Waste Management 171 (2023) 599–609

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Research Paper

Integrated evaluation of the performance of phosphogypsum recycling technologies in China

Xianhao Meng [a,b], Ning Ding [a], Bin Lu [a], Jianxin Yang [a,b,*]

[a] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

[b] College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Keywords:
Phosphogypsum
Multi-criteria decision analysis
Game theory
Utility theory
Uncertainty analysis

ABSTRACT

The Chinese government is implementing policies, such as the "Guidance on comprehensive utilization of bulk solid waste for the 14th Five-Year Plan period", to stimulate phosphogypsum (PG) reduction and recycling. Thus, the comprehensive evaluation of PG recycling technologies for sustainable development is crucial. This study proposes a novel multi-criteria decision analysis (MCDA) method that considers the criteria of resources, environment, economy, and society and risk attitudes of decision-makers and integrates game theory (GT) and utility theory for criteria weighting and ranking to assess industrial-scale PG recycling technologies in China. The results demonstrate that GT provides more reasonable criteria weights than individual weighting methods. PG-based lightweight plaster is the top performer in the resource and environmental dimensions owing to its exceptional resource and energy efficiency. PG utilized for dry-mix mortar and organic fertilizer production exhibited the best utility performance of 0.74 and 0.73, respectively. Measures, such as subsidies and product publicity, should be implemented to promote these technologies. However, technologies with poor performance, such as PG used for the co-production of sulfuric acid and fertilizer or cement, may require optimization or substitution for the sustainable recycling of PG. The proposed MCDA method is robust and can serve as a reliable decision-making tool for other waste-recycling technologies. However, caution must be exercised when determining risk attitude using the MCDA method as it may vary with the number of technologies and affect the final rankings.

1. Introduction

Phosphogypsum (PG) is a major by-product of the wet process used to produce phosphoric acid, with approximately five tons of PG generated for every ton of phosphoric acid produced (Meskini et al., 2021). Currently, the cumulative stockpile exceeds 500 million tons in China (Zhou et al., 2021), posing potential risks to the environment and human health. One notable concern is that heavy metals, such as Mn, Zn, and Cd, can migrate with the leachate, thereby contaminating nearby surface water. These pollutants enter the food chain and accumulate in critical organs, such as the liver, posing a risk of toxicity to humans (Wang et al., 2023). Given these challenges, the rational disposal of PG has become an urgent issue to mitigate the potential environmental risks associated with PG stockpiles.

Various technologies, such as cement retarders and road material production, have been applied to recycle PG in China (Wu et al., 2022). Each technology differs significantly in technical, economic, environmental, and social aspects. The dominant recycling technology for PG is to use it in construction materials because of the massive consumption of PG and higher technological readiness (Huang et al., 2020). However,

Abbreviations: AHP, Analytical hierarchy process; BWM, Best-worst method; CF, Net cash flow in each year; CI, Consistency index; CR, Consistency ratio; DEMATEL, Decision-making trial and evaluation laboratory; ELECTRE, Elimination and choice translating reality; EO, Expert opinion; EWM, Entropy weight method; GT, Game theory; IC, Total investment cost; LCA, Life cycle assessment; LU, The area of land occupation; MAUT, Multi-attribute utility theory; MCDA, Multi-criteria decision analysis; NJ, Number of jobs; NP, Net profit; PG, Phosphogypsum; PROMETHEE, Preference ranking organization method for enrichment evaluation; RI, Random index; RW, The actual recycled weight of pretreated phosphogypsum; SR, Sale revenue; TOPSIS, Technique for order of preference by similarity to ideal solution; TW, The total weight of phosphogypsum; VIKOR, VIekriterijumsko KOmpromisno Rangiranje; WASPAS, Weighted aggregates sum product assessment; WI, Weight vector.

* Corresponding author: State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China.

