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A GREY-BASED HYBRID DECISION SUPPORT FRAMEWORK FOR ASSESSING THE ENVIRONMENTAL, SOCIAL, AND GOVERNANCE (ESG) SUSTAINABLE PERFORMANCE: A CASE STUDY OF BIST-LISTED BANKS

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Abstract. The present research has been designed to address two significant gaps in the existing literature pertaining to the banking industry. Firstly, it presents a set of criteria derived from the Refinitiv database for the evaluation of ESG sustainability performance. Secondly, it puts forward a novel methodological framework that is both novel and noteworthy in the MCGDM field. This framework employs a grey-based multi-criteria group decision-making (MCGDM) technique with Bonferroni aggregation to comparatively analyze banks' ESG sustainable performance. The developed methodology uses extended versions of three very recent methods, like the Modified Standard Deviation (MSD), Symmetry Point of Criterion (SPC), and Simple Ranking Process (SRP), based on the utilization of interval grey numbers. The Bonferroni aggregation operator is utilized for the aggregation of the experts' evaluations concerning the alternatives based on the selected criteria. A real-life case study on seven publicly traded banks in the Borsa Istanbul Sustainability Index is conducted with the aid of five experts. The research results imply that among the three main ESG dimensions, environmental management practices emerged as the most important factor influencing banks' sustainable performance. This finding also signals that banks that adopt sound environmental management practices into their business models may gain a competitive edge over their competitors in terms of environmental regulations, resilience to environmental risks, and achieving high performance and stability. Finally, the model's validity is checked via comparison and sensitivity assessments. The outcomes of the two-stage validation analysis corroborate the robustness and dependability of the suggested grey MCGDM model.

Keywords: sustainability measurement, banking sector, grey theory, Environmental, Social, and Governance (ESG), Modified Standard Deviation (MSD), Symmetry Point of Criterion (SPC), Simple Ranking Process (SRP).

JEL Classification: C44, C61, G21, M14, Q56.

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1. Introduction

In today's modern business landscape, Environmental, Social, and Governance (ESG) performance has become a cornerstone of corporate accountability and sustainability for companies (Liu et al., 2023; Shabir et al., 2024). ESG factors, which encapsulate the non-financial dimensions of organizational operations, serve as pivotal indicators of long-term resilience and societal impacts (Bilyay-Erdogan & Öztürkkal, 2023; Sariyer et al., 2024). Assessing corporate sustainability through ESG criteria is particularly critical in the banking sector, where regulatory requirements and stakeholder expectations are stringent (Işık, 2023).

The integration of ESG considerations into investment strategies, banking products, insurance offerings, and other financial services facilitates banking organizations' ability to adapt to the evolving expectations of stakeholders (Cao et al., 2024; Mandas et al., 2023). This process thus not only facilitates optimizing sustainability practices, supporting social causes, and promoting responsible governance, but also contributes to maintaining long-term profitability (Fatemi et al., 2018; Yoon et al., 2018).

On the other hand, incorporating ESG principles into the bank business model is of paramount importance for effective risk management (Bilyay-Erdogan et al., 2023; Palmieri et al., 2024). For example, environmental risks like climate change can result in asset devaluation and broader economic disruptions. Similarly, social risks related to labour practices and community relations may harm a bank's reputation and operational stability (Horváthová, 2010; Yoon et al., 2018). Besides, governance-related risks involving regulatory compliance and ethical misconduct can directly undermine stakeholder trust (Bilyay-Erdogan, 2022; Cao et al., 2024; Olteanu et al., 2024). Consequently, by incorporating ESG issues into their business models, banks can more effectively identify, assess, and mitigate these risks, which can contribute to their long-term stability.

From an operational research standpoint, the comparison and assessment of banks' ESG sustainable performance is regarded as a critical and intricate multi-criteria decision-making (MCDM) problem in which a select group of banks are ranked according to multiple conflicting criteria that exert influence on the assessment process. In this regard, the existing work aims to develop a new grey-based hybrid decision support framework to comparatively analyze banks' ESG sustainable performance. The developed integrated grey approach involves extended versions of the conventional Modified Standard Deviation (MSD), Symmetry Point of Criterion (SPC), and Simple Ranking Process (SRP) approaches with the aid of the grey system theory (GST). A case study containing five experts, ten ESG assessment criteria and seven alternative commercial banks was conducted with the objective of indicating the practicality and aptness of the newly introduced grey-based hybrid decision making framework.

Grey numbers are one of the well-known uncertainty sets that are often incorporated into MCGDM models to capture the imprecision, uncertainty, ambiguity, and inconsistency of information in a decision-making environment (Shaju et al., 2023; Tirkolaee & Torkayesh, 2022). Compared to fuzzy logic and neutrosophic sets, the grey interval numbers have some critical advantages; (i) its lower computational complexity enables decision makers (DMs) to make more effective decisions (Aslani et al., 2021; Ulutaş et al., 2021), (ii) it allows DMs to minimize inconsistencies arising from uncertainties and complicated situations about the decision problem using internal numbers (Julong, 1982, 1988), (iii) it provides the opportunity to obtain more robust, stable, and reliable results when it comes to the small, limited, and uncertain data, and (iv) it enables group consensus to be formed in an objective and logical way, even in the presence of conflicting groups (Bai & Sarkis, 2010; Liu & Qiao, 2014; Xia et al., 2015), (v) it does not need any membership function and distribution for the application (Karadağ Albayrak, 2021; Mahmoudi et al., 2020), (vi) while fuzzy logic and neutrosophic sets provide valuable tools for expressing uncertain information, they are not as effective as interval grey numbers in representing diversified uncertain information (Tirkolaee & Torkayesh, 2022).

Consequently, the introduced grey-based integrated procedure combines three mathematical tools like MSD, SPC, and SRP under interval grey numbers and makes valuable and critical contributions to the existing literature as outlined below.

- The model provides a hybrid assessment framework that integrates Grey MSD (G-MSD), Grey SPC (G-SPC), and Grey SRP (G-SRP) techniques for ESG sustainable performance in the banking context, which contributes to the methodological diversity of the literature regarding sustainability performance.
- The application of the model in the banking sector provides a practical framework for the bank's board of directors and executive management to make more reasonable and realistic decisions regarding the assessment of ESG practices. This framework can facilitate the integration of practice and theory, thereby enabling more effective decision-making.
- Grey-based decision-making methodology with Bonferroni aggregation offers a holistic decision-support system that assists banks in effectively analyzing the outcomes of ESG practices by taking into account and expert views and multiple conflicting criteria, which in turn can boost the overall efficiency of sustainability performance.
- The decision model containing interval grey number based on grey system theory is capable of handling and reducing the imprecision, uncertainty, and subjectivity in practical decision-making scenarios, which stresses the suitability and feasibility of the methodology developed based on grey system theory in dealing with highly complicated real-life decision problems.
- The existing work makes an original contribution to empirical knowledge in the area of sustainability by validating the trustworthiness and feasibility of the introduced framework in real-world scenarios. It also provides insights into the model's performance in practical applications.

We structure the remaining Sections of this research as follows. Section 2 presents the overall results of a comprehensive literature review of multi-criteria decision-making applications in the banking industry. This Section also outlines the contributions of prior research related to the analysis of bank sustainability performance and underscores the gaps in existing research that have not been filled. Section 3 elucidates the developed integrated procedure and its implementation steps. Section 4 presents the case study and the application results of the introduced grey-based approach. The outcomes of the research are discussed in Section 5. This Section also outlines the managerial implications. Lastly, in Section 6, the research is concluded and the constraints of the study, along with suggestions for future research, are outlined.

2. Research background and research gaps

Multi-criteria decision-making approaches, offering invaluable support in addressing intricate problems in real-world scenarios, are among the most prevalent methodologies of decision theory and decision analysis as a sub-branch of management science and operations research (Więckowski & Sałabun, 2024). multi-criteria decision-making tools, which have been extensively applied across various disciplines such as management, engineering, logistics, and economics, have also gained considerable traction in the banking industry, where decision-making processes often involve multiple and conflicting criteria (Mardani et al., 2015, 2018). These tools empower decision-makers in the banking industry to formulate more comprehensive and realistic assessments, thereby enhancing the quality and dependability of banking decisions.

A review of existing literature reveals that multi-criteria decision-making tools are extensively employed in the banking industry to solve different decision-making problems, such as financial performance assessment (Fazeli et al., 2023; Gupta et al., 2021; Iç et al., 2022; Marković et al., 2020; Stathas et al., 2002), multidimensional performance measurement (Abdel-Basset et al., 2021; Seçme et al., 2009; Wu et al., 2009), sustainability evaluation (Aras et al., 2017, 2018; Ecer & Pamucar, 2022; Marković et al., 2020; Rao & Shukla, 2023; Korzeb & Samaniego-Medina, 2019), bank selection (Al-Shammari & Milli, 2021), mobile banking selection (Ecer, 2018; Roy & Shaw, 2023), the quality evaluation of internet banking websites (Liang et al., 2019), the measurement of digital transformation (Ecer et al., 2024), investigating new service development capabilities (Dincer & Yüksel, 2018), the comparison of competitive policies (Dincer, 2019), measuring customer satisfaction (Dincer & Hacioglu, 2013), efficiency analysis (Shi et al., 2023), personnel selection (Polychroniou & Giannikos, 2009), evaluating bank regions (Tüysüz & Yıldız, 2020), bank branch ranking (Kiani-Ghalehno & Mahmoodirad, 2024), operational risk factor assessment (Bayrakdaroğlu & Yalçın, 2013), and so on.

When the existing studies in the preceding banking literature are examined in detail, Shi et al. (2023) proffered the improved slacks-based DEA model to assess the efficiency performance of commercial banks with different status in China. In a recent paper utilizing MEREC and MARCOS algorithms, Rao and Shukla (2023) explored sustainability performance in the Indian banking sector by adopting the Sustainable Balanced Scorecard (SBSC) approach. Roy and Shaw (2023) employed a novel approach that combined two fuzzy multi-criteria decision-making methods, namely fuzzy BWM and fuzzy TOPSIS, for a comprehensive analysis of the performance of mobile banking services. Gupta et al. (2021) analyzed the financial performance of listed Indian banks an integrated framework based on AHP and interval-valued TOPSIS methodologies. Rao et al. (2021) analyzed the performance of privately owned banks in India comparatively by applying the standard deviation, CRITIC, ARAS and MOORA methods. Abdel-Basset et al. (2021) applied a combination of AHP, VIKOR, COPRAS and TOPSIS under the plithogenic environment to rank the multidimensional performance of Egyptian deposit banks. Al-Shammari and Milli (2021) identified the critical factors influencing customers' bank selection decision in the Bahraini banking industry via fuzzy AHP model and ranked the most preferred deposit banks by taking these factors into account. In a study conducted by Marković et al. (2020), a new integrated methodology was developed with the objective of investigating the financial performance of Serbian banks. To obtain the weights of the selected financial criteria, the researchers deployed the CRITIC and PIPRECIA procedures. Subsequently, objective and subjective weighting models were combined to ascertain the integrated optimal weights. Additionally, the I-Distance Method was employed to estimate the financial performance score of alternative banks. Liang et al. (2019) employed a novel decision methodology based on Pythagorean fuzzy information to assess the quality of internet banking websites. To determine the relative importance of the assessment criteria, the researchers utilized entropy and cross-entropy methods. They then deployed the VIKOR procedure based on TODIM to generate a ranking of the decision alternatives. Korzeb and Samaniego-Medina (2019) put forward TOPSIS approach, which was designed to allow for the benchmarking and comparison of the deposit banks' sustainability performance in Poland. Wu et al. (2010) deployed a methodological framework that combined Delphi, BSC, AHP and GRA to analyses and assess the asset management banks' business performance in Taiwan. In a research conducted by Wu et al. (2009), a combined multi-criteria decision-making methodology comprising of fuzzy AHP, VIKOR, SAW, and TOPSIS, was implemented to evaluate multidimensional performance of Taiwanese banks by considering the Balanced Scorecard (BSC) approach. The financial performance of Greek deposit banks was investigated by Stathas et al. (2002) utilizing the PROMETHEE model.

