direct economic value generated and distributed	EC 1	1
Financial assistance received from government	EC 4	2
Coverage of the organization's defined benefit plan obligations	EC 3	3
Ratios of standard entry-level wage by gender compared to local minimum wage at significant locations of operation	EC 5	4
Financial implications and other risks and opportunities for the organization's activities due to climate change	EC 2	5
Development and impact of infrastructure investments and services supported	EC 7	6
Proportion of spending on local suppliers at significant locations of operation	EC 9	7
Significant indirect economic impacts, including the extent of impacts	EC 8	8
Proportion of senior management hired from the local community at significant locations of operation	EC 6	9

4 Validation and Sensitivity Analysis

4.1 Comparison of MCDM as Validation Instrument

Due to the difference in numerical algorithms and other reasons, such as a change in criteria weight, including and excluding alternatives, MCDM methods can exhibit different rankings. This necessitates the validation and sensitivity analysis of the outcome. In this study, MOORA and SAW are considered for validating the results and checking the correlation between the three MCDM methods. The rankings with MOORA and SAW were performed (Table 9) with the help of Eqs. (13) and (14).

It is evident from Table 9 that the three MCDM methods have given almost similar rankings within one rank up or down between the three methods for most of the environmental indicators. Indicator EN27 shows a disparity of four places down in ranking from MOORA.

Similar results have been obtained for the GRI social and economic indicators and are shown in Appendix Tables 19, 20, 21 and 22.

4.2 Exchange of Entropy Weight as a Sensitivity Analysis Instrument

Any MCDM technique must conclude with a process called sensitivity analysis, which is used to determine how much uncertainty exists in the source data, process step, and criteria weights (either individually or in combination) and has an impact

Table 9 Rank comparison of TOPSIS with MOORA and SAW for 33 GRI environmental sustainability indicators by different methods of MCDM

Indicator code	TOPSIS	MOORA	SAW	Indicator code	TOPSIS	MOORA	SAW
EN 30	1	1	1	EN 15	18	19	19
EN 7	2	2	2	EN 25	19	18	18
EN 21	3	3	3	EN 16	20	20	20
EN 20	4	4	4	EN 5	21	22	21
EN 22	5	5	5	EN 27	22	26	23
EN 28	6	6	6	EN 19	23	21	22
EN 9	7	7	7	EN 4	24	24	24
EN 33	8	8	8	EN 1	25	23	25
EN 8	9	10	10	EN 31	26	27	27
EN 24	10	9	9	EN 6	27	25	26
EN 26	11	11	11	EN 12	28	28	28
EN 29	12	12	12	EN 10	29	29	29
EN 17	13	13	13	EN 3	30	30	30
EN 14	14	14	14	EN 13	31	32	31
EN 23	15	15	15	EN 2	32	31	32
EN 18	16	17	16	EN 11	33	33	33
EN 32	17	16	17				

Table 10 Exchange of weight for environmental indicators for four attributes

Attributes	Practicality	Relevance	Reliability	Importance
Original weight	0.22091	0.19253	0.22556	0.36098
Exchange 1	0.19253	0.22091	0.22556	0.36098
Exchange 2	0.22556	0.19253	0.22091	0.36098
Exchange 3	0.36098	0.19253	0.22556	0.22091
Exchange 4	0.22091	0.22556	0.19253	0.36098
Exchange 5	0.22091	0.36098	0.22556	0.19253
Exchange 6	0.22091	0.19253	0.36098	0.22556

on the ranking of alternatives [64, 65]. Unlike existing approaches of increasing/decreasing criteria weight or removing input, this study utilizes the exchange of criteria weight to investigate the stability of rankings.

Tables 10 and 11 present the exchange of entropy weight and changes in the TOPSIS ranking of GRI environmental sustainability indicators.

Entropy weight exchange tables and the results of sensitivity analysis for social and economic indicators are shown in the Appendix (Tables 23, 24, 25, 26, 27, 28, 29 and 30).

It is clear from Table 11 that the exchange of entropy weight did not alter the ranking for most of the indicators for the environmental, social (society), social (product responsibility), and economic categories. However, in social (labor practices and decent work), exchange 1 and exchange 3 exhibit minor displacements of rank.

4.3 Stakeholder Perceptual Mapping as an Optimization Instrument

Stakeholder perceptual mapping also serves as a validation method as well as an optimization tool.

Stakeholder perceptual mapping for 33 GRI environmental sustainability indicators for the attribute "practicality" is shown below (Fig. 2). Indicators falling in the "high mean–low SD" quadrant of the stakeholder perception map are further selected for use with the three MCDM methods to validate their ranking against the original ranking.

Individual stakeholder perception mapping is shown in Appendix Figs. 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, and 21.

The three MCDM methods are again applied to the prioritized indicators of all sustainability categories under all attributes. Tables 12, 13, 14, 15, and 16 show the ranking of the original and prioritized numbers of indicators (shown in parentheses) under environmental, social, and economic categories:

The similarity in the final ranking of GRI indicators by TOPSIS, MOORA, and SAW validates the results of these MCDM methods. It also confirms their applicability in real time for large as well as small data. The methodologies are simple and flexible to execute without any complications in the calculation or use of dedicated software.

The study also supports the argument of Salabun et al. (2020) for the applicability of TOPSIS for a large number of alternatives (indicators in our study). Similar

Table 11 TOPSIS ranking of environmental indicators after sensitivity analysis

Ind code	Original weight	Exchange 1	Exchange 2	Exchange 3	Exchange 4	Exchange 5	Exchange 6	Ind code	Original weight	Exchange 1	Exchange 2	Exchange 3	Exchange 4	Exchange 5	Exchange 6
EN 30	1	1	1	1	1	1	1	EN 15	18	18	18	18	18	19	17
EN 7	2	2	2	2	2	2	2	EN 25	19	19	19	17	19	17	18
EN 21	3	3	3	3	3	3	3	EN 16	20	21	20	20	21	23	21
EN 20	4	4	4	4	4	4	4	EN 5	21	20	21	26	20	20	25
EN 22	5	6	5	5	5	7	8	EN 27	22	22	22	23	22	26	26
EN 28	6	5	6	8	6	5	5	EN 19	23	23	23	22	23	24	22
EN 9	7	7	7	6	7	6	6	EN 4	24	24	24	25	24	22	23
EN 33	8	8	8	7	8	8	7	EN 1	25	26	25	21	27	25	19
EN 8	9	9	9	10	10	9	9	EN 31	26	25	26	27	25	27	27
EN 24	10	10	10	9	9	10	10	EN 6	27	27	27	24	26	21	24
EN 26	11	11	11	11	11	11	11	EN 12	28	28	28	28	28	28	28
EN 29	12	12	12	12	12	12	13	EN 10	29	29	29	30	29	29	30
EN 17	13	14	13	13	13	13	14	EN 3	30	30	30	29	30	30	29
EN 14	14	13	14	14	14	14	12	EN 13	31	31	31	32	31	33	32
EN 23	15	15	15	15	15	15	16	EN 2	32	32	32	31	32	31	31
EN 18	16	16	16	19	16	16	20	EN 11	33	33	33	33	33	32	33
EN 32	17	17	17	16	17	18	15								