E-mail address: yangjx@rcees.ac.cn (J. Yang).

https://doi.org/10.1016/j.wasman.2023.09.029
Received 11 January 2023; Received in revised form 30 August 2023; Accepted 21 September 2023
Available online 10 October 2023
0956-053X/

challenges such as high pretreatment costs and limited value-added products have hindered their further development (Cao et al., 2021; Kulczycka et al., 2016). Polymer composites produced from PG, such as polyethylene/PG (Liu et al., 2022) and polypropylene/PG (Zhang et al., 2022), offer value-added benefits. Nevertheless, these technologies are energy-intensive (Xu et al., 2023), leading to substantial environmental burdens. Thus, the adoption of these technologies requires caution. Furthermore, studies have shown that PG-based soil conditioners exhibit better environmental and economic performances than PG-based construction materials (Tsioka and Voudrias, 2020). However, these technologies face limited promotion because of their low PG consumption and limited product applications. Consequently, the selection of the most suitable PG recycling technologies is a complex task that involves balancing multiple criteria. To make informed decisions, it is crucial to evaluate the performance of these technologies comprehensively. Multi-criteria decision analysis (MCDA) has proven effective in addressing such complex matters as evaluating the comprehensive performance of technologies to support decision-making (Garcia-Garcia, 2022; Vlachokostas et al., 2021). Therefore, this study seeks to explore integrated evaluation of the performance of PG recycling technologies using MCDA methods.

2. Background research

2.1. Multi-criteria decision analysis in solid waste management

Many MCDA methods have been implemented in the field of solid waste management, including the analytical hierarchy process (AHP) (Xi et al., 2022), multi-attribute utility theory (MAUT) (Chadderton et al., 2017), best-worst method (BWM) (Torkayesh et al., 2021), technique for order of preference by similarity to ideal solution (TOPSIS) (Chen et al., 2022), viekriterijumsko kompromisno rangiranje (VIKOR) (Fu et al., 2021), preference ranking organization method for enrichment evaluation (PROMETHEE) (Stankovic et al., 2021), weighted aggregates sum product assessment (WASPAS) (Sharma et al., 2021), elimination and choice translating reality (ELECTRE) (Biluca et al., 2020), and decision-making trial and evaluation laboratory (DEMATEL) (Abdullah et al., 2019; Wu et al., 2016). Researchers have divided these methods into three groups: value-based (or single synthesizing), outranking, and distance-based methods (Coban et al., 2018). AHP and MAUT are two common value-based methods, that rank alternatives based on a single score (Coban et al., 2018). Outranking methods, including PROMETHEE, ELECTRE, BWM, and DEMATEL, rank the alternatives after a binary comparison based on each criterion (Soltani et al., 2015). TOPSIS and VIKOR are distance-based methods because they rank the alternatives by comparing their proximity to the ideal alternative (Mir et al., 2016). These methods use expected values or weights as decision criteria to rank or select technologies. The evaluation results, which are objective and rational, support many decision-making solutions. However, the subjective factors of decision-makers, such as risk preference or attitude, which can also play a key role in the final decision-making (Wood and Khosravanian, 2015), have not been explored in previous MCDA techniques for solid waste management.

2.2. Performance evaluation in PG recycling

Several studies have evaluated the performances of PG recycling technologies. Nevertheless, most only focused on the environmental performance of PG recycling technologies and using life cycle assessment (Gettu et al., 2019; Saadé-Sbeih et al., 2019; Tsioka and Voudrias, 2020; Wu et al., 2020). Currently, only two studies have comprehensively evaluated PG recycling technologies. Mohammed et al. (2018) assessed the performance of PG-based paper and fertilizers in terms of environmental, economic, and social aspects by calculating the scores of sub-indicators for each criterion. Cao et al. (2022) compared the comprehensive performances of four types of PG recycling technologies based on a single score called the synergetic degree index. These studies provide references for evaluation methods of PG recycling technologies. However, decision-making in the case of multiple objectives or multiple sub-objectives (which means a more complex structure) has not been thoroughly explored in these studies. Decision-makers may lack references for making decisions in such situations. Therefore, it is necessary to construct a methodology and perform a case study on the performance evaluation of PG recycling technologies, strictly following MCDA procedures, to support technology screening and optimization.