Among the papers that have concentrated on the Turkish banking industry, Ecer et al. (2024) employed a hybrid model, combining the WASPAS and SWARA approaches, to assess the digitalization performance of deposit banks operating in Turkey. Iç et al. (2022) used a combination of AHP and DOE techniques to assess the financial performance of deposit-taking banks in Turkey. A mathematical model based on LOPCOW and DOBI methodologies for measuring the sustainability performance of Turkish deposit banks was developed by Ecer and Pamucar (2022). The authors considered three key dimensions, namely social, environmental and economic, to analyze the sustainability of banks. Tüysüz and Yıldız (2020) utilized a combination of two decision-making models for the comparison and analysis of the performance of Turkish banks with regard to agricultural banking. In this context, the authors deployed the Simulation-integrated HFLTS-AHP technique for the estimation of the weight values of the decision criteria and the GRA approach for the ranking of alternative bank regions. Aras et al. (2018) conducted a comprehensive analysis of the sustainability performance of deposit banks in Turkey. The study employed a multi-dimensional approach, encompassing social, environmental, corporate governance, financial, and economic dimensions. To this end, the researchers utilized content analysis, entropy, and TOPSIS methods. Dincer and Yüksel (2018) adopted a decision-making approach that integrated a range of methods, including ANP, AHP, VIKOR, BSC, and content analysis. This approach was utilized to assess and compare the performance related to new service development in Turkish deposit banks with diverse ownership structures. Aras et al. (2017) presented an integrated methodological approach based on content analysis, entropy, and TOPSIS. This methodology is designed to assess Garantibank's sustainability performance in terms of environmental, social, economic, and governance indicators. Dincer and Hacioglu (2013) conducted a customer satisfaction assessment for Turkish banks with diverse ownership structures by deploying AHP and Fuzzy VIKOR procedures. In the integrated framework, AHP was utilized to ascertain weights, while fuzzy VIKOR was employed to estimate the priorities of alternative banks. Bayrakdaroğlu and Yalçın (2013) analyzed operational risk components for deposit banks with different ownership structures in Turkey by implementing a fuzzy AHP procedure. Seçme et al. (2009) propounded a hybrid approach based on fuzzy AHP and TOPSIS for comparing the leading Turkish deposit banks in terms of financial and non-financial performance indicators.

Following an extensive analysis of past literature in the banking industry, it has become evident that several significant research gaps exist. These gaps are outlined in detail below.

The findings of the present work revealed two critical gaps in the past literature. Firstly, following an extensive review of the existing literature, it was realized that no generally accepted or implemented set of criteria exists for evaluating the banks' ESG sustainability performance. Despite the existence of numerous studies proposing various frameworks for assessing the ESG performance of firms across different industries, none of them have conducted an assessment of banks using the ESG framework developed by the Refinitiv Eikon ESG database. Despite the existence of several ESG frameworks, such as MSCI ESG Ratings, Sustainalytics, and SASB Standards, which are employed for the evaluation of companies' sustainability performance, this research has opted for Refinitiv Eikon as the data source for ESG criteria. The rationale behind this selection is threefold. Firstly, the methodological transparency of Refinitiv Eikon is noteworthy, given that it encompasses 10 pillars across three dimensions, utilizing over 400 objective metrics. Secondly, its application is not limited to a specific industry; it is pertinent to both the non-financial and financial sectors. Thirdly, and perhaps most significantly, Refinitiv Eikon is well-suited for academic and empirical research, particularly within the financial sector.

The second crucial gap pertains to the methodological framework that can be utilized to assess the ESG performance of financial institutions. The results of the aforementioned literature review demonstrate that, within the context of sustainability assessment, earlier papers have proposed a number of methodological frameworks for different decision-making problems in the banking sector. These frameworks utilize some decision-making frameworks based on crisp numbers or fuzzy numbers. However, to the best of the authors' knowledge, the MSD and SPC models, or their grey extensions, have not been employed to ascertain the importance weights of critical factors affecting sustainability performance in the banking sector. Additionally, neither the SRP model nor its gray extension has been suggested for prioritizing alternative banks in past literature.

To date, there is no existing study that has leveraged the flexibility and effective use of grey numbers to address uncertainties inherent in banking decision-making processes. Thus, to address and fill these gaps highlighted above, this research has developed a grey-based MSD-SPC-SRP methodology and applies it to the measurement and evaluation of banks' ESG sustainable performance.

3. Research methodology

This research adopts a hybrid methodological approach that integrates Bonferroni aggregation with grey interval numbers to effectively address the challenges of evaluating ESG sustainable performance in the banking industry under conditions of uncertainty. The methodological framework, as illustrated in Figure 1, is grounded in Grey System Theory, which is initially introduced to provide theoretical background on handling imprecise and incomplete information. Following this, the grey-based MSD-SPC-SRP hybrid model is delineated in detail to ensure clarity and reproducibility in assessment procedures. In the proposed gray hybrid group decision-making model, key decision-making elements, including ESG performance

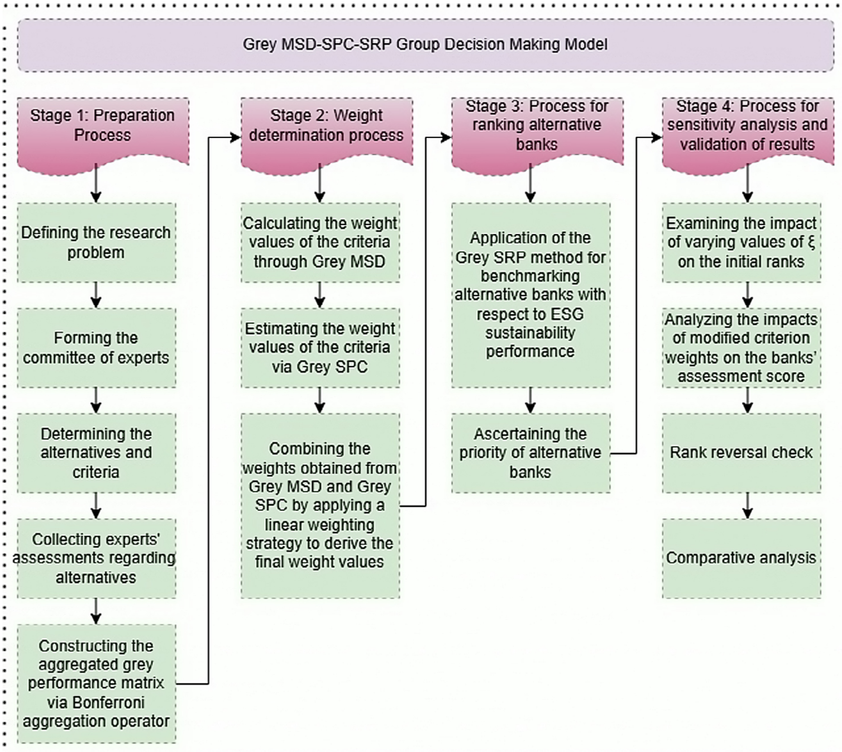

Figure 1. Flowchart of the proposed methodology

criteria (indicators), alternatives (listed commercial banks) and experts, are first identified to create a structured and systematic analytical framework. Subsequently, the developed grey methodology is applied through five sequential phases. In the first phase, the first criterion weights are determined based on the G-MSD procedure. In the second phase, the second criterion weights are obtained through the application of the G-SPC procedure. In the third phase, the criterion weights derived from both G-MSD and G-SPC are synthesized through an aggregation operator based on a linear weight integration method, enhancing the robustness and balance of the final weight vector. In the fourth phase, the G-SRP is employed to identify the ESG sustainable performance rankings of the listed commercial banks based on the aggregated criterion weights. In the final phase, several validation analyses are conducted to assess the consistency, stability, and effectiveness of the proposed grey model, thereby confirming its methodological soundness and practical applicability in uncertain decision-making environments.

3.1. Grey system theory

The grey system theory (GST) was proposed by Deng (1982) and can be helpful in solving uncertainties in situations involving discrete data and incomplete information (Fu et al., 2021; Karadağ Albayrak, 2021). Grey system analysis is carried out with grey numbers, grey equations and/or grey matrices (Deng, 1989). A grey number indicates that the information about the number is not complete and sufficient. Also, it belongs to a range and does not contain a crisp value (Lin et al., 2008). A grey number g denotes by $\otimes z$, $\otimes z \in [\underline{\otimes} z, \ \bar{\otimes} z] = \{g \in \otimes z | \underline{\otimes} z \leq g \leq \bar{\otimes} z\}$, where $\underline{\otimes} z$ and $\bar{\otimes} z$ correspond to the lower and upper limits of the interval, respectively. Let $\otimes z_1$ and $\otimes z_2$ be two grey numbers, and z be a crisp number, then basic mathematical operations for grey numbers can be shown as follows:

$$\otimes z_1 + \otimes z_2 = [\underline{z_1} + \underline{z_2}, \overline{z_1} + \overline{z_2}]; \tag{1}$$

$$\otimes z_1 - \otimes z_2 = [\underline{z_1} - \overline{z_2}, \overline{z_1} - \underline{z_2}]; \tag{2}$$

$$\otimes z_1 \otimes z_2 = \left[\min\left(\underline{z_1}.\underline{z_2}, \underline{z_1}.\overline{z_2}, \overline{z_1}.\underline{z_2}, \overline{z_1}.\overline{z_2}\right), \ \max\left(\underline{z_1}.\underline{z_2}, \underline{z_1}.\overline{z_2}, \overline{z_1}.\underline{z_2}, \overline{z_1}.\overline{z_2}\right)\right]; \tag{3}$$

$$\otimes z_1 : \otimes z_2 = [\underline{z_1}, \overline{z_1}].\left[\frac{1}{\underline{z_2}}, \frac{1}{\overline{z_2}}\right]; \tag{4}$$

$$k \in \mathcal{R}^+, \ k.\otimes z = [k.\underline{z}, \ k.\bar{z}]. \tag{5}$$

The crisp value for a grey number is identified by implementing Eq. (6).

$$C = 0.5 \times \otimes z = 0.5 \times [\underline{\otimes} z + \bar{\otimes} z]. \tag{6}$$

3.2. Grey-based MSD-SPC-SRP methodology

3.2.1. Grey Modified Standard Deviation (G-MSD) algorithm for criterion weighting

The SD technique, which is utilized to measure risk in the field of finance, is also applied to estimate the objective weights of the assessment criteria in the multi-criteria decision-making domain. This approach, proffered by Diakoulaki et al. (1995), first identifies the objective weights on the basis of the computed standard deviation of each criterion, taking into account the data structure in the decision matrix. The SD procedure was later modified by Puška et al., (2022) by taking the total values of the criteria into account. Its advantages are that it is easy to understand and apply, does not take much time and is practical. The SD technique and its extensions have been successfully deployed in a variety of areas like financial performance measurement (Baydaş et al., 2024; Baydaş & Elma, 2021; Baydaş & Pamucar, 2022; Nguyen et al., 2020), and market performance evaluation (Işık & Koşaroğlu, 2020), location selection (Şahin, 2021), efficiency assessment of cultural services (Vavrek & Bečica, 2020), assessment of the best water distribution system (Narayanamoorthy et al., 2023), ranking groundnut sites (Deepa et al., 2019), hospital site selection (Hezam et al., 2023a), efficiency assessment (Vavrek & Bečica, 2020), and numerical example (Rani et al., 2023a). A step-by-step procedure concerning how G-MSD is applied to the decision problem as below.

Step 1-1: Construct a grey performance matrix comprising alternative banking institutions and ESG criteria.

At this stage, each DM evaluates the bank alternatives separately in accordance with the pre-determined ESG criteria, utilising the linguistic parameters illustrated in Table 1. Subsequently, the linguistic data obtained from the DMs is converted into the grey numbers

Table 1. The Linguistic scale and GNs used for rating

Linguistics values	Symbol	Related grey numbers	
Very bad	VB	1	10
Bad	B	11	20
Moderately bad	MB	21	30
Fair	F	31	40
Moderately good	MG	41	50
Good	G	51	60
Very good	VG	61	70

displayed in Table 1 for each DM. Let m, n, and k denote the total number of alternatives, criteria, and experts, respectively. The opinion of k experts is represented as the matrix $Z^{(t)} = \left[\otimes z_{ij}^{(t)}\right]_{m\times n}$ where $t = 1,\ldots,k$. Later, these matrices are converted into a main grey performance matrix with the aid of the Bonferroni aggregation operator (Bonferroni, 1950) shown in Eq. (7) (Pamucar et al., 2021).