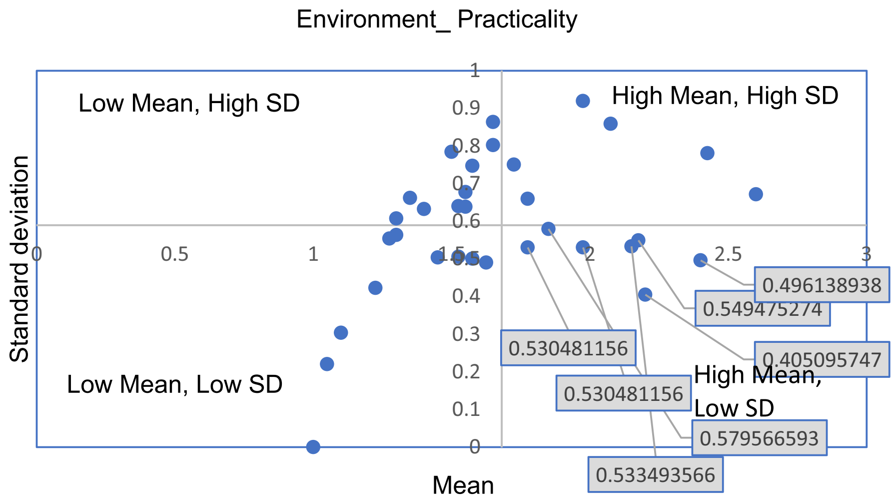

Fig. 2 Stakeholder perceptual mapping of GRI environmental sustainability indicators for the attribute "practicality"

rankings of TOPSIS with MOORA and SAW for economic, social (society), and social (product responsibility) indicators also indicate the applicability of these methodologies for smaller data (> 5).

4.4 Correlation of the MCDM Methods

The Spearman correlation coefficient was used to compare the MCDM procedures, taking into account the minimal differences in ranks between the three methods.

Table 12 Rank comparison of the prioritized number of indicators and original number of indicators (shown in parentheses) under environmental sustainability

Environment							
Sr. no.	Indicator code	TOPSIS (11)	TOPSIS (33)	MOORA (11)	MOORA (33)	SAW (11)	SAW (33)
1	EN 30	1	1	1	1	1	1
2	EN 7	2	2	2	2	2	2
3	EN 21	3	3	3	3	3	3
4	EN 20	4	4	4	4	4	4
5	EN 22	5	5	5	5	5	5
6	EN 28	7	6	6	6	6	6
7	EN 9	6	7	7	7	7	7
8	EN 8	8	9	9	10	9	10
9	EN 24	9	10	8	9	8	9
10	EN 14	10	14	10	14	10	14
11	EN 23	11	15	11	15	11	15

Table 13 Rank comparison of the prioritized number of indicators and original number of indicators (shown in parentheses) under social (labor practices and decent work) sustainability

Social (LPDW)							
Sr. no.	Indicator code	TOPSIS (8)	TOPSIS (16)	MOORA (8)	MOORA (16)	SAW (8)	SAW (16)
1	SL 6	1	1	1	1	1	1
2	SL 5	2	2	2	2	2	2
3	SL 8	3	3	4	5	4	3
4	SL 7	4	5	3	3	3	4
5	SL 16	5	4	5	4	5	5
6	SL 10	6	10	6	6	6	7
7	SL 9	7	13	7	8	7	13
8	SL 11	8	15	8	13	8	15

Table 17 indicates that all decision-making procedures at all levels have a positive correlation greater than 0.85. In the environmental sustainability category, TOPSIS has a strong correlation (> 0.9) with MOORA and SAW. For the social sustainability subcategory labor practices and decent work, TOPSIS showed slightly less correlation with MOORA (0.85) than SAW (0.965). The social sustainability subcategory society in TOPSIS has a strong correlation (> 0.9) with MOORA and SAW. In the social sustainability subcategory product responsibility, TOPSIS showed slightly less correlation with MOORA (0.85) than SAW (0.95). In economic sustainability, TOPSIS has a stronger correlation with MOORA (0.98) than SAW (0.966).

The results of the Spearman correlation coefficient exhibit an acceptable range of correlation, which is comparable to the work of Moradian et al. [59]. As a result, we can say that the ranks in the compared methodologies are statistically reliable with a probability of 95%, and the experimental results were statistically reliable.

Table 14 Rank comparison of the prioritized number of indicators and original number of indicators (shown in parentheses) under social (society) sustainability

Social (society)							
Sr. no.	Indicator code	TOPSIS (6)	TOPSIS (11)	MOORA (6)	MOORA (11)	SAW (6)	SAW (11)
1	SS 1	1	1	1	1	1	1
2	SS 2	2	2	2	2	2	2
3	SS 6	3	3	3	3	3	3
4	SS 11	4	4	4	4	4	4
5	SS 8	5	7	5	6	5	6
6	SS 7	6	8	6	8	6	8

Table 15 Rank comparison of the prioritized number of indicators and original number of indicators (shown in parentheses) under social (product responsibility) sustainability

Social (product responsibility)							
Sr. no.	Indicator code	TOPSIS (4)	TOPSIS (9)	MOORA (4)	MOORA (9)	SAW (4)	SAW (9)
1	SP1	1	1	1	1	1	1
2	SP9	2	2	2	4	2	2
3	SP3	3	6	3	7	3	6
4	SP5	4	9	4	8	4	8

Table 16 Rank comparison of the prioritized number of indicators and original number of indicators (shown in parentheses) under economic sustainability

Economic							
Sr. no.	Ind code	TOPSIS (6)	TOPSIS (9)	MOORA (6)	MOORA (9)	SAW (6)	SAW (9)
1	EC 1	1	1	1	1	1	1
2	EC 4	2	2	2	2	2	2
3	EC 3	3	3	3	3	3	3
4	EC 2	4	5	4	4	4	4
5	EC 5	5	4	5	5	5	5
6	EC 7	6	6	6	6	6	6

Table 17 Spearman's rho correlation coefficient

		TOPSIS	MOORA	SAW
ENV	TOPSIS	-	0.994	0.999
	MOORA		-	0.997
	SAW			-
Social (LPDW)	TOPSIS	-	0.850	0.965
	MOORA		-	0.915
	SAW			-
Social (society)	TOPSIS	-	0.9909	0.9727
	MOORA		-	0.9909
	SAW			-
Social (prod resp.)	TOPSIS	-	0.85	0.95
	MOORA		-	0.917
	SAW			-
Economic	TOPSIS	-	0.983	0.967
	MOORA		-	0.983
	SAW			-