2.3. The contributions of this study

The gaps that emerged from the literature review are as follows: (1) limited attention to MCDA techniques incorporating the risk attitudes of decision-makers in solid waste management; and (2) the necessity to comprehensively evaluate PG recycling technologies using MCDA methods to support decision-making for stimulating PG reduction in China.

Thus, the contributions of this study are to (1) develop a novel integrated approach considering risk attitude of decision-maker for comprehensively evaluating solid waste recycling technologies and (2) identify and rank the PG recycling technologies applied in China based on the proposed approach, providing targeted suggestions for the sustainable development of the PG recycling industry.

3. Research methodology

3.1. Integrated evaluation approach

This study developed an integrated evaluation approach involving the criteria of resource, environment, economy, and society, based on utility theory and game theory (GT). The utility theory, which incorporates risk attitudes, was used to identify the utility performance of PG recycling technologies and GT was applied to weight the criteria and indicators.

The proposed integrated evaluation approach for the current study includes the following stages, as shown in the flowchart in Fig. 1:

(1) Define the goals. The goals determine the depth of technology evaluation (Dodgson et al., 2009). The goal of the performance evaluation in the current study was to prioritize options by identifying the utility performance of PG recycling technologies.
(2) Determine the technological solutions to be evaluated. Technologies that were already being industrialized and operating for more than one operation cycle in China were considered. Fifteen types of PG recycling technology were selected. Information, such as key features and potential benefits, regarding these technologies is summarized in Table S1.
(3) Develop an indicator system by identifying the criteria and indicators through an exhaustive literature review and expert judgement.
(4) Evaluate the utility performance by integrating GT and utility theory.
(5) Rank the PG recycling technologies based on their utility performance.
(6) Implement an uncertainty analysis to identify the effects of uncertain elements on the ranking results.

3.2. Development of indicator system

The indicator system was developed by integrating the indicators of the PG recycling technologies into four dimensions or criteria: resources, environment, economy, and society. There were 16 indicators, as shown in Table 1.