For $p, q \geq 0$,

$$\otimes z_{ij} = \left[z_{ij}^{l}, z_{ij}^{u}\right] = \begin{cases} z_{ij}^{l} = \left(\dfrac{1}{k(k-1)}\sum_{\substack{i,j=1\\ i\neq j}}^{k} (z_i^{l})^p (z_j^{l})^q\right)^{\frac{1}{p+q}} \\ z_{ij}^{u} = \left(\dfrac{1}{k(k-1)}\sum_{\substack{i,j=1\\ i\neq j}}^{k} (z_i^{u})^p (z_j^{u})^q\right)^{\frac{1}{p+q}} \end{cases}. \tag{7}$$

Accordingly, the main grey performance matrix has the following form:

$$Z = \left[\otimes z_{ij}\right]_{m\times n}, \tag{8}$$

where, $\otimes z_{ij}$ ($\otimes z_{ij} = \left[z_{ij}^{l}, z_{ij}^{u}\right]$) demonstrates the grey performance value of the i^{th} bank alternative against the j^{th} ESG criterion $(i = 1,\ldots,m,\ j = 1,\ldots,n)$. Also, z_{ij}^{l} and z_{ij}^{u} stand for lower and upper limits of grey numbers, respectively.

Step 1-2: Normalized grey performance matrix $Y = \left[\otimes y_{ij}\right]_{m\times n}$ is obtained via Eq. (9) (for beneficial criteria) and Eq. (10) (for non-beneficial criteria). Traditional normalization methods, such as the min–max or the vector normalization may result in distortions or loss of meaningful information when applied to uncertain or incomplete datasets. Therefore, the normalization techniques adopted in Eqs. (9)–(10) were selected based on their appropriateness for processing grey interval numbers and their ability to maintain the relative relationships between alternatives in uncertain environments.

$$\otimes y_{ij} = \begin{cases} \otimes y_{ij}^{+} = \dfrac{\otimes z_{ij}}{\max\left\{\otimes z_{ij} | 1 \leq i \leq m\right\}} = \left[\dfrac{z_{ij}^{l}}{\max\left\{z_{ij}^{u} | 1 \leq i \leq m\right\}}, \dfrac{z_{ij}^{u}}{\max\left\{z_{ij}^{u} | 1 \leq i \leq m\right\}}\right]; & (9) \\ \otimes y_{ij}^{-} = \dfrac{\min\left\{\otimes z_{ij} | 1 \leq i \leq m\right\}}{\otimes z_{ij}} = \left[\dfrac{\min\left\{z_{ij}^{l} | 1 \leq i \leq m\right\}}{\left(z_{ij}^{u}\right)}, \dfrac{\min\left\{z_{ij}^{l} | 1 \leq i \leq m\right\}}{\left(z_{ij}^{l}\right)}\right]. & (10) \end{cases}$$

Step 1-3. Find the modified value of the standard deviation of each criterion with the aid of Eq. (11).

$$\otimes s_j = \left[s_j^l, s_j^u\right] = \left[\min\left(\left(\frac{\sigma^l}{\sum_{i=1}^{m}\left(y_{ij}^l\right)}\right), \left(\frac{\sigma^u}{\sum_{i=1}^{m}\left(y_{ij}^u\right)}\right)\right), \max\left(\left(\frac{\sigma^l}{\sum_{i=1}^{m}\left(y_{ij}^l\right)}\right), \left(\frac{\sigma^u}{\sum_{i=1}^{m}\left(y_{ij}^u\right)}\right)\right)\right]. \quad (11)$$

Step 1-4. Compute the grey weights from G-MSD.

$$\otimes w_{j,msd} = \left[w_{j,msd}^l, w_{j,msd}^u\right] = \left[\frac{\otimes s_j}{\sum_{j=1}^{n} \otimes s_j}\right] = \left[\min\left(\frac{s_j^l}{\sum_{j=1}^{n}\left(s_j^l\right)}, \frac{s_j^u}{\sum_{j=1}^{n}\left(s_j^u\right)}\right),\right.$$

$$\left.\max\left(\frac{s_j^l}{\sum_{j=1}^{n}\left(s_j^l\right)}, \frac{s_j^u}{\sum_{j=1}^{n}\left(s_j^u\right)}\right)\right]. \quad (12)$$

3.2.2. Grey Symmetry Point of Criterion (G-SPC) algorithm for criterion weighting

SPC is a relatively new technique for estimating criteria weights. The algorithm, developed by Gligorić et al. (2023), exhibits the following characteristics: (i) It computes the weights of criteria by assessing the utility based on criteria symmetry. Specifically, it computes both the symmetry point (the midpoint of the interval [a, b] considering the lower (a) and upper (b) limits of the criteria) and the absolute deviation for each criterion in the decision problem to measure its impact on the weight values, (ii) It is independent of normalization and is designed to balance the influence of the criteria to improve the effectiveness of the algorithm's outcomes, (iii) It has a basic mathematical algorithm that can be easily applied by decision makers and does not require complicated computations. The SPC method and its various extensions have been effectively implemented in several areas like assessment of sustainable enterprise resource planning (Mishra et al., 2024), sustainable supplier selection (Ali, 2024), evaluation of preparedness of SMEs (Biswas et al., 2023), sustainable recycling partner selection (Rani et al., 2023b), and prioritization of biofuel industry sustainability factors (Hezam et al., 2023b). Mathematically, a step-by-step procedure on how to apply the G-SPC to the decision problem can be explained as indicated below.

Step 1-5. Construct the grey performance matrix by following the procedure in Step 1-1.

Step 1-6. Find the symmetry points of the performance values of each criterion.

$$\otimes f_j = \left[f_j^l, f_j^u\right] = \frac{\max\left\{\otimes z_{ij} | 1 \le i \le m\right\} + \min\left\{\otimes z_{ij} | 1 \le i \le m\right\}}{2} =$$

$$\left[\frac{\max\left\{z_{ij}^l | 1 \le i \le m\right\} + \min\left\{z_{ij}^l | 1 \le i \le m\right\}}{2}, \frac{\max\left\{z_{ij}^u | 1 \le i \le m\right\} + \min\left\{z_{ij}^u | 1 \le i \le m\right\}}{2}\right]. \quad (13)$$

Step 1-7. Form the absolute distance matrix $D = \left[\otimes d_{ij}\right]_{m \times n}$,

$$\otimes d_{ij} = \left[d_{ij}^l, d_{ij}^u\right] = \left|\otimes z_{ij} - \otimes f_j\right| = \left[\min\left(\left|z_{ij}^l - f_j^l\right|, \left|z_{ij}^u - f_j^u\right|\right), \max\left(\left|z_{ij}^l - f_j^l\right|, \left|z_{ij}^u - f_j^u\right|\right)\right]. \quad (14)$$

Step 1-8. Obtain the matrix of the moduli of the symmetry $S = \left[\otimes s_{ij}\right]_{m\times n}$,

$$\otimes s_{ij} = \left[s_{ij}^{l}, s_{ij}^{u}\right] = \left[\frac{\sum_{i=1}^{m} \frac{\otimes d_{ij}}{\otimes z_{ij}}}{m}\right] = \left[\min\left(\frac{\sum_{i=1}^{m} \frac{d_{ij}^{l}}{z_{ij}^{l}}}{m}, \frac{\sum_{i=1}^{m} \frac{d_{ij}^{u}}{z_{ij}^{u}}}{m}\right), \max\left(\frac{\sum_{i=1}^{m} \frac{d_{ij}^{l}}{z_{ij}^{l}}}{m}, \frac{\sum_{i=1}^{m} \frac{d_{ij}^{u}}{z_{ij}^{u}}}{m}\right)\right]. \quad (15)$$

Step 1-9. Construct the modulus of symmetry of criterion

$$\otimes c_{j} = \left[c_{j}^{l}, c_{j}^{u}\right] = \left[\frac{\sum_{j=1}^{n} \otimes s_{ij}}{m}\right] = \left[\frac{\sum_{j=1}^{n} d_{ij}^{l}}{m}, \frac{\sum_{j=1}^{n} d_{ij}^{u}}{m}\right]. \quad (16)$$

Step 1-10. Compute the grey weights from G-SPC

$$\otimes w_{j,spc} = \left[w_{j,spc}^{l}, w_{j,spc}^{u}\right] = \left[\frac{\otimes c_{j}}{\sum_{j=1}^{n} \otimes c_{j}}\right] = \left[\min\left(\frac{c_{j}^{l}}{\sum_{j=1}^{n}\left(c_{j}^{l}\right)}, \frac{c_{j}^{u}}{\sum_{j=1}^{n}\left(c_{j}^{u}\right)}\right),\right.$$

$$\left.\max\left(\frac{c_{j}^{l}}{\sum_{j=1}^{n}\left(c_{j}^{l}\right)}, \frac{c_{j}^{u}}{\sum_{j=1}^{n}\left(c_{j}^{u}\right)}\right)\right]. \quad (17)$$

3.2.3. Obtain the integrated grey weights from the G-MSD and the G-SPC procedures

The application of diverse multi-criteria decision-making methodologies to ascertain weight values frequently results in minor discrepancies in the computed weights. These discrepancies are attributable to the disparate mechanisms employed by each decision-making method for the assessment of criterion significance level. To handle this issue, we have developed an aggregation operator based on a linear weight integration method. This effectively synthesizes the outputs from multiple multi-criteria decision-making algorithms. This approach guarantees a more rational, stable and dependable computation of the criteria weights, taking into account the impact of each technique. The combination of these different decision-making algorithms results in optimized weighting coefficients that enable a more comprehensive and objective understanding of the relative significance of the criteria. Adopting this approach in the decision-making process increases both the dependability of the decision-making approach and allows the final weights to be representative of the chosen different methodologies, which in turn contributes to improving the robustness and quality of the performed performance analysis. The final weight of each criterion from the G-MSD and G-SPC procedures are integrated with the following Equation.

$$\otimes w_{j,int} = \left[w_{j,int}^{l}, w_{j,int}^{u}\right] = \left[\left(\xi \otimes w_{j,msd}\right) + \left(\left(1-\xi\right) \otimes w_{j,spc}\right)\right] = \begin{bmatrix}\left(\xi w_{j,msd}^{l}\right) + \left(\left(1-\xi\right) w_{j,spc}^{l}\right), \\ \left(\xi w_{j,msd}^{u}\right) + \left(\left(1-\xi\right) w_{j,spc}^{u}\right)\end{bmatrix}, \quad (18)$$

where, $\otimes w_{j,int}$ (j = 1, 2,..., n) denotes the combined grey weight of j^{th} evaluation criterion. In current study, grey weights of criteria obtained from G-MSD and G-SPC are represented as $\otimes w_{j,msd}$ and $\otimes w_{j,spc}$, respectively. In Eq. (18), $\xi \in [0, 1]$ is a parameter expressing the value of the coefficient representing the percentage share of the weights of criteria, the value of this parameter was considered as 0.5 for the initial solution.

3.2.4. Grey Simple Ranking Process (G-SRP) approach for ranking orders of alternatives

SPC was developed by Gligorić et al. (2023) for ranking the decision alternatives in a decision-making problem. This algorithm considers the effect of each criterion separately in the solution process and is capable of solving complex problems more efficiently. Besides, it is not restricted by the selection of the normalization technique, which directly influences the solution's stability. The SRP methodology has been utilized effectively in several areas, including choosing the proper material for knee orthoses (Mian et al., 2024), ranking the performance of universities (Do, 2024), financial performance assessment for banking institutions (Trung et al., 2024), and evaluation of preparedness of SMEs (Biswas et al., 2023). The following section outlines a step-by-step process concerning the application of G-SRP to a decision problem.

Step 2-1. Construct the grey performance matrix presented in Eq. (8).

Step 2-2. Formulate a grey ranking matrix to compare each bank alternative considering each criterion.

When forming the ranking matrix, if the relevant criterion is benefit-oriented, the alternative having the highest performance value is ranked as the best alternative. However, if the relevant criterion is cost-oriented, the alternative having the lowest performance value is ranked as the best alternative. Grey ranking matrix is presented in Eq. (19).

$$\otimes R = \left[\otimes r_{ij}\right]_{m \times n}, \tag{19}$$

where, $\otimes r_{ij}\left(\otimes r_{ij} = \left[r_{ij}^{l}, r_{ij}^{u}\right]\right)$ demonstrates the ranking performance of the i^{th} bank alternative against the j^{th} ESG criterion $(i = 1,\ldots,m,\ j = 1,\ldots,n)$.