Table 18 Prioritized set of indicators

Sr. no.	Category	Ind. code	Indicator description
1	Environment	EN 30	Total environmental protection expenditures and investments by type
2		EN 21	Total water withdrawal by source
3		EN 7	Total water discharge by quality and destination
4		EN 20	NOx, SOx, and other significant air emissions
5	Social (LPDW)	SL 6	Type of injury and rates of injury, occupational diseases, lost days, and absenteeism and total number of work-related fatalities, by region and by gender
6		SL 5	Percentage of total workforce represented in formal joint management–worker health and safety committees that help monitor and advise on occupational health and safety programs
7		SL 8	Health and safety topics covered in formal agreements with trade unions
8		SL 16	Number of grievances about labor practices filed, addressed, and resolved through formal grievance mechanisms
9	Social (society)	SS 1	Percentage of operations with implemented local community engagement, impact assessments, and development programs
10		SS 2	Operations with significant actual and potential negative impacts on local communities
11		SS 6	Total value of political contributions by country and recipient/beneficiary
12		SS 11	Number of grievances about impacts on society filed, addressed, and resolved through formal grievance mechanisms
13	Social (prod res)	SP 1	Percentage of significant product and service categories for which health and safety impacts are assessed for improvement
14		SP 9	Monetary value of significant fines for noncompliance with laws and regulations concerning the provision and use of products and services
15		SP 7	Total number of incidents of noncompliance with regulations and voluntary codes concerning marketing communications, including advertising, promotion, and sponsorship, by type of outcomes
16		SP 6	Sale of banned or disputed products
17	Economic	EC 1	Direct economic value generated and distributed
18		EC 4	Financial assistance received from the government
19		EC 3	Coverage of the organization's defined benefit plan obligations
20		EC 5	Ratios of standard entry-level wage by gender compared to local minimum wage at significant locations of operation

4.5 Prioritized Set of Indicators

The comparison of MCDM methods and the results of sensitivity analysis enable us to obtain a set of prioritized numbers of indicators (Table 18) that are viewed as most significant by the participatory stakeholders. The prioritized indicator set can serve as common indicators for local coal mine sites. Furthermore, indicators ranked until the fourth position by all methods can be selected as priorities when beginning a study, supporting the arguments of Janoušková et al. [66] that instead of developing new indicators, the assessment of existing indicators should be used as a policy decision-making tool, as sustainability is a dynamic process that is always changing.

5 Limitations and Future Research

Finally, there are some potential research avenues that may be explored to go beyond the constraints of our study.

While the TOPSIS method is suitable for cardinal data, due to practical considerations and simplification, the study employs ordinal data transformed into a numeric form using a 3-point scale to apply the TOPSIS technique.

The study considers entropy weight only for the decision-making matrices. The equal weight method is not performed separately, as lowering the entropy weight of this study to two decimal places yields an equal weight. The study also does not check the effect on ranking by other popular weighting methods, such as the analytic hierarchy process (AHP) method, since it was computationally intensive to perform pairwise comparisons for a large number of indicator sets. Rank reversal issues [67] in MCDM methods were also not studied, as the study started with a fixed number of indicators and criteria ratings after Delphi discussion rounds. This area can be an interesting direction for future research.

Other MCDM methods, such as complex proportional assessment (COPRAS), preference ranking organization method for enrichment evaluations (PROMETHEE), elimination et choix traduisant la realite´ (ELECTRE), and vlsekriterijumska optimizacija i kompromisno resenje (VIKOR), could also be compared with TOPSIS.

Despite this limitation, it is believed that the current study can serve as a foundation for future research.

6 Conclusion

The depletion of natural mineral resources is a major issue in the debate over the long-term viability of mining. Mining companies require a commitment to sustainable environmental and social development from exploration to extraction, as coal is still in demand worldwide as a low-cost energy source to meet the sustainable development goal of energy security.

Seventy-eight GRI indicators are prioritized to 20 indicators using entropy and MCDM approaches along with stakeholder perception mapping. Comparison of the MCDM approach exhibits close agreement between the approaches establishing the efficacy of these indicators singly or in combination to inform the decision-making process to prioritize indicators, assess sustainability at coal mining sites, and establish benchmarking between adjacent mining sites. To stay sustainable, the mining sector must focus on the challenges of climate change as well as preventing and reducing pollution.

The key insights from this study contribute to generating more consistent and comparable sustainability reports with a manageable set of GRI sustainability indicators, which will improve sustainable mining operations. The study suggests that MCDM approaches are a straightforward, effective, and efficient method for solving a variety of challenges involving the ranking and selection of sustainability indicators. Measuring and reporting on progress against the indicators will help coal mining companies in delivering the Sustainable Development Goals (SDGs) of the UN 2030 Agenda for Sustainable Development in the regions surrounding their mine sites and the nations in which they conduct business.

Appendix

See Tables 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, and 30

See Figs. 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, and 21.

Table 19 Ranking 16 GRI social sustainability (subcategory labor practices and decent work) indicators by different methods of multicriteria decision-making

Indicator code	TOPSIS	MOORA	SAW	Indicator code	TOPSIS	MOORA	SAW
SL 6	1	1	1	SL 12	9	7	8
SL 5	2	2	2	SL 10	10	6	7
SL 8	3	5	3	SL 3	11	15	12
SL 16	4	4	5	SL 13	12	12	11
SL 7	5	3	4	SL 9	13	8	13
SL 2	6	9	6	SL 14	14	14	14
SL 15	7	11	10	SL 11	15	13	15
SL 1	8	10	9	SL 4	16	16	16

Table 20 Ranking 9 GRI social sustainability (subcategory society) indicators by different methods of multicriteria decision-making

Indicator code	TOPSIS	MOORA	SAW	Indicator code	TOPSIS	MOORA	SAW
SS 1	1	1	1	SS 8	7	6	6
SS 2	2	2	2	SS 7	8	8	7
SS 6	3	3	3	SS 5	9	9	9
SS 11	4	4	4	SS 10	10	10	10
SS 3	5	5	5	SS 9	11	11	11
SS 4	6	7	8				

Table 21 Ranking 9 GRI social sustainability (subcategory product responsibility) indicators by different methods of multicriteria decision-making

Indicator code	TOPSIS	MOORA	SAW	Indicator code	TOPSIS	MOORA	SAW
SP 1	1	1	1	SP 3	6	7	6
SP 9	2	4	2	SP 8	7	9	9
SP 7	3	3	3	SP 4	8	6	7
SP 6	4	2	4	SP 5	9	8	8
SP 2	5	5	5				

Table 22 Ranking 9 GRI economic sustainability indicators by different methods of multicriteria decision-making

Indicator code	TOPSIS	MOORA	SAW	Indicator code	TOPSIS	MOORA	SAW
EC 1	1	1	1	EC 7	6	6	6
EC 4	2	2	2	EC 9	7	7	8
EC 3	3	3	3	EC 8	8	8	7
EC 5	4	5	5	EC 6	9	9	9
EC 2	5	4	4				