The detailed procedure for selecting the indicators involves two

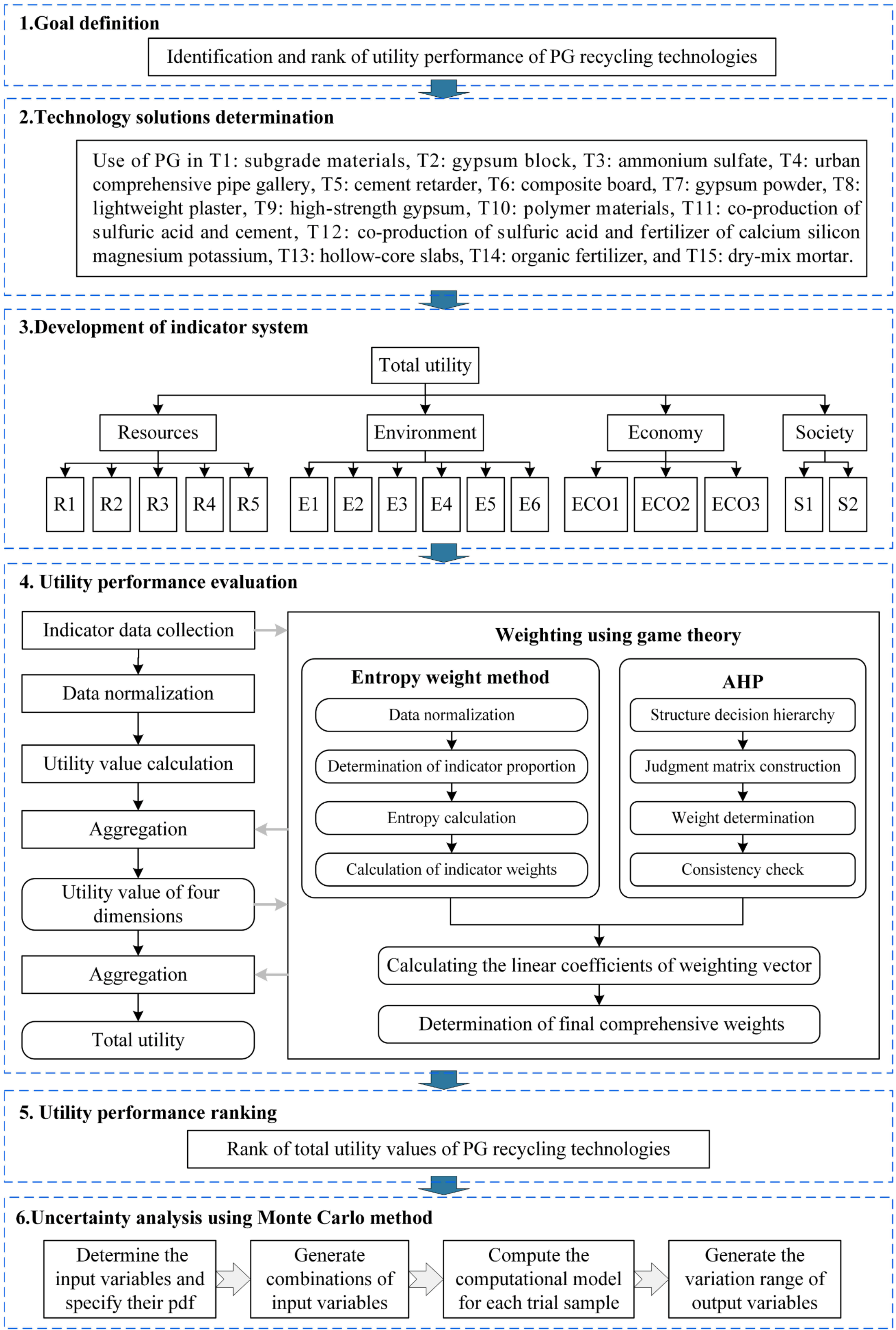


Fig. 1. Flowchart of integrated evaluation.

steps. First, preliminary indicators were identified based on national standards for the comprehensive utilization of industrial solid waste, relevant literatures, and the actual situation of the PG recycling industry. Second, the final set of indicators was determined through consultations with waste management experts to ensure their scientific basis, representativeness, and applicability.

The evaluation of PG recycling technology was based on the functional unit of "the treatment of one ton PG". Therefore, the indicator

Table 1
Summary of indicators used in evaluation system of PG recycling technologies.