Step 2-3. Form the weighted ranking matrix.

$$\otimes h_{ij} = \left[h_{ij}^{l}, h_{ij}^{u}\right] = \left[\otimes r_{ij} \times \otimes w_{j,int}\right] = \left[\left(r_{ij}^{l} \times w_{j,int}^{l}\right), \left[r_{ij}^{u} \times w_{j,int}^{u}\right]\right]. \tag{20}$$

Step 2-4. Compute the total ranking score of each alternative bank.

$$\otimes t_i = \left[t_i^{l}, t_i^{u}\right] = \sum_{j=1}^{n} \otimes h_{ij} = \left[\sum_{j=1}^{n} h_{ij}^{l}, \sum_{j=1}^{n} h_{ij}^{u}\right]. \tag{21}$$

Step 2-5. Derive the priority score of each alternative bank.

$$\otimes p_i = \left[m - \otimes t_i\right] = \left[m - t_i^{u}, m - t_i^{l}\right]. \tag{22}$$

Step 2-6. Identify the crisp performance score of the alternative banks

In this step, the crisp performance scores for the alternative banks are identified by applying Eq. (23):

$$Q_i = 0.5 \times \otimes p_i = 0.5 \times \left[p_i^{l} + p_i^{u}\right]. \tag{23}$$

Alternative banks are prioritized in descending order on the basis of the Q_i values.

4. A real case study

The present research introduces a novel grey group decision-making approach. In the existing research, a real-time case study based on the assessment of banks' ESG sustainable performance in Turkey is designed to indicate the effectiveness and credibility of the developed grey-based decision-making methodology. In this context, a grey decision matrix is constructed based on the input data from an expert committee comprising five professionals with different backgrounds from the banking sector to conduct the case study. The evaluation criteria cover ten ESG criteria, while the decision alternatives are composed of seven listed commercial banks.

This Section is divided into four distinct sub-stages. In the first sub-stage, the formulation of the sustainable performance measurement problem, the composition of the expert committee, the selection of ESG criteria, and the identification of bank alternatives under evaluation are explained in detail. In the second sub-stage, G-MSD and G-SPC methodologies are employed to estimate the weight coefficients of the identified criteria. The obtained weight values are then presented in this sub-stage. The next sub-stage presents the application of the G-SRP methodology to rank the bank alternatives according to their ESG sustainable performance and the corresponding results. Finally, the fourth sub-stage provides robustness checks to assess the consistency and reliability of the results obtained.

4.1. Stage 1: preparation process

4.1.1. Problem definition

The assessment of ESG sustainability performance in the banking sector is a complex and multi-dimensional challenge, requiring structured evaluation methodologies capable of capturing uncertainty, expert-driven judgments, and multi-criteria interactions. Moreover, there is no universally accepted framework for measuring the ESG performance of banks, leading to methodological discrepancies and difficulties in comparing financial institutions objectively. Existing approaches frequently overlook uncertainty-handling techniques, particularly grey-based multi-criteria group decision-making (MCGDM) models, which provide a more robust mechanism for evaluating ESG dimensions in uncertain environments. Similarly, expert evaluations play a critical role in ESG performance assessments, yet many models lack a systematic approach for aggregating expert opinions in a transparent and balanced manner.

To address these gaps, the existing work introduces a hybrid decision support framework that integrates MCGDM methodologies (i.e., G-MSD, G-SPC, G-SRP) and Bonferroni aggregation to provide a more objective, reliable, and uncertainty-conscious approach for assessing ESG sustainability performance in banks. As a result, the introduced grey methodology is tested through a case study of BIST-listed banks, demonstrating its feasibility for financial institutions seeking structured ESG assessments.

4.2. Construction of a team of experts

Experts' subjective opinions are necessary to identify the industry-specific significance levels of ESG sustainability indicators and to compute the performance scores of commercial banks. For the present research, we invited seven banking executives who are experts in the ESG field to participate in the ESG performance assessment process. Two of them, however, declined our invitation due to their workload. At the end of the interviews, we assembled a team of experts with the remaining five experts. Information and details for five highly experienced professionals who participated in this research are provided in Table 2. To ensure the objectivity and credibility of the expert-driven evaluation process, several measures were implemented to mitigate potential biases and conflicts of interest among the five decision-makers (DMs) participating in the study. Firstly, none of the experts have any affiliation with or employment ties to the BIST-listed banks analyzed in this research, ensuring that evaluations were conducted independently and without external influence. Secondly, before their participation, all experts were fully briefed on the study's objectives and asked to formally disclose any potential conflicts of interest. Based on this information, none of them declared any conflict of interest. Thirdly, to minimize the impact of individual bias and prevent dominance effects, expert assessments were collected through an independent online evaluation platform that ensured anonymity and eliminated direct interactions among the DMs during the scoring process. Lastly, the implementation of the Bonferroni-based aggregation mechanism played a crucial role in reducing potential biases by systematically balancing and synthesizing expert judgments.

Table 2. The profile of the members of the team of experts

Experts	Graduation	Education	Duty	Experience
DM_1	Economy	Master's degree	Corporate governance committee member	23
DM_2	Business	Bachelor's degree	Head of sustainability committee	26
DM_3	Business	Bachelor's degree	Independent board member	30
DM_4	Engineering	Doctoral degree	Academician (Prof.) providing banking courses	28
DM_5	Engineering	Bachelor's degree	Sustainability committee member	20

4.3. Definition of criteria

In this research, ten key performance indicators, designed by Refinitiv Eikon to assess the relative environmental, social and governance performance of financial and non-financial firms, are employed as assessment criteria for the comparison of bank sustainable business performance.

Each of Refinitiv Eikon's ESG sub-criteria is based on a standardized scoring methodology that converts a firm's raw disclosure data into a scale ranging from 0 to 100, where higher scores demonstrate better performance. The scores are computed by assessing the disclosure performance of the firm relative to its industry peers employing a percentile ranking technique.

In contradistinction to the ESG systems of MSCI and Sustainalytics, Refinitiv Eikon's ESG framework provides disaggregated scores for individual ESG dimensions and sub-indicators, thus enabling a more detailed multi-criteria assessment. Additionally, Refinitiv's ESG indicators demonstrate a high degree of congruence with widely accepted international standards, including those established by the Sustainability Accounting Standards Board, the Global

Reporting Initiative, and the United Nations Sustainable Development Goals. Besides, Refinitiv Eikon's ESG system comprises a balanced and non-overlapping set of sub-criteria, thereby enabling a detailed assessment of environmental, social, and governance risks and opportunities in the banking industry.

Accord to the Refinitiv Eikon's ESG system, the resource utilization score, emissions score, and environmental innovations score represent three sub-criteria that reflect the environmental performance of firms. The workforce score, human rights score, community investment score, and product responsibility score comprise the four sub-criteria that define social performance. The management structure and compensation score, shareholder rights score and CSR strategy score constitute the three sub-criteria that indicate governance performance.

The resource utilization score (C_1): It measures a company's potential to produce more environmentally friendly solutions by minimising the utilisation of energy, water and other materials in its operational and production phases, based on improvements in supply chain management.

The emissions score (C_2): This indicator evaluates a firm's commitment to reducing its environmental footprint by adopting an environmentally-friendly business model in its operations.

The environmental innovations score (C_3): It measures a company's dedication to developing innovative and eco-sensitive technologies and eco-designed products aimed at mitigating environmental costs.

The workforce score (C_4): This criterion assesses a company's commitment to its employees in relation to occupational safety and health, employee development, workforce diversity and job satisfaction.

The human rights score (C_5): This indicator focuses on the bank's adherence to fundamental human rights principles, often in alignment with international treaties.

The community investment score (C_6): It captures tangible investments in communities, including health, education, and ethical labour practices.

The product responsibility score (C_7): This criterion assesses an organisation's capacity to produce high quality goods and services, taking into account not only the customers' health and safety but also data integrity and confidentiality.

The management structure and compensation score (C_8): It gauges a firm's level of effectiveness and commitment in applying best practice corporate governance principles.

The shareholder rights score (C_9): This indicator assesses a company's capacity to treat all shareholders in a fair and impartial manner, while simultaneously evaluating its ability to implement effective anti-takeover measures.

The CSR strategy score (C_{10}): This criterion reflects a firm's procedures for communicating that it incorporates financial, environmental, and social dimensions into its day-to-day decisions.

It should be noted that all ESG indicators in the present study are considered beneficial as they contribute positively to sustainability performance assessment in the recommended decision-making framework. This classification ensures that higher values of ESG indicators reflect better performance, in line with sustainability goals and best practices in environmental, social and governance assessments.

4.4. Definition of decision alternatives

The banking industry plays an indispensable role in ensuring the stability and sustainable growth of the Turkish economy, acting as a pivotal driver of economic activity. As of December 2023, there were 34 banks operating in the Turkish commercial banking sector. In 2023, seven commercial banks that released sustainability reports in terms of environmental, social and governance indicators were included in the set of alternatives and analyzed. These banks, whose shares are also listed on the Borsa İstanbul (BIST) Sustainability Index, collectively account for approximately 54.21% of the total market share in the Turkish banking industry, reflecting a concentration among larger and systemically important institutions. While this selection criterion (BIST listing status and sustainability reporting) ensures data reliability and comparability, it may also introduce a degree of sample bias by underrepresenting smaller banks, which may exhibit different sustainability performance patterns due to their limited resources, different risk profiles, or varying levels of regulatory exposure. In addition, it is well known that smaller banks often encounter challenges in integrating ESG principles, including limited financial capacity for sustainability-related investments, lower regulatory pressure, and less access to ESG expertise. These constraints can negatively influence performance metrics and transparency in ESG reporting.

The following Section provides a detailed overview of the banking institutions that were considered as decision alternatives within the considered decision-making problem.

Akbank Co. (A_1): Akbank commenced its financial intermediation activities in 1948 as a privately owned commercial bank. As of December 2023, it held a market share of 8.88% in the Turkish banking industry, ranking as the sixth-largest bank in Turkey according to total assets. It provides comprehensive financial services to a broad customer base, including retail banking, commercial banking, corporate and investment banking, SME banking, private banking, investment services treasury operations, and payment systems. In addition to banking services, ıt also serves as the insurance agency of two major insurers in the Turkish insurance industry via its own branches.

Garanti BBVA Co. (A_2): Garanti BBVA, which commenced its banking activities in 1946, is a foreign-owned commercial bank. As of December 2023, it is the fifth-largest bank in the banking industry with a market share of 9.58%. It offers a wide range of financial solutions to a diverse customer base in line with its financial sustainability approach that takes into account the economic, social and environmental impacts of its financial intermediation activities.

Halkbank Co. (A_3): Established in 1938 to support tradespeople and craftsmen, Halkbank is a state-owned deposit bank with a market share of 10.90% in terms of total assets as of the end of 2023. Thanks to the responsible banking approach, Halkbank provides support for a number of economic actors, in particular tradesmen, craftspeople, small and medium-sized enterprises (SMEs), women and young entrepreneurs, through its loan facilities. In addition, the bank provides backing for pioneering projects that encourage economic development.

İşbank Co. (A_4): Founded in 1923, İşbank is Turkey's largest private bank and also the third largest bank. As of the end of 2023, its market share in terms of total assets was 12.18%. It is a prominent financial institution within the banking industry, offering a comprehensive range of products and services across multiple areas, including SME, commercial, corporate, retail, and private banking.

Şekerbank Co. (A_5): Şekerbank, established in 1953 to support the agricultural sector, local development and sustainable production, is one of the privately owned banks, and it is among the first banks in Türkiye to take into account environmental and social impacts in its lending activities. It engages in a range of banking activities, including those related to agricultural finance.

Vakıfbank Co. (A_6): Vakıfbank, which focuses on creating value for its stakeholders in line with the goals of sustainable society, sustainable environment, and sustainable economy, was established in 1954 and is the second largest bank in Turkey as of 2023. Vakıfbank, a commercial bank having state-owned capital, contributes to the sustainable development of the national economy by financing export, investment and production activities with its innovative products and services.

Yapı Kredi Co. (A_7): Established in 1944, Yapı Kredi is a private commercial bank that currently occupies the seventh position in terms of market share among banking institutions in Turkey. It operates in several business lines such as SME banking, commercial banking, retail banking and corporate banking. Additionally, Yapı Kredi strives to facilitate the adoption of a socially and environmentally responsible banking approach by integrating leading sustainability strategies and policies into its operational procedures.