Table 23 Exchange of weight for social (labor practices and decent work) indicators for four attributes

Attributes	Practicality	Relevance	Reliability	Importance
Original weight	0.41147	0.15344	0.27013	0.16495
Exchange 1	0.15344	0.41147	0.27013	0.16495
Exchange 2	0.27013	0.15344	0.41147	0.16495
Exchange 3	0.16495	0.15344	0.27013	0.41147
Exchange 4	0.41147	0.27013	0.15344	0.16495
Exchange 5	0.41147	0.16495	0.27013	0.15344
Exchange 6	0.41147	0.15344	0.16495	0.27013

Table 24 Exchange of weight for social (society) indicators for four attributes

Attributes	Practicality	Relevance	Reliability	Importance
Original weight	0.24168	0.20444	0.30481	0.24906
Exchange 1	0.20444	0.24168	0.30481	0.24906
Exchange 2	0.30481	0.20444	0.24168	0.24906
Exchange 3	0.24906	0.20444	0.30481	0.24168
Exchange 4	0.24168	0.30481	0.20444	0.24906
Exchange 5	0.24168	0.24906	0.30481	0.20444
Exchange 6	0.24168	0.20444	0.24906	0.30481

Table 25 Exchange of weight for social (product responsibility) indicators for four attributes

Attributes	Practicality	Relevance	Reliability	Importance
Original weight	0.15171	0.38008	0.14396	0.32425
Exchange 1	0.38008	0.15171	0.14396	0.32425
Exchange 2	0.14396	0.38008	0.15171	0.32425
Exchange 3	0.32425	0.38008	0.14396	0.15171
Exchange 4	0.15171	0.14396	0.38008	0.32425
Exchange 5	0.15171	0.32425	0.14396	0.38008
Exchange 6	0.15171	0.38008	0.32425	0.14396

Table 26 Exchange of weight for economic indicators for four attributes

Attributes	Practicality	Relevance	Reliability	Importance
Original weight	0.26703	0.28523	0.24405	0.20369
Exchange 1	0.28523	0.26703	0.24405	0.20369
Exchange 2	0.24405	0.28523	0.26703	0.20369
Exchange 3	0.20369	0.28523	0.24405	0.26703
Exchange 4	0.26703	0.24405	0.28523	0.20369
Exchange 5	0.26703	0.20369	0.24405	0.28523
Exchange 6	0.26703	0.28523	0.20369	0.24405

Table 27 TOPSIS ranking social (labor practices and decent work) indicators after sensitivity analysis

Ind. code	Original weight	Exchange 1	Exchange 2	Exchange 3	Exchange 4	Exchange 5	Exchange 6
SL 6	1	1	1	1	1	1	1
SL 5	2	2	2	2	2	2	2
SL 8	3	4	3	3	3	3	3
SL 16	4	5	5	5	4	4	4
SL 7	5	3	4	4	5	5	5
SL 2	6	11	8	12	6	6	6
SL 15	7	14	7	9	9	7	8
SL 1	8	9	6	10	10	8	10
SL 12	9	7	10	7	7	9	7
SL 10	10	6	9	6	8	10	9
SL 3	11	15	13	15	11	11	11
SL 13	12	12	12	13	12	12	12
SL 9	13	8	11	8	13	13	13
SL 14	14	13	14	14	15	14	15
SL 11	15	10	15	11	14	15	14
SL 4	16	16	16	16	16	16	16

Table 28 TOPSIS ranking social (society) indicators after sensitivity analysis

Ind. code	Original weight	Exchange 1	Exchange 2	Exchange 3	Exchange 4	Exchange 5	Exchange 6
SS 1	1	1	1	1	1	1	1
SS 2	2	2	2	2	2	2	2
SS 6	3	3	3	3	3	3	3
SS 11	4	4	4	4	4	4	4
SS 3	5	5	5	5	5	5	5
SS 4	6	6	7	7	6	7	6
SS 8	7	7	6	6	7	6	7
SS 7	8	8	8	8	8	8	8
SS 5	9	9	9	9	9	9	9
SS 10	10	10	10	10	10	10	10
SS 9	11	11	11	11	11	11	11

Table 29 TOPSIS ranking social (product responsibility) indicators after sensitivity analysis

Ind code	Original weight	Exchange 1	Exchange 2	Exchange 3	Exchange 4	Exchange 5	Exchange 6
SP 1	1	1	1	1	1	1	1
SP 9	2	2	2	2	3	2	2
SP 7	3	3	3	3	4	3	3
SP 6	4	4	4	4	2	4	4
SP 2	5	5	5	5	5	5	5
SP 3	6	7	6	7	9	7	7
SP 8	7	8	7	9	8	6	9
SP 4	8	6	8	6	6	8	6
SP 5	9	9	9	8	7	9	8

Table 30 TOPSIS ranking economic indicators after sensitivity analysis

Ind. code	Original weight	Exchange 1	Exchange 2	Exchange 3	Exchange 4	Exchange 5	Exchange 6
EC 1	1	1	1	1	1	1	1
EC 4	2	2	2	2	2	2	2
EC 3	3	3	3	3	3	3	3
EC 5	4	4	4	5	4	4	4
EC 2	5	6	5	4	5	5	5
EC 7	6	5	6	6	6	6	6
EC 9	7	7	7	8	7	7	7
EC 8	8	8	8	7	8	8	8
EC 6	9	9	9	9	9	9	9

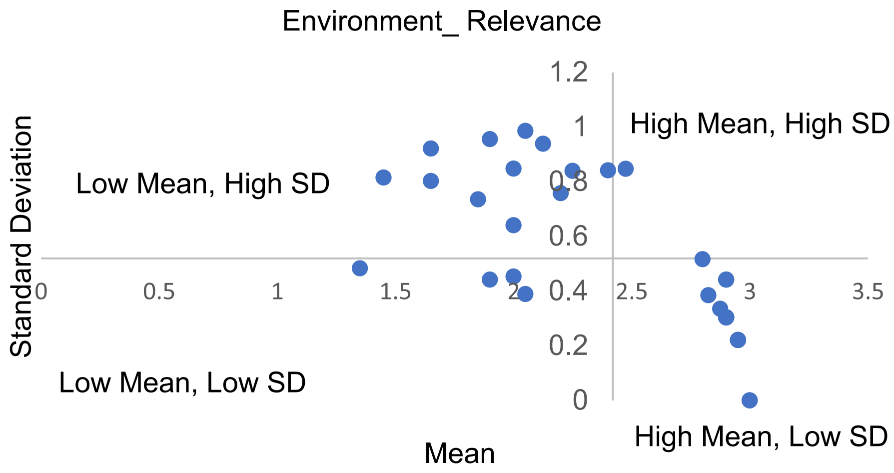

Fig. 3 Stakeholder perceptual mapping of GRI environmental sustainability indicators for attribute "relevance"

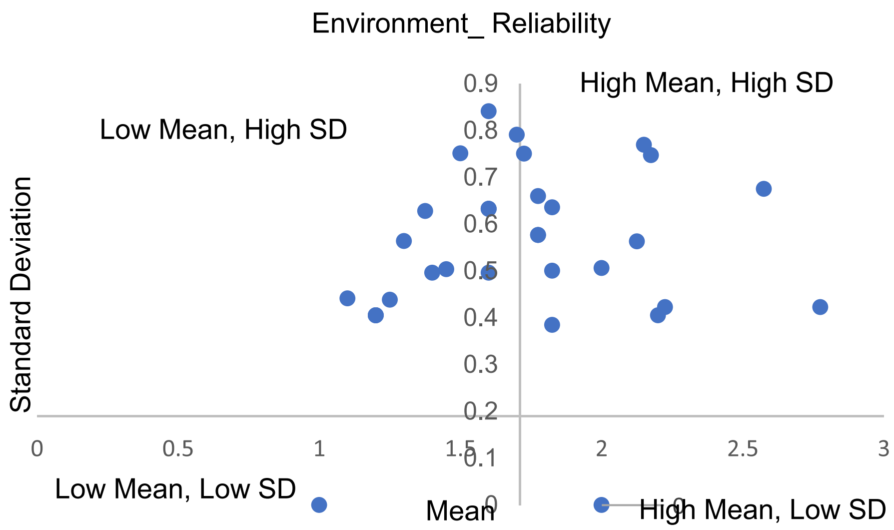

Fig. 4 Stakeholder perceptual mapping of GRI environmental sustainability indicators for attribute "reliability"

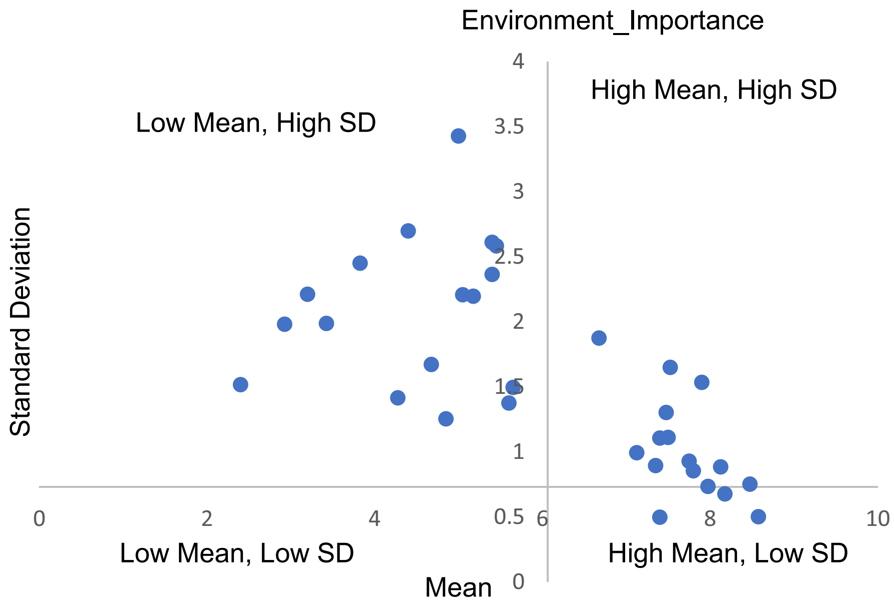

Fig. 5 Stakeholder perceptual mapping of GRI environmental sustainability indicators for attribute "importance"

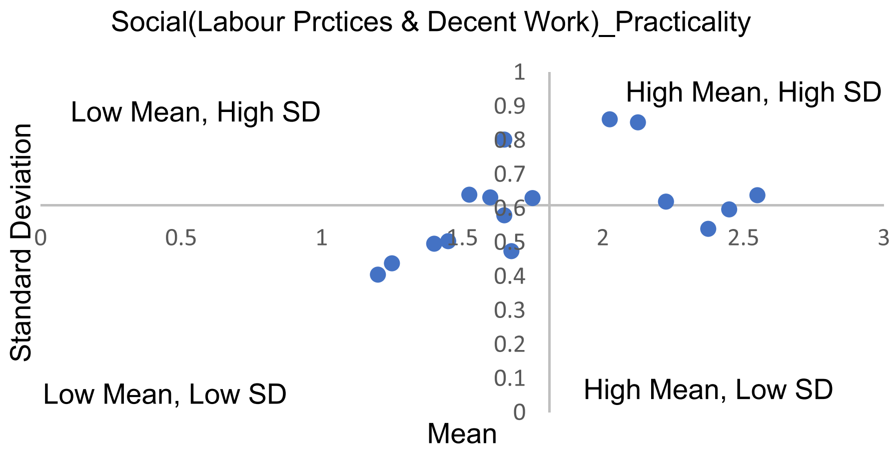

Fig. 6 Stakeholder perceptual mapping of GRI social (labor practices and decent work) sustainability indicators for attribute "practicality"

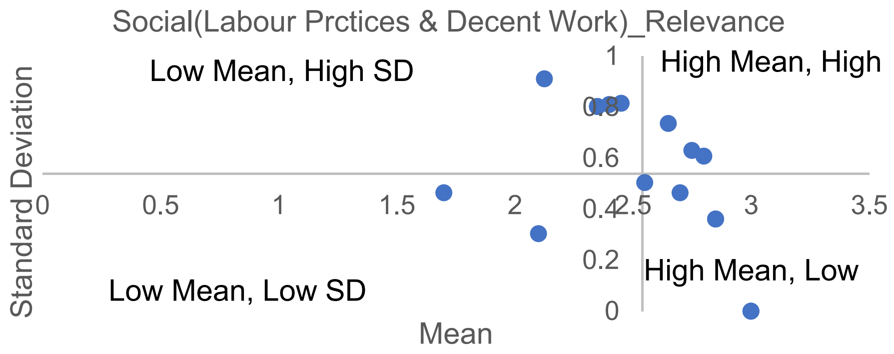

Fig. 7 Stakeholder perceptual mapping of GRI social (labor practices and decent work) sustainability indicators for attribute "relevance"

Fig. 8 Stakeholder perceptual mapping of GRI social (labor practices and decent work) sustainability indicators for attribute "reliability"