4.5. Stage 2: determination of importance weights of ESG criteria

4.5.1. The applications of G-MSD and G-SPC for computing the criteria weights

In the current work, a novel grey-based MCGDM framework incorporating Bonferroni aggregation and interval grey numbers is formulated and implemented to assess ESG sustainable performance under uncertainty. G-MSD and G-SPC algorithms were used to determine the importance weights of the criteria in the introduced framework. The criteria weights obtained through the application of G-MSD and G-SPC algorithms are subsequently integrated based on a linear weighting strategy, ensuring methodological consistency and robustness in ESG sustainability assessments.

4.5.2. Implementation of the G-MSD model

In the initial phase, each DM evaluated each decision alternative based on a set of predetermined criteria. This evaluation was conducted according to a linguistic scale presented in Table 1. The linguistic assessments of each DM, reflecting their preferences for the decision alternatives and the corresponding individual grey performance matrices, are presented in Appendix, respectively. Subsequently, Eq. (7) was employed to aggregate the DMs' opinions and derive a main grey performance matrix (in our case, the values $p = q = 1$ were adopted for the initial solution).

At this stage of the analysis, to ensure consistency and mitigate subjective bias in expert evaluations, this study assumes equal importance levels for all decision-makers (DMs), given that each expert has at least 20 years of experience in banking and ESG-related fields. This assumption prevents disproportionate weighting and ensures that expert evaluations are aggregated without bias, thereby maintaining methodological consistency. The analysis is based on the assumption that by assigning an equal weight of 1/5 to each DM, expert influence in the MCGDM process can be distributed equitably unless specific expertise differentiation is explicitly justified. Table 3 presents the GN-based performance matrix obtained by aggregating the ratings of the five DMs for the analyzed banks. Since the 10 ESG drivers in the decision-making problem are benefit-oriented, the normalization process was executed only with the aid of Eq. (9). The resulting normalized performance matrix is given in Table 4.

Table 3. Grey performance matrix

	A_1	A_2	A_3	A_4	A_5	A_6	A_7
C_1	[40.39, 49.50]	[44.82, 53.85]	[25.75, 35.07]	[42.84, 51.87]	[34.63, 43.70]	[18.36, 27.57]	[44.71, 53.76]
C_2	[40.14, 49.30]	[44.60, 53.67]	[17.23, 26.83]	[44.60, 53.67]	[40.63, 49.70]	[27.87, 37.15]	[38.82, 47.85]
C_3	[42.25, 51.38]	[44.71, 53.76]	[17.23, 26.83]	[48.75, 57.79]	[46.51, 55.59]	[26.13, 35.36]	[50.61, 59.67]
C_4	[52.87, 61.89]	[44.60, 53.67]	[22.47, 31.62]	[52.87, 61.89]	[40.01, 49.19]	[40.76, 49.80]	[44.93, 53.94]
C_5	[35.68, 44.94]	[46.94, 55.95]	[24.88, 33.91]	[48.86, 57.88]	[44.49, 53.57]	[28.58, 37.68]	[50.80, 59.83]
C_6	[39.64, 48.89]	[52.87, 61.89]	[36.37, 45.50]	[50.90, 59.92]	[22.69, 31.78]	[30.18, 39.37]	[44.82, 53.85]
C_7	[48.65, 57.71]	[54.95, 63.95]	[36.37, 45.50]	[54.85, 63.87]	[31.86, 41.11]	[30.51, 39.62]	[46.72, 55.77]
C_8	[32.48, 41.59]	[52.87, 61.89]	[26.13, 35.36]	[44.93, 53.94]	[29.85, 39.12]	[44.82, 53.85]	[40.88, 49.90]
C_9	[36.24, 45.39]	[50.90, 59.92]	[28.23, 37.42]	[52.77, 61.81]	[40.63, 49.70]	[38.56, 47.64]	[44.82, 53.85]
C_{10}	[42.60, 51.67]	[52.87, 61.89]	[38.56, 47.64]	[50.90, 59.92]	[36.10, 45.28]	[42.37, 51.48]	[50.80, 59.83]

Table 4. Normalized grey performance matrix

	A_1	A_2	A_3	A_4	A_5	A_6	A_7
C_1	[0.750, 0.919]	[0.832, 1.000]	[0.478, 0.651]	[0.795, 0.963]	[0.643, 0.812]	[0.341, 0.512]	[0.830, 0.998]
C_2	[0.748, 0.919]	[0.831, 1.000]	[0.321, 0.500]	[0.831, 1.000]	[0.757, 0.926]	[0.519, 0.692]	[0.723, 0.892]
C_3	[0.708, 0.861]	[0.749, 0.901]	[0.289, 0.450]	[0.817, 0.969]	[0.779, 0.932]	[0.438, 0.593]	[0.848, 1.000]
C_4	[0.854, 1.000]	[0.721, 0.867]	[0.363, 0.511]	[0.854, 1.000]	[0.647, 0.795]	[0.659, 0.805]	[0.726, 0.872]
C_5	[0.596, 0.751]	[0.784, 0.935]	[0.416, 0.567]	[0.817, 0.967]	[0.744, 0.895]	[0.478, 0.630]	[0.849, 1.000]
C_6	[0.640, 0.790]	[0.854, 1.000]	[0.588, 0.735]	[0.822, 0.968]	[0.367, 0.514]	[0.488, 0.636]	[0.724, 0.870]
C_7	[0.761, 0.902]	[0.859, 1.000]	[0.569, 0.711]	[0.858, 0.999]	[0.498, 0.643]	[0.477, 0.620]	[0.731, 0.872]
C_8	[0.525, 0.672]	[0.854, 1.000]	[0.422, 0.571]	[0.726, 0.872]	[0.482, 0.632]	[0.724, 0.870]	[0.661, 0.806]
C_9	[0.586, 0.734]	[0.824, 0.969]	[0.457, 0.605]	[0.854, 1.000]	[0.657, 0.804]	[0.624, 0.771]	[0.725, 0.871]
C_{10}	[0.688, 0.835]	[0.854, 1.000]	[0.623, 0.770]	[0.822, 0.968]	[0.583, 0.732]	[0.685, 0.832]	[0.821, 0.967]

Following normalization procedure, sum of the columns and standard deviations were computed. The modified value of the standard deviation of each criterion and the grey weights were found by applying Eqs. (11)–(12), respectively. The results of the G-MSD algorithm are given in Table 5.

Table 5. The results of G-MSD method

	$\sum_{j=1}^{n} \otimes y_j$	$\otimes\sigma_j$	$\otimes s_j$	$\otimes w_{j,msd}$
C_1	[4.670, 5.855]	[0.190, 0.191]	[0.032, 0.041]	[0.112, 0.115]
C_2	[4.731, 5.929]	[0.185, 0.188]	[0.031, 0.040]	[0.108, 0.111]
C_3	[4.629, 5.705]	[0.210, 0.213]	[0.037, 0.046]	[0.127, 0.129]
C_4	[4.823, 5.849]	[0.166, 0.166]	[0.028, 0.034]	[0.096, 0.098]
C_5	[4.683, 5.745]	[0.172, 0.173]	[0.030, 0.037]	[0.103, 0.104]
C_6	[4.484, 5.513]	[0.176, 0.177]	[0.032, 0.039]	[0.110, 0.111]
C_7	[4.752, 5.747]	[0.162, 0.163]	[0.028, 0.034]	[0.096, 0.098]
C_8	[4.395, 5.424]	[0.154, 0.156]	[0.028, 0.035]	[0.099, 0.099]
C_9	[4.727, 5.755]	[0.137, 0.138]	[0.024, 0.029]	[0.082, 0.083]
C_{10}	[5.077, 6.103]	[0.106, 0.107]	[0.017, 0.021]	[0.059, 0.060]

4.5.3. Implementation of the G-SPC model

The initial performance matrix that is required for the computation of the G-SPC weights is illustrated in Table 3. The next step is to obtain the symmetry point for each criterion from Eq. (13) as given in Table 6. In the next step, the absolute distance matrix as seen Table 7 is produced from Eq. (14).

Table 6. The symmetric point of each indicator

	Min.	Max.	Symmetry point
C_1	[18.36, 27.57]	[44.82, 53.85]	[31.59, 40.71]
C_2	[17.23, 26.83]	[44.60, 53.67]	[30.92, 40.25]
C_3	[17.23, 26.83]	[50.61, 59.67]	[33.92, 43.25]
C_4	[22.47, 31.62]	[52.87, 61.89]	[37.67, 46.75]
C_5	[24.88, 33.91]	[50.80, 59.83]	[37.84, 46.87]
C_6	[22.69, 31.78]	[52.87, 61.89]	[37.78, 46.83]
C_7	[30.51, 39.62]	[54.95, 63.95]	[42.73, 51.79]
C_8	[26.13, 35.36]	[52.87, 61.89]	[39.50, 48.62]
C_9	[28.23, 37.42]	[52.77, 61.81]	[40.50, 49.61]
C_{10}	[36.10, 45.28]	[52.87, 61.89]	[44.48, 53.58]

Table 7. Resulting matrix of absolute distances

	A_1	A_2	A_3	A_4	A_5	A_6	A_7
C_1	[8.79, 8.80]	[13.14, 13.23]	[5.64, 5.84]	[11.16, 11.25]	[2.99, 3.04]	[13.14, 13.23]	[13.05, 13.12]
C_2	[9.05, 9.22]	[13.42, 13.68]	[13.42, 13.68]	[13.42, 13.68]	[9.45, 9.72]	[3.04, 3.10]	[7.60, 7.90]
C_3	[8.13, 8.33]	[10.51, 10.79]	[16.42, 16.69]	[14.54, 14.83]	[12.34, 12.59]	[7.79, 7.89]	[16.42, 16.69]
C_4	[15.13, 15.20]	[6.91, 6.93]	[15.13, 15.20]	[15.13, 15.20]	[2.34, 2.44]	[3.04, 3.09]	[7.19, 7.26]
C_5	[1.93, 2.16]	[9.07, 9.09]	[12.96, 12.96]	[11.01, 11.02]	[6.64, 6.70]	[9.19, 9.26]	[12.96, 12.96]
C_6	[1.86, 2.05]	[15.05, 15.09]	[1.34, 1.41]	[13.08, 13.12]	[15.05, 15.09]	[7.46, 7.60]	[7.02, 7.04]
C_7	[5.92, 5.92]	[12.16, 12.22]	[6.29, 6.36]	[12.09, 12.13]	[10.68, 10.87]	[12.16, 12.22]	[3.98, 3.99]
C_8	[7.02, 7.03]	[13.27, 13.27]	[13.27, 13.27]	[5.32, 5.43]	[9.51, 9.65]	[5.23, 5.32]	[1.28, 1.38]
C_9	[4.22, 4.27]	[10.31, 10.40]	[12.19, 12.27]	[12.19, 12.27]	[0.09, 0.13]	[1.94, 1.97]	[4.24, 4.32]
C_{10}	[1.88, 1.91]	[8.31, 8.39]	[5.92, 5.94]	[6.33, 6.42]	[8.31, 8.39]	[2.10, 2.11]	[6.25, 6.32]

Next, the matrix of the moduli of the symmetry shown in Table 3 is obtained by applying Eq. (15). In the last step, as seen at the bottom of Table 8, the modulus of the symmetry of criterion ($\otimes c_j$) and the G-SPC weights are estimated via Eqs. (16)–(17).

Table 8. Matrix of moduli and criteria weights

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	$\otimes c_j$	$\otimes w_{j,spc}$
C_1	[0.198, 0.240]	[0.182, 0.216]	[0.279, 0.377]	[0.189, 0.226]	[0.224, 0.280]	[0.335, 0.528]	[0.182, 0.217]	[0.230, 0.298]	[0.121, 0.124]
C_2	[0.206, 0.247]	[0.189, 0.222]	[0.378, 0.575]	[0.189, 0.222]	[0.204, 0.244]	[0.273, 0.356]	[0.212, 0.255]	[0.236, 0.303]	[0.124, 0.127]
C_3	[0.244, 0.291]	[0.233, 0.275]	[0.467, 0.714]	[0.217, 0.252]	[0.226, 0.265]	[0.355, 0.471]	[0.210, 0.243]	[0.279, 0.359]	[0.146, 0.150]
C_4	[0.151, 0.176]	[0.174, 0.208]	[0.295, 0.413]	[0.151, 0.176]	[0.189, 0.232]	[0.187, 0.228]	[0.173, 0.207]	[0.188, 0.234]	[0.098, 0.099]
C_5	[0.204, 0.255]	[0.164, 0.194]	[0.270, 0.366]	[0.158, 0.186]	[0.171, 0.205]	[0.243, 0.319]	[0.153, 0.179]	[0.195, 0.244]	[0.102, 0.102]
C_6	[0.179, 0.219]	[0.142, 0.164]	[0.193, 0.239]	[0.146, 0.171]	[0.276, 0.383]	[0.223, 0.288]	[0.163, 0.194]	[0.188, 0.238]	[0.099, 0.099]
C_7	[0.158, 0.186]	[0.142, 0.165]	[0.200, 0.249]	[0.142, 0.165]	[0.221, 0.284]	[0.230, 0.296]	[0.163, 0.193]	[0.180, 0.220]	[0.092, 0.094]
C_8	[0.191, 0.241]	[0.128, 0.148]	[0.224, 0.300]	[0.147, 0.175]	[0.203, 0.263]	[0.147, 0.175]	[0.159, 0.192]	[0.171, 0.213]	[0.089, 0.090]
C_9	[0.144, 0.178]	[0.109, 0.127]	[0.174, 0.229]	[0.105, 0.122]	[0.131, 0.159]	[0.137, 0.167]	[0.121, 0.144]	[0.131, 0.161]	[0.067, 0.069]
C_{10}	[0.109, 0.131]	[0.091, 0.106]	[0.118, 0.145]	[0.094, 0.110]	[0.125, 0.155]	[0.110, 0.132]	[0.094, 0.110]	[0.106, 0.127]	[0.053, 0.056]

4.5.4. Computing the final weights based on integrated linear weighting procedure

The last step of the weight estimation procedure requires the integration of the resulting weight values from the G-MSD and G-SPC methods as expressed in Eq. (18). The combined grey weight values ($\otimes w_{j,int}$) are presented in Table 9. Finally, the grey weight values are then translated into crisp coefficients by Eq. (6). A thorough examination of the findings presented in Table 9 reveals that the three most significant determinants of banks' ESG sustainable performance are environmental innovation (C_3), resource utilization (C_1), and emissions (C_2), respectively.

Table 9. The combined weight values

	Combined grey weights	Crisp weights	Rank
C_1	[0.117, 0.119]	0.118	**2**
C_2	[0.116, 0.119]	0.117	**3**
C_3	[0.137, 0.139]	0.138	**1**
C_4	[0.097, 0.099]	0.098	6
C_5	[0.103, 0.103]	0.103	5
C_6	[0.104, 0.105]	0.105	4
C_7	[0.094, 0.096]	0.095	7
C_8	[0.094, 0.095]	0.094	8
C_9	[0.075, 0.076]	0.075	9
C_{10}	[0.056, 0.058]	0.057	10

4.6. Stage 3: ranking of bank alternatives

4.6.1. Implementation of the G-SRP for ranking bank alternatives

Following the determination of the grey integrated weight values of the criteria, the decision alternatives are ranked in accordance with the G-SRP algorithm using the initial grey performance matrix in Table 3. The ranking matrix is formed via Eq. (19) and displayed in Table 10. Employing Eq. (20), weighted ranking matrix are obtained and presented in Table 11. At last, the total grey ranking score, grey priority score, and crisp performance score of each bank are computed according to the Eqs. (21)–(23), respectively. Table 12 presents the grey-based hybrid model's results where the performances of bank alternatives A_i are ranked as: A_4 > A_2 > A_7 > A_1 > A_5 > A_6 > A_3.

Table 10. Ranking matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
A_1	[4, 4]	[3, 3]	[5, 5]	[1, 1]	[5, 5]	[4, 4]	[3, 3]	[5, 5]	[6, 6]	[4, 4]
A_2	[1, 1]	[1, 1]	[4, 4]	[3, 3]	[3, 3]	[1, 1]	[1, 1]	[1, 1]	[2, 2]	[1, 1]
A_3	[6, 6]	[6, 6]	[7, 7]	[6, 6]	[7, 7]	[5, 5]	[5, 5]	[7, 7]	[7, 7]	[6, 6]
A_4	[3, 3]	[1, 1]	[2, 2]	[1, 1]	[2, 2]	[2, 2]	[2, 2]	[2, 2]	[1, 1]	[2, 2]
A_5	[5, 5]	[2, 2]	[3, 3]	[5, 5]	[4, 4]	[7, 7]	[6, 6]	[6, 6]	[4, 4]	[7, 7]
A_6	[7, 7]	[5, 5]	[6, 6]	[4, 4]	[6, 6]	[6, 6]	[7, 7]	[3, 3]	[5, 5]	[5, 5]
A_7	[2, 2]	[4, 4]	[1, 1]	[2, 2]	[1, 1]	[3, 3]	[4, 4]	[4, 4]	[3, 3]	[3, 3]

Table 11. Weighted ranking matrix

	A_1	A_2	A_3	A_4	A_5	A_6	A_7
C_1	[0.466, 0.478]	[0.117, 0.119]	[0.699, 0.717]	[0.350, 0.358]	[0.583, 0.597]	[0.816, 0.836]	[0.233, 0.239]
C_2	[0.348, 0.357]	[0.116, 0.119]	[0.695, 0.713]	[0.116, 0.119]	[0.232, 0.228]	[0.579, 0.595]	[0.464, 0.476]
C_3	[0.685, 0.696]	[0.548, 0.557]	[0.959, 0.975]	[0.274, 0.278]	[0.411, 0.418]	[0.822, 0.835]	[0.137, 0.139]
C_4	[0.097, 0.099]	[0.291, 0.296]	[0.582, 0.591]	[0.097, 0.099]	[0.485, 0.493]	[0.388, 0.394]	[0.194, 0.197]
C_5	[0.512, 0.516]	[0.307, 0.309]	[0.717, 0.722]	[0.205, 0.206]	[0.410, 0.412]	[0.615, 0.619]	[0.102, 0.103]
C_6	[0.418, 0.419]	[0.104, 0.105]	[0.522, 0.524]	[0.209, 0.210]	[0.731, 0.734]	[0.627, 0.629]	[0.313, 0.315]
C_7	[0.281, 0.288]	[0.094, 0.096]	[0.469, 0.480]	[0.188, 0.192]	[0.563, 0.576]	[0.656, 0.672]	[0.375, 0.384]
C_8	[0.469, 0.473]	[0.094, 0.095]	[0.657, 0.662]	[0.188, 0.189]	[0.563, 0.567]	[0.281, 0.284]	[0.375, 0.378]
C_9	[0.447, 0.456]	[0.149, 0.152]	[0.522, 0.532]	[0.075, 0.076]	[0.298, 0.304]	[0.373, 0.380]	[0.224, 0.228]
C_{10}	[0.224, 0.232]	[0.056, 0.058]	[0.336, 0.348]	[0.112, 0.116]	[0.392, 0.406]	[0.280, 0.290]	[0.168, 0.174]

Table 12. Ranking of the alternatives

	$\otimes t_i$	$\otimes p_i$	Q_i	Rank
A_1	[3.947, 4.013]	[2.987, 3.053]	3.020	4
A_2	[1.876, 1.906]	[5.094, 5.124]	5.109	**2**
A_3	[6.158, 6.264]	[0.736, 0.842]	0.789	7
A_4	[1.812, 1.843]	[5.157, 5.188]	5.172	**1**
A_5	[4.667, 4.745]	[2.255, 2.333]	2.294	5
A_6	[5.437, 5.534]	[1.466, 1.563]	1.515	6
A_7	[2.585, 2.633]	[4.367, 4.415]	4.391	**3**

4.7. Stage 4: robustness checks

4.7.1. Validation and sensitivity analysis

For any decision-making problem, the ranking outputs obtained through MCGDM techniques are expected to be reliable, stable, reasonable, and objective. Nevertheless, it is possible that discrepancies may arise between the initial ranking results of the decision alternatives in certain instances. These discrepancies may be attributed to alterations in the criterion weights, the employed normalization procedures, the selection of assessment criteria, the used MCGDM tools having limitations and structural problems, the presence of subjectivity arising from the structuring of the decision-making problem, rank reversal phenomenon, etc. Hence, it is necessary to empirically test the effectiveness and robustness of the developed grey-based decision-making framework. This section is comprised of three sub-sections. The first part delves into the influence of the parameter designated as 'ξ' within Eq. (12). Subsection two focuses on debating the ramifications of the rank reversal issue. The last part deals with the comparative analysis of the rankings derived from alternative grey MCGDM frameworks with that of the developed model.

4.7.2. Examining the impact of varying values of ξ on the initial ranks

The sensitivity analysis conducted in this section investigates the effect of varying values of the ξ parameter on the prioritization of bank alternatives within the grey-based decision support framework. In Eq. (18), ξ is a stabilizing parameter taking values from the interval 0 ≤ ξ ≤1. This interval is split into 20 equal sequences corresponding to 20 scenarios. In the first scenario (S1), the threshold value ξ = 0 was taken, while it was increased by 0.05 in each subsequent scenario to analyze the sensitivity. In conclusion, the ranking scores for each commercial bank were recomputed across all scenarios, and the obtained outcomes are illustrated in Figure 2. The findings from Figure 2 indicates that the variation in the ξ parameter in the interval [0,1] has no impact on the priority rankings of the alternative banks.

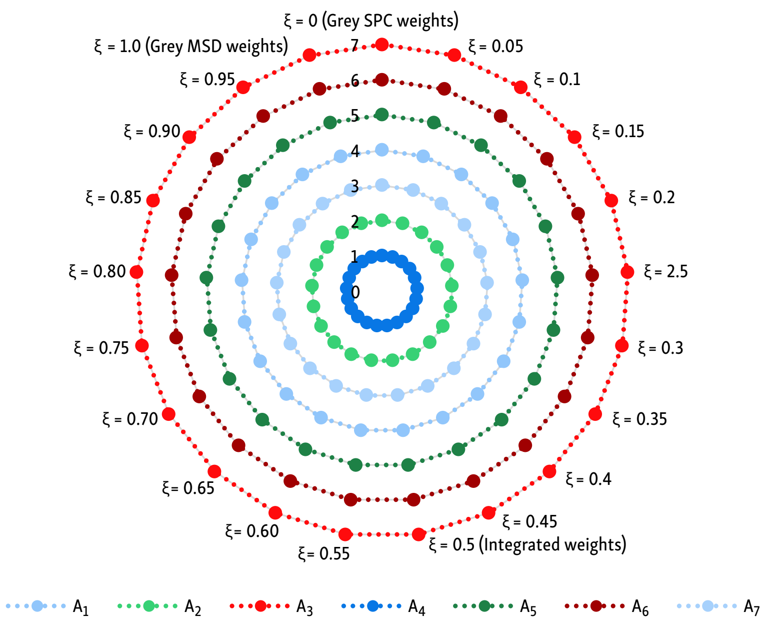

Figure 2. The influence of various values of the parameter ξ on the prioritisation order of alternatives

4.7.3. Rank reversal check

In recent times, MCGDM algorithms have been employed extensively in performance assessment studies within the financial field. However, in a considerable number of these studies, the rank reversal issue is not incorporated into the processes of validation. Rank reversal represents a typical challenge associated with MCGDM methodologies. It is a common problem associated with variations in the prioritization of alternatives for a predetermined group owing to the addition of a new alternative or the removal of an existing alternative (Belton &

Gear, 1985). In the current work, we conduct the rank reversal test for the introduced grey-based methodology in two experimental cases: deleting each bank once and adding each bank individually. For the first experimental case, we designed seven scenarios to observe the influence of bank elimination on the initial ranking result. In each scenario, alternative banks were deleted once according to their original order in the database and the ranking position of the remaining six banks was recalculated. For example, in the S1, A1 was deleted and the performance score of the remaining banks was re-computed. This procedure was repeated for all remaining banks in the other scenarios. The outcomes of the seven scenarios regarding the ranking of banks are illustrated in Table 13 and Figure 3. When Figure 3 is investigated, it can be concluded that the line of any bank does not intersect the line of any other bank, which reveals that the relative ranking of banks does not change.

For the second experimental case, six scenarios were formulated to analyses the impact of adding a bank on the initial ranking output. In each scenario, a bank was introduced to the existing dataset and the ranking scores of the alternatives were re-estimated for each scenario. In S1, the ranking performance of A1 and A2 were compared considering their original positions in the dataset. In each subsequent scenario, the dataset is expanded again by adding a bank for each scenario and the performance scores of the banks in each scenario were recalculated.