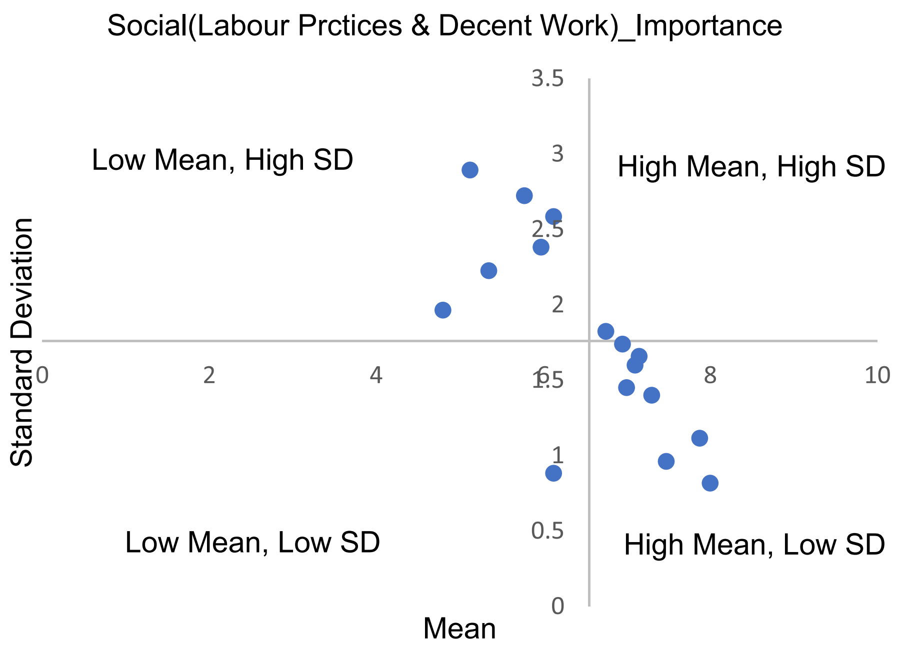

Fig. 9 Stakeholder perceptual mapping of GRI social (labor practices and decent work) sustainability indicators for attribute "importance"

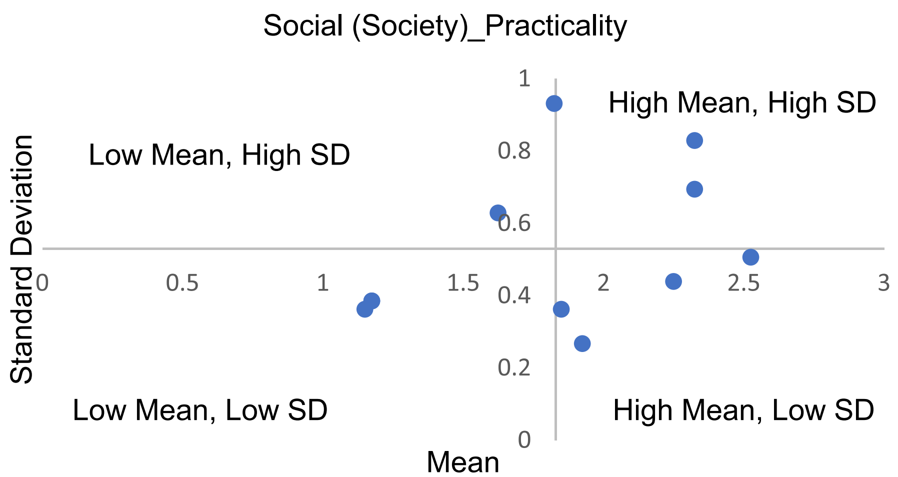

Fig. 10 Stakeholder perceptual mapping of GRI social (society) sustainability indicators for attribute "practicality"

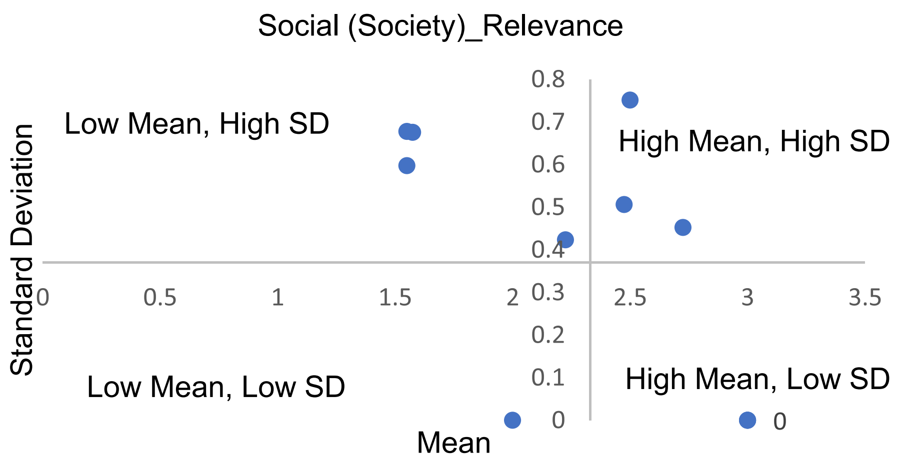

Fig. 11 Stakeholder perceptual mapping of GRI social (society) sustainability indicators for attribute "relevance"

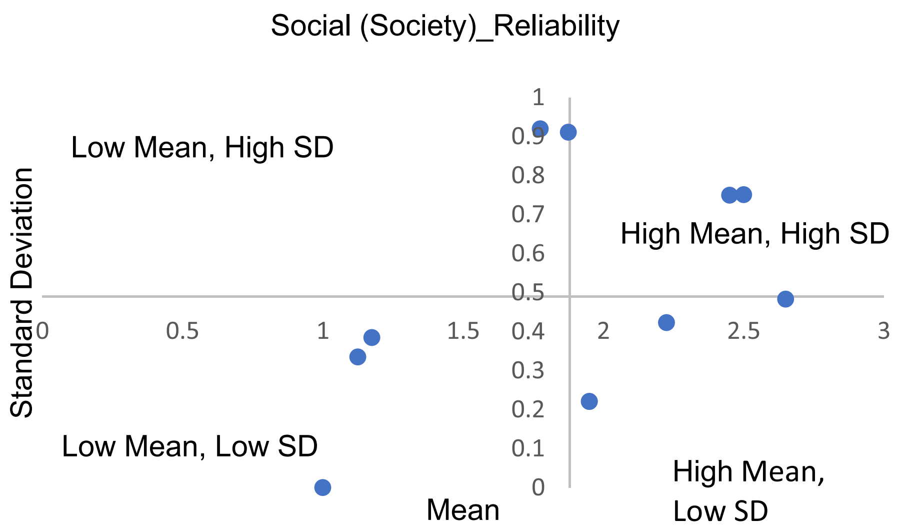

Fig. 12 Stakeholder perceptual mapping of GRI social (society) sustainability indicators for attribute "reliability"