Table 13. Order of banks after deleting a bank

	S_1	S_2	S_3	S_4	S_5	S_6	S_7
A_1		3	4	3	4	4	3
A_2	2		2	1	2	2	2
A_3	6	6		6	6	6	6
A_4	1	1	1		1	1	1
A_5	4	4	5	4		5	4
A_6	5	5	6	5	5		5
A_7	3	2	3	2	3	3	

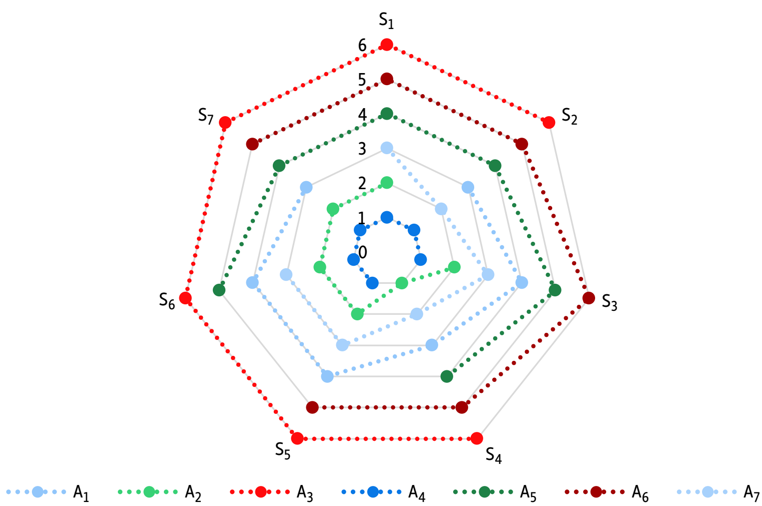

Figure 3. Order of banks after deleting a bank

Table 14 and Figure 4 indicate the results of the six scenarios concerning the prioritization order of banks. Considering Figure 4, it can be seen that the line of any bank does not intersect with that of any other bank. This finding implies that the relative ranking position of banks remains unchanged.

Given the two empirical cases, it is deduced that the solution suggested by the developed grey-based methodology is not subject to the rank reversal problem.

Table 14. Order of the banks after adding the banks one by one

	S_1	S_2	S_3	S_4	S_5	S_6
A_1	2	2	3	3	3	4
A_2	1	1	2	2	2	2
A_3		3	4	5	6	7
A_4			1	1	1	1
A_5				4	4	5
A_6					5	6
A_7						3

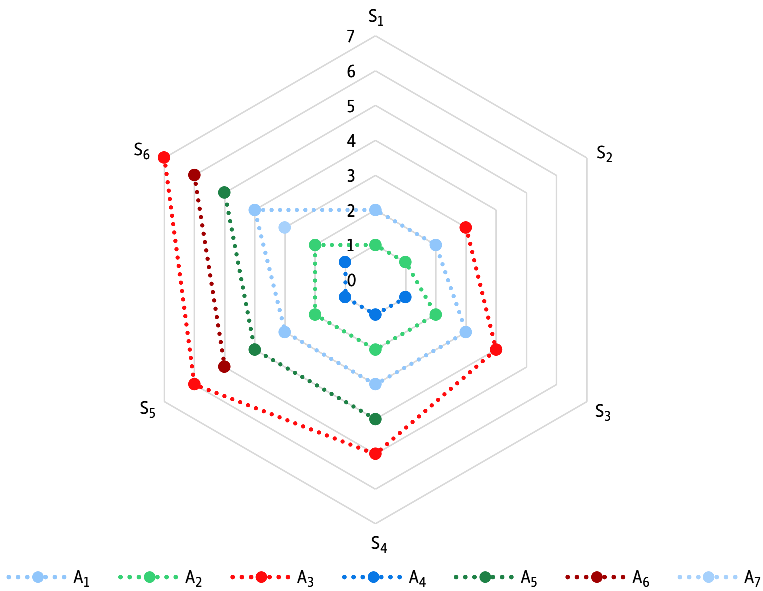

Figure 4. Order of the banks after adding the banks one by one

4.7.4. Comparative analysis

To check the consistency and robustness of newly introduced grey-based model, five grey-based MCGDM approaches, including Grey EDAS (Stanujkic et al., 2017), Grey MAIRCA (Esangbedo & Tang, 2023), Grey MARCOS (Pamucar et al., 2021; Torkayesh et al., 2021), Grey PIV (Reyes-Norambuena et al., 2024; Ulutaş et al., 2021), and Grey SAW (Zolfani et al., 2012) are employed for comparative analysis. The key similarities and differences between the methodologies regarding ranking results, parameter sensitivity, and computational performance are provided in Table 15.

Figure 5 presents a comparative analysis of the ranking order produced by the integrated grey MCGDM model against those generated by other well-established grey MCGDM approaches. As illustrated in Figure 5, the comparative analysis confirms that the priority ranking of the alternatives does not change regardless of the method utilized, which provides substantial evidence for the consistency and trustworthiness of the initial solution.

Table 15. Ranking consistency, sensitivity and computational efficiency of grey-based methods

	Ranking consistency	Sensitivity to ξ variation	Computational efficiency
Proposed Hybrid Grey Model	High	Low	High
Grey EDAS	High	Low	Moderate
Grey MAIRCA	Moderate	Moderate	High
Grey MARCOS	High	Low	Moderate
Grey PIV	Moderate	Moderate	High
Grey SAW	Low	High	High

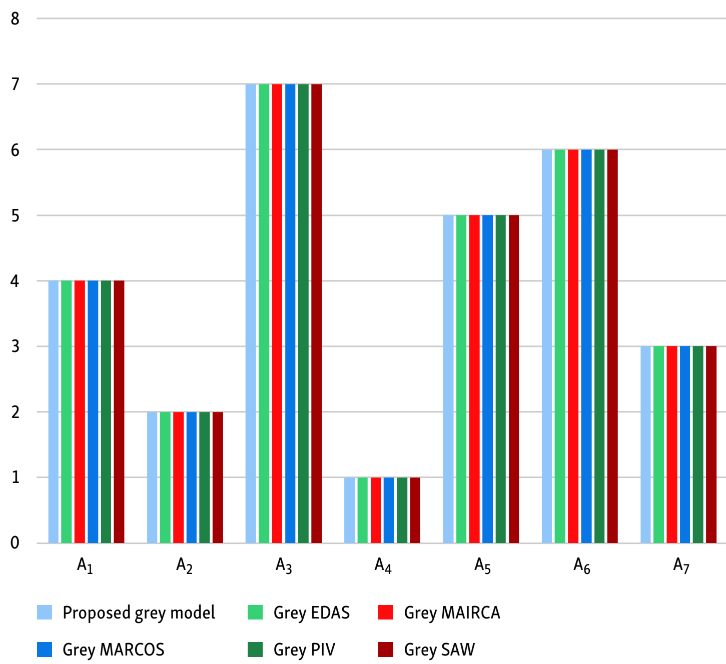

Figure 5. Comparisons of results of the diverse procedures

5. Discussion and managerial insights

Environmental innovation (0.1381) is the most influential driver of bank ESG sustainability performance in the current study, followed by resource use (0.1180), emissions (0.1174), social investment (0.1047), human rights (0.1028), labour (0.0978), product responsibility (0.0949), management structure and remuneration (0.0942), shareholder rights (0.0752) and CSR strategy (0.0570).

As the empirical findings indicate, the most influential dimension among the three ESG dimensions analyzed in the present research is the environmental dimension, followed by the social and governance dimensions, respectively. More specifically, environmental innovation is the most essential driver of the environmental dimension, whereas community investment and product responsibility are the most crucial drivers for the social dimension, and governance dimension respectively.

To translate these findings into actionable strategies, it is recommended that the listed commercial banks consider incorporating environmental innovation, which is identified as a top ESG driver, into both their core operations and their long-term sustainability agendas. One practical approach that could be adopted is the development and promotion of green financial products. Such products may be constituted of, for example, green bonds, sustainability-linked loans, or environmentally focused investment funds. These instruments contribute to climate-related goals and align with global ESG standards, attracting environmentally conscious investors and enhancing the bank's reputational capital.

In light of these findings, banks should concentrate on environmental issues in order to optimize their ESG performance and attain a competitive superiority. On the other hand, the outcomes of this analysis demonstrate that the performance rankings among the seven commercial banks are A4, A2, A7, A1, A5, A6 and A3. Further, sensitivity and comparison controls support the initial ranking outputs derived from the introduced grey decision-making framework in this research, which confirms that the reported results are robust and reliable.

The findings obtained by applying the developed framework in the present research offer valuable managerial implications as follows.

- The model's results provide critical information to the bank's executive management and board of directors to better understand ESG risks that are categorised as non-financial risks, improve the quality of the ESG reporting process and identify the drivers of ESG performance. Additionally, in light of the model's empirical findings, the executive team can respond to multiple stakeholder expectations pertaining to ESG risks in a timely and effective manner.
- Our findings are of vital importance for bank shareholders, as the performance of ESG factors directly influences a financial institution's business model, risk exposure, and long-term financial stability and performance. Hence, banks that demonstrate robust ESG performance are able to generate higher shareholder value over an extended period and attract more investment compared to their competitors.
- Our findings, which are also of particular interest to investors in the banking sector, may help large investors in financial markets such as investment funds, asset managers and pension funds to make more conscious investment decisions by avoiding the risks associated with poor ESG performance.

- The results of banks' ESG sustainable performance analysis are a vital factor affecting the financial decision-making processes of international credit institutions that provide long-term credit opportunities to banks. A strong ESG performance reduces banks' credit risk and increases their creditworthiness, which makes it easier for them to borrow from international credit institutions.
- The proposed MCGDM methodology can be employed by regulatory and supervisory institutions for the purpose of monitoring the ESG practices of banking sector, which plays a pivotal role in economic activities.
- The developed framework can also be adapted by DMs or practitioners involved in the strategic decision-making process of firms in other financial and non-financial sectors to analyse ESG sustainable performance and help monitor ESG reporting more effectively.

6. Conclusions

In response to stakeholder demands and regulatory requirements in the past two decades, financial firms as well as non-financial firms have commenced integrating ESG considerations into their strategic decision-making processes and business models. Banks are one of the most critical and indispensable financial institutions of both money and capital markets in the financial landscape of any national economy. Additionally, the banking sector, which is characterized by a high level of complexity in its operational procedures, is a dynamic and competitive field. Thus, the measurement and assessment of banks' performance in relation to environmental, social, and governance factors can assist banks in improving their risk management capabilities, aligning themselves with the expectations of diverse stakeholder groups, and enhancing their financial performance. Furthermore, such an analysis is vital to bolster the resilience of banks in an uncertain market, to establish an assessment framework that is transparent and accountable, to gain a competitive edge, and to ensure their survival in the context of intense market competition.

The existing paper puts forward an innovative extension of the MSD-SPC-SRP combination with Bonferroni aggregation based on the use of grey interval numbers, with the aim of solving decision problem regarding the ESG sustainable performance of banking institutions.

The usage of interval numbers provides an opportunity for DMs to articulate their views and assessments of a decision alternative as an interval value instead of a crisp value. Additionally, grey interval numbers enable DMs not only to mitigate the discrepancy and incorrectness associated with their subjective judgements, but also to boost their capacity to convey their thoughts of the performance of decision alternatives.

This research, therefore, develops a new mathematical tool by drawing on grey system theory, which is one of the methods employed to deal with uncertainty, subjectivity and ambiguity related to human judgment via the application of linguistic assessments. The proffered methodological frame enables the measurement of banks' ESG sustainable performance by taking into account ten assessment criteria, organized into three dimensions. The developed methodological framework to handle uncertainty assists industry decision-makers and practitioners in identifying critical ESG drivers and making more informed, realistic, and optimal decisions by comparing the outcomes of banks' lending activities, investments and other financial services from a sustainability perspective. To demonstrate the practicality and robustness of the introduced approach, we present a case study based on the ESG sustainable performance of commercial banks in Turkey. We conducted several sensitivity and comparative analysis tests to demonstrate the dependability and robustness of the outcomes of the grey interval-based MSD-SPC-SRP methodology.

While the existing work presents a comprehensive and methodologically robust grey-based hybrid decision support framework, several limitations should be highlighted, particularly with respect to expert judgments and the methodological choice for uncertainty handling.

First, although procedural measures have been taken to reduce subjectivity, such as expert anonymity, use of multiple weighting techniques, and Bonferroni-based aggregation, expert-based evaluations are inherently susceptible to cognitive biases, including anchoring, overconfidence, or consistency pressure. Although no conflicts of interest were reported and experts were drawn from independent institutions, the potential influence of personal interpretation and expertise domain cannot be entirely ruled out.

Second, the current paper adopts grey system theory to model uncertainty through interval grey numbers, which are advantageous in representing incomplete and partially known data without requiring probabilistic assumptions. However, alternative approaches such as fuzzy set theory or intuitionistic fuzzy logic could offer richer representations of ambiguity and vagueness, particularly when linguistic assessments or graded preferences are more prominent.

On the other hand, these limitations also provide valuable opportunities for researchers. Expanding expert involvement to include professionals with banking and ESG expertise from diverse international contexts could enable the construction of a more comprehensive and globally representative sample. By incorporating perspectives from multiple financial markets, researchers can assess variations in ESG performance across different regulatory environments, economic structures, and sustainability policies. This approach would enhance the generalizability of ESG assessment results, providing deeper insights into regional best practices, sectoral differences, and emerging sustainability trends.

Future studies may explore the comparative strengths and trade-offs of grey and fuzzy-based approaches in ESG performance assessments, especially when expert judgments are expressed in qualitative or linguistic terms. Addressing these aspects could enhance the methodological adaptability and generalizability of the proposed framework across different uncertainty environments.

To expand the scope of future research directions, the existing study acknowledges the potential benefits of incorporating dynamic ESG criteria, particularly by leveraging real-time information to enhance decision-making accuracy and responsiveness. Integrating real-time ESG data into the proposed grey model could improve sustainability assessments by capturing rapid shifts in corporate ESG performance, regulatory updates, and emerging market trends. Unlike static evaluations, dynamic criteria would allow banks to continuously adjust ESG rankings, ensuring that assessments remain contextually relevant and reflective of ongoing sustainability commitments.

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APPENDIX

Table A1. Linguistic evaluations of the alternatives by the DMs

	DM$_1$																			
	C$_1$		C$_2$		C$_3$		C$_4$		C$_5$		C$_6$		C$_7$		C$_8$		C$_9$		C$_{10}$	
A$_1$	F	MB	F	MG	MB	G	G	MB	F	G	F	MB	F	MG	MB	G	G	MB	F	G
A$_2$	MG	F	F	MB	G	VG	VG	G	G	G	MG	F	F	MB	G	VG	VG	G	G	G
A$_3$	F	F	MB	MB	F	G	G	MB	B	MB	F	F	MB	MB	F	G	G	MB	B	MB
A$_4$	F	F	F	G	MG	MG	VG	G	MG	MG	F	F	F	G	MG	MG	VG	G	MG	MG
A$_5$	G	MG	G	VG	VG	F	VG	VG	MB	VG	G	MG	G	VG	VG	F	VG	VG	MB	VG
A$_6$	MB	B	F	G	MG	MB	MG	G	G	G	MB	B	F	G	MG	MB	MG	G	G	G
A$_7$	VG	F	VG	G	MG	G	VG	MG	MG	MG	VG	F	VG	G	MG	G	VG	MG	MG	MG
	DM$_2$																			
	C$_1$		C$_2$		C$_3$		C$_4$		C$_5$		C$_6$		C$_7$		C$_8$		C$_9$		C$_{10}$	
A$_1$	MG	G	MG	G	MB	B	MG	MB	B	G	MG	G	MG	G	MB	B	MG	MB	B	G
A$_2$	MG	F	G	G	G	G	VG	G	G	VG	MG	F	G	G	G	G	VG	G	G	VG
A$_3$	VB	VB	VB	B	MB	MB	MB	G	F	G	VB	VB	VB	B	MB	MB	MB	G	F	G
A$_4$	G	F	G	VG	G	G	VG	MG	MG	G	G	F	G	VG	G	G	VG	MG	MG	G
A$_5$	MB	F	MB	F	MB	MB	MB	F	MG	MB	MB	F	MB	F	MB	MB	MB	F	MG	MB
A$_6$	VB	B	VB	MG	B	B	B	G	G	VG	VB	B	VB	MG	B	B	B	G	G	VG
A$_7$	MG	MG	MG	MG	VG	MG	F	F	MG	VG	MG	MG	MG	MG	VG	MG	F	F	MG	VG
	DM$_3$																			
	C$_1$		C$_2$		C$_3$		C$_4$		C$_5$		C$_6$		C$_7$		C$_8$		C$_9$		C$_{10}$	
A$_1$	VG	VG	VG	VG	VG	VG	VG	G	G	G	VG	VG	VG	VG	VG	VG	VG	G	G	G
A$_2$	MG	G	MG	G	MG	MG	G	MG	MG	MG	MG	G	MG	G	MG	MG	G	MG	MG	MG
A$_3$	G	MG	MG	MG	F	G	G	F	G	G	G	MG	MG	MG	F	G	G	F	G	G
A$_4$	G	VG	G	VG	G	G	VG	MG	VG	G	G	VG	G	VG	G	G	VG	MG	VG	G
A$_5$	MG	MG	G	G	MG	MB	MG	MB	MG	MB	MG	MG	G	G	MG	MB	MG	MB	MG	MB
A$_6$	MB	MG	MG	F	F	F	F	F	MB	MB	MB	MG	MG	F	F	F	F	F	MB	MB
A$_7$	G	G	VG	G	MG	G	G	G	VG	VG	G	G	VG	G	MG	G	G	G	VG	VG
	DM$_4$																			
	C$_1$		C$_2$		C$_3$		C$_4$		C$_5$		C$_6$		C$_7$		C$_8$		C$_9$		C$_{10}$	
A$_1$	G	G	VG	VG	VG	VG	VG	MG	MG	MG	G	G	VG	VG	VG	VG	VG	MG	MG	MG
A$_2$	MG	G	MG	G	MG	VG	G	VG	G	G	MG	G	MG	G	MG	VG	G	VG	G	G
A$_3$	F	VB	VB	MB	MB	MB	MB	B	F	F	F	VB	VB	MB	MB	MB	MB	B	F	F
A$_4$	MG	G	G	MG	VG	G	MG	G	VG	VG	MG	G	G	MG	VG	G	MG	G	VG	VG
A$_5$	F	F	G	B	G	B	B	B	G	G	F	F	G	B	G	B	B	B	G	G
A$_6$	F	G	F	F	F	MG	MG	MG	MG	F	F	G	F	F	F	MG	MG	MG	MG	F
A$_7$	MG	MG	VG	MG	G	F	MG	MG	MG	G	MG	MG	VG	MG	G	F	MG	MG	MG	G
	DM$_5$																			
	C$_1$		C$_2$		C$_3$		C$_4$		C$_5$		C$_6$		C$_7$		C$_8$		C$_9$		C$_{10}$	
A$_1$	MB	MB	MB	G	MB	MB	F	F	G	MB	MB	MB	MB	G	MB	MB	F	F	G	MB
A$_2$	VG	VG	VG	G	G	G	G	VG	VG	VG	VG	VG	VG	G	G	G	G	VG	VG	VG
A$_3$	MB	MB	F	MB	MB	MG	MG	MB	MB	MG	MB	MB	F	MB	MB	MG	MG	MB	MB	MG
A$_4$	MG	G	VG	G	MG	VG	G	MG	VG	G	MG	G	VG	G	MG	VG	G	MG	VG	G
A$_5$	F	VG	VG	G	G	F	F	F	G	F	F	VG	VG	G	G	F	F	F	G	F
A$_6$	MB	F	F	G	F	G	F	G	F	G	MB	F	F	G	F	G	F	G	F	G
A$_7$	F	F	F	MG	VG	G	G	MG	MG	MG	F	F	F	MG	VG	G	G	MG	MG	MG

Table A2. Grey performance matrices for each DM

	DM_1																			
	C_1		C_2		C_3		C_4		C_5		C_6		C_7		C_8		C_9		C_{10}	
A_1	31	40	21	30	31	40	41	50	21	30	51	60	51	60	21	30	31	40	51	60
A_2	41	50	31	40	31	40	21	30	51	60	61	70	61	70	51	60	51	60	51	60
A_3	31	40	31	40	21	30	21	30	31	40	51	60	51	60	21	30	11	20	21	30
A_4	31	40	31	40	31	40	51	60	41	50	41	50	61	70	51	60	41	50	41	50
A_5	51	60	41	50	51	60	61	70	61	70	31	40	61	70	61	70	21	30	61	70
A_6	21	30	11	20	31	40	51	60	41	50	21	30	41	50	51	60	51	60	51	60
A_7	61	70	31	40	61	70	51	60	41	50	51	60	61	70	41	50	41	50	41	50
	DM_2																			
	C_1		C_2		C_3		C_4		C_5		C_6		C_7		C_8		C_9		C_{10}	
A_1	41	50	51	60	41	50	51	60	21	30	11	20	41	50	21	30	11	20	51	60
A_2	41	50	31	40	51	60	51	60	51	60	51	60	61	70	51	60	51	60	61	70
A_3	1	10	1	10	1	10	11	20	21	30	21	30	21	30	51	60	31	40	51	60
A_4	51	60	31	40	51	60	61	70	51	60	51	60	61	70	41	50	41	50	51	60
A_5	21	30	31	40	21	30	31	40	21	30	21	30	21	30	31	40	41	50	21	30
A_6	1	10	11	20	1	10	41	50	11	20	11	20	11	20	51	60	51	60	61	70
A_7	41	50	41	50	41	50	41	50	61	70	41	50	31	40	31	40	41	50	61	70
	DM_3																			
	C_1		C_2		C_3		C_4		C_5		C_6		C_7		C_8		C_9		C_{10}	
A_1	61	70	61	70	61	70	61	70	61	70	61	70	61	70	51	60	51	60	51	60
A_2	41	50	51	60	41	50	51	60	41	50	41	50	51	60	41	50	41	50	41	50
A_3	51	60	41	50	41	50	41	50	31	40	51	60	51	60	31	40	51	60	51	60
A_4	51	60	61	70	51	60	61	70	51	60	51	60	61	70	41	50	61	70	51	60
A_5	41	50	41	50	51	60	51	60	41	50	21	30	41	50	21	30	41	50	21	30
A_6	21	30	41	50	41	50	31	40	31	40	31	40	31	40	31	40	21	30	21	30
A_7	51	60	51	60	61	70	51	60	41	50	51	60	51	60	51	60	61	70	61	70
	DM_4																			
	C_1		C_2		C_3		C_4		C_5		C_6		C_7		C_8		C_9		C_{10}	
A_1	51	60	51	60	61	70	61	70	61	70	61	70	61	70	41	50	41	50	41	50
A_2	41	50	51	60	41	50	51	60	41	50	61	70	51	60	61	70	51	60	51	60
A_3	31	40	1	10	1	10	21	30	21	30	21	30	21	30	11	20	31	40	31	40
A_4	41	50	51	60	51	60	41	50	61	70	51	60	41	50	51	60	61	70	61	70
A_5	31	40	31	40	51	60	11	20	51	60	11	20	11	20	11	20	51	60	51	60
A_6	31	40	51	60	31	40	31	40	31	40	41	50	41	50	41	50	41	50	31	40
A_7	41	50	41	50	61	70	41	50	51	60	31	40	41	50	41	50	41	50	51	60
	DM_5																			
	C_1		C_2		C_3		C_4		C_5		C_6		C_7		C_8		C_9		C_{10}	
A_1	21	30	21	30	21	30	51	60	21	30	21	30	31	40	31	40	51	60	21	30
A_2	61	70	61	70	61	70	51	60	51	60	51	60	51	60	61	70	61	70	61	70
A_3	21	30	21	30	31	40	21	30	21	30	41	50	41	50	21	30	21	30	41	50
A_4	41	50	51	60	61	70	51	60	41	50	61	70	51	60	41	50	61	70	51	60
A_5	31	40	61	70	61	70	51	60	51	60	31	40	31	40	31	40	51	60	31	40
A_6	21	30	31	40	31	40	51	60	31	40	51	60	31	40	51	60	31	40	51	60
A_7	31	40	31	40	31	40	41	50	61	70	51	60	51	60	41	50	41	50	41	50