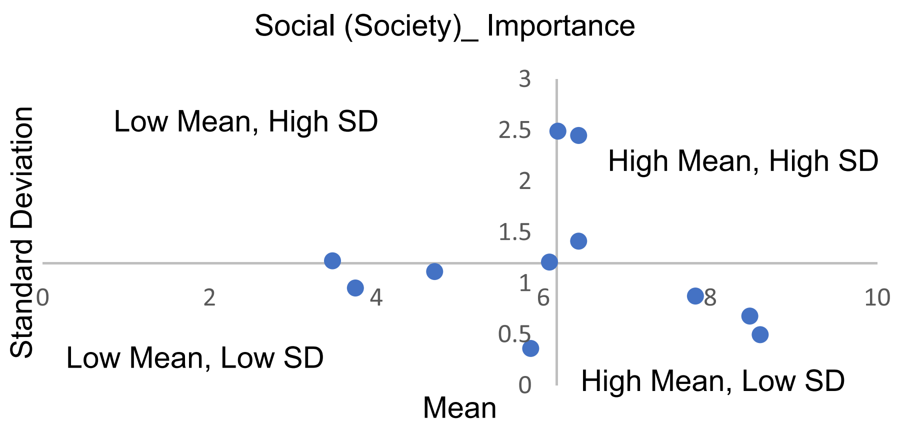

Fig. 13 Stakeholder perceptual mapping of GRI social (society) sustainability indicators for attribute "importance"

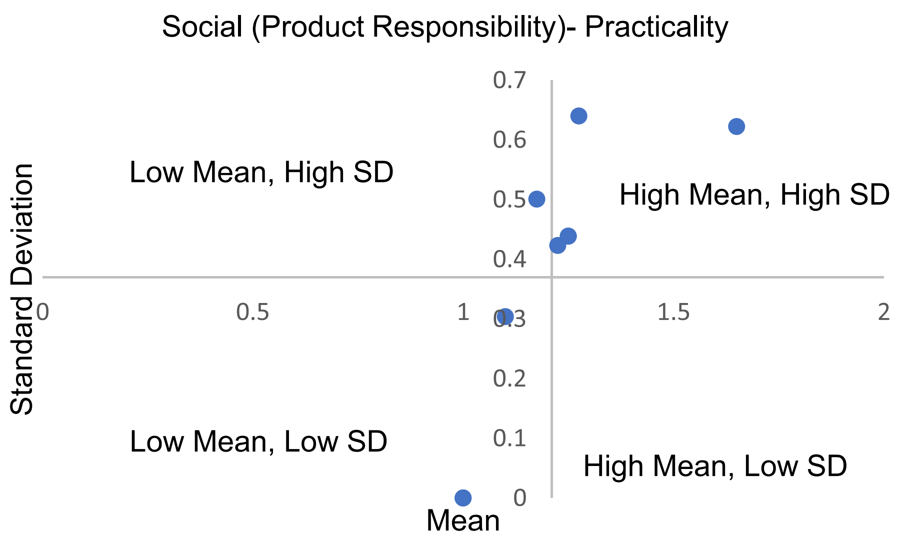

Fig. 14 Stakeholder perceptual mapping of GRI social (product responsibility) sustainability indicators for attribute "practicality"

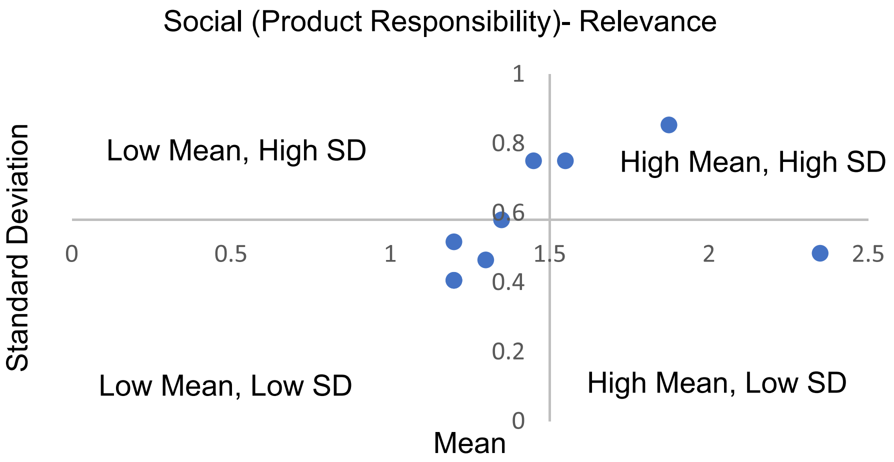

Fig. 15 Stakeholder perceptual mapping of GRI social (product responsibility) sustainability indicators for attribute "relevance"

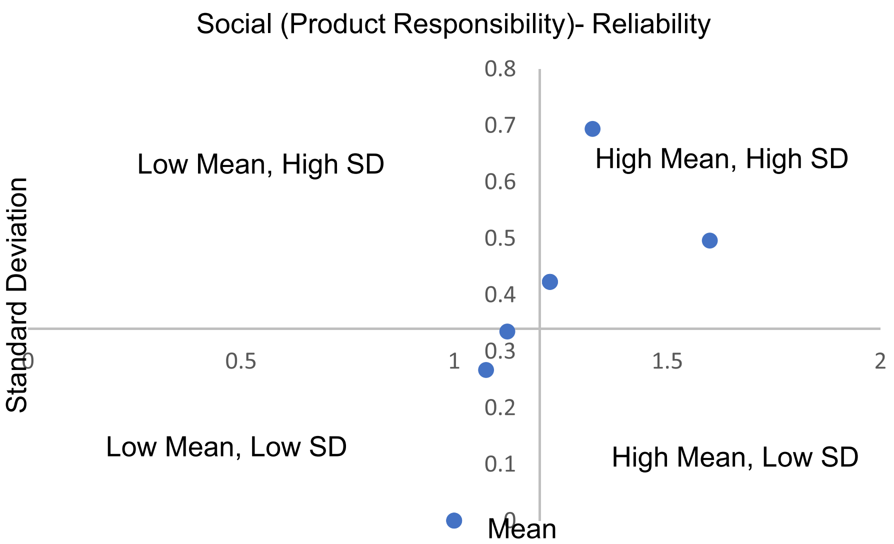

Fig. 16 Stakeholder perceptual mapping of GRI social (product responsibility) sustainability indicators for attribute "reliability"

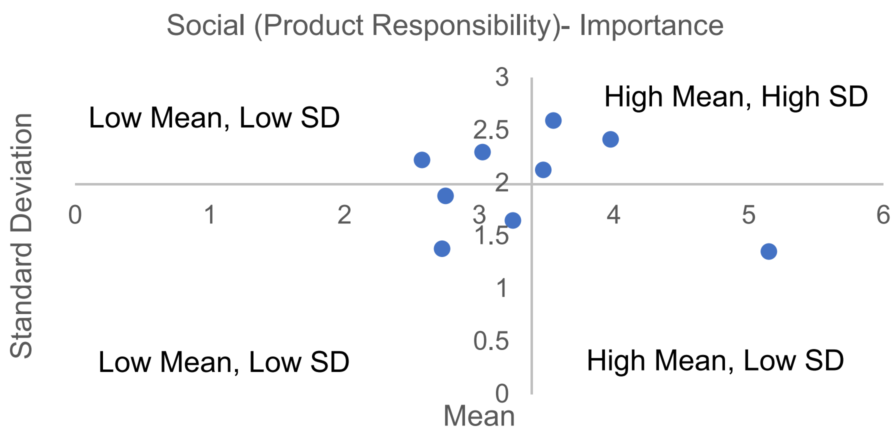

Fig. 17 Stakeholder perceptual mapping of GRI social (product responsibility) sustainability indicators for attribute "importance"

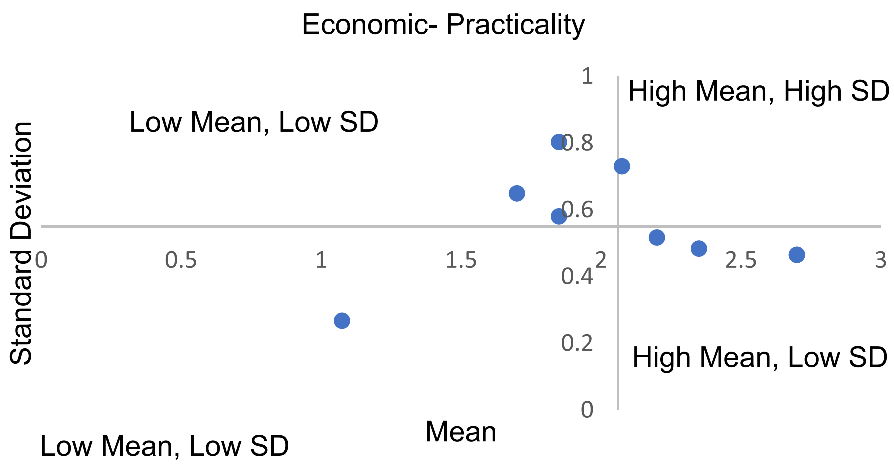

Fig. 18 Stakeholder perceptual mapping of GRI economic sustainability indicators for attribute "practicality"

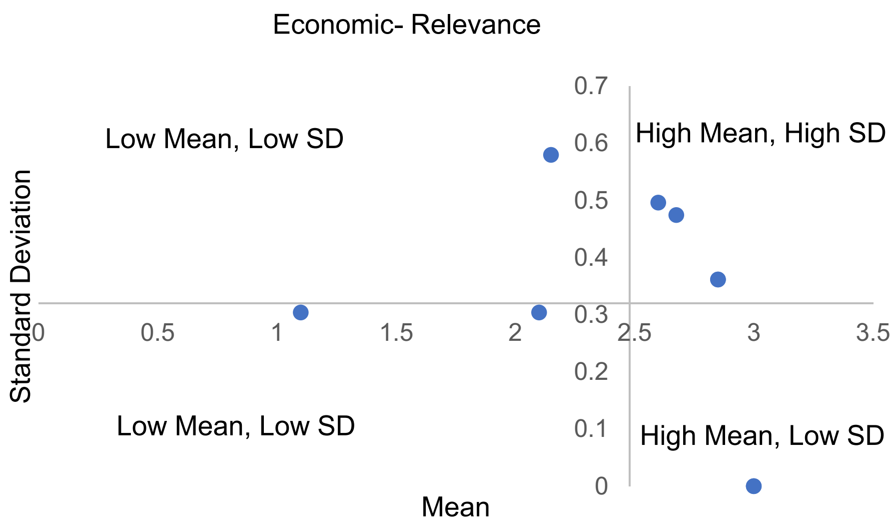

Fig. 19 Stakeholder perceptual mapping of GRI economic sustainability indicators for attribute "relevance"

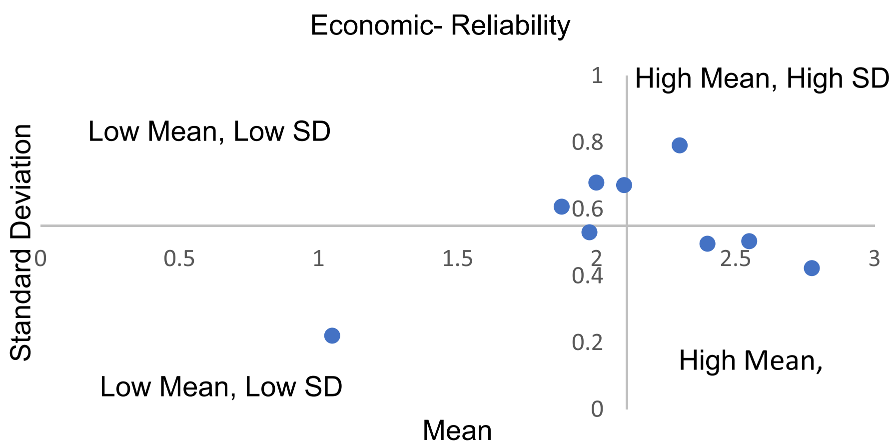

Fig. 20 Stakeholder perceptual mapping of GRI economic sustainability indicators for attribute "reliability"

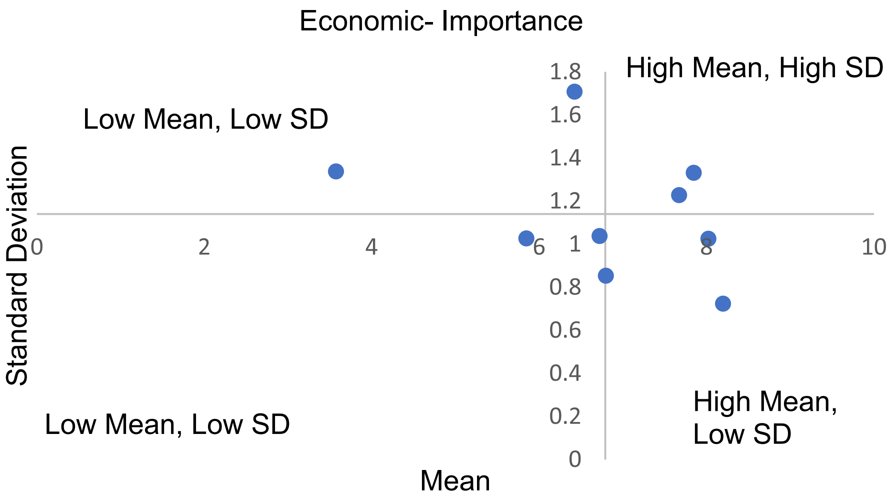

Fig. 21 Stakeholder perceptual mapping of GRI economic sustainability indicators for attribute "importance"

Author Contribution VP conceptualized the study, performed data collection and analysis, and wrote the first draft of the manuscript. KA conceptualized, supervised, and reviewed the study. GB supervised the methodologies applied in the study and reviewed the results. SG performed data analysis and prepared the figures. All authors read and approved the final manuscript.

Data Availability The data that support the findings of this study are available on request from the corresponding author. There is no personal data about the research participants other than their views on the research questions provided to them; hence, this information is not publicly available.

Code Availability Not applicable.

Declarations

Ethics Approval Not applicable.

Consent to Participate Verbal informed consent was obtained before the interviews.

Consent for Publication Not applicable.

Conflict of Interest The authors declare no competing interests.

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