Indicators	Connotation	Unit	Calculation[1]	Sources
Resource				
Raw and auxiliary material consumption (R1)	The level of material consumption associated with the technology.	t/t	$\sum_{i=1}^{n} m_i/PG$	(China Standardization Administration, 2013; China Association of Circular Economy, 2022)
Comprehensive energy consumption (R2)	The energy-saving capacity of the technology.	t ce/t	$\sum_{j=1}^{k} e_j/PG$	(China Standardization Administration, 2013; China Association of Circular Economy, 2022)
Fresh water consumption (R3)	The water-saving capability of the technology	m^3/t	W/PG	(China Standardization Administration, 2013; China Association of Circular Economy, 2022)
Land occupation (R4)	The capability of the technology to utilize land resources.	m^2/t	LU/PG	(Mohammed et al., 2018; Zhang et al., 2013)
Resource utilization rate of solid waste (R5)	The ability of technology to efficiently recycle solid waste.	%	RW/TW	EO
Environment[2]				
Global warming potential (E1)	The increasing concentrations of CO_2, CH_4, and other greenhouse gas emissions have the potential to cause climate change.	kg CO_2-eq/t	LCA	EO
Acidification potential (E2)	Acidifying pollutants (SO_2, NOx, HCl, NH_3, HF) have the potential to form H^+ ions which are precursors to acid rain.	kg SO_2-eq/t	LCA	EO
Eutrophication potential (E3)	The potential for over-fertilization of water and soil, resulting in increased growth of aquatic plant (Uek et al., 2015).	kg P-eq/t	LCA	EO
Photochemical ozone creation potential (E4)	The chemicals including NOx, CO, and volatile organic compounds have the potential to form photochemical smog, negatively impacting human health and the environment.	kg NO_x-eq/t	LCA	EO
Terrestrial ecotoxicity potential (E5)	It focuses on the emissions of toxic substances into the air, water, and soil (Uek et al., 2015).	kg 1,4-DCB-eq/t	LCA	EO
Human toxicity potential (E6)	It shows that chemicals may contribute to cancer or other negative human effects for the infinite time horizon (Uek et al., 2015).	kg 1,4-DCB-eq/t	LCA	EO
Economy				
Investment cost (ECO1)	The actual or budgeted expenditure for the application of the technology.	¥ 10^4/t	IC/PG	(China Association of Circular Economy, 2022)
Net profit margin on sales (ECO2)	The ability of technology to generate net profit when applied.	%	NP/SR	(China Standardization Administration, 2015; Huang, 2017)
Net profit value (ECO3)	The feasibility of investing in or adopting technology.	¥ 10^6	$\sum_{t=0}^{n} CF_t/(1+i)^t$	(Kulczycka et al., 2016; Pathak and Wassmann, 2007)
Society				
Employment opportunity (S1)	The jobs created by technology applications.	piece/¥ 10^4	NJ/IC	(Soni et al., 2022)
Exposure risk[3] (S2)	Potential health risks in the work environment for employees.	–	Onsite survey	(China Association of Circular Economy, 2022; Huang, 2017)

[1] *PG*: the total weight of PG processed by specific technology. *m*: the total weight of material consumption. *e*: the total quantity of energy consumption. *W*: the total water consumption. The meaning of abbreviations refers to the abbreviation list.
[2] CML2001 – Jan. 2016 is selected to calculate the environmental burdens, based on the functional unit of the treatment of one ton PG.
[3] The work environment considers the following elements: a. exposure to corrosive/toxic chemicals, b. high temperature, c. high-speed component or splash conditions, d. high voltage, e. high decibel, f. peculiar smell, and g. dusty. Experts rate the work environment on a scale of 1 to 7 based on on-site investigation or enterprise reports.

units were normalized to the functional units.

3.3. Determination of indicator weights using GT

This study employs GT to integrate weighting vectors from AHP and the entropy weight method (EWM) to determine the final weights of the four dimensions and 16 indicators (Table 1).

3.3.1. Calculation of indicator weights using AHP

The AHP method for weighting indicators includes the following steps:

Step 1. The decision hierarchy was structured. The decision hierarchy consists of three main levels: goal level (utility), criteria level (dimensions of resources, environment, economy, and society), and sub-criteria level (all indicators), as shown in Step 2 of Fig. 1.

Step 2. A judgment matrix was constructed. Indicators at the lower level were determined relative to the upper-level indicator through a pairwise comparison using the comparison scaling method (see Table S2). The judgment matrix A can be constructed as follows.

$$A = (a_{ij})_{n\times n} \tag{1}$$

where n is the number of compared indicators.

Step 3. The sum-product algorithm was used to calculate the weighting factors W_i, as shown in Eqs. (2) and (3).

$$\overline{W_i} = \sum\nolimits_{j=1}^{n} (a_{ij}/\sum\nolimits_{i=1}^{n} a_{ij}) \tag{2}$$

$$W_i = \overline{W_i}/\sum\nolimits_{i=1}^{n} \overline{W_i} \tag{3}$$

Step 4. The consistency of the judgment matrix was checked, that is, when a is more important than b and b is more important than c, then a must be more important than c. Eq. (4) was used to calculate the consistency index (CI).

$$CI = (\lambda_{max} - n)/(n-1) \tag{4}$$

where λ_{max} is the maximum eigenvalue of the judgment matrix and n is the indicator number of the criteria or sub-criteria.

The consistency ratio (CR) was calculated using Eq. (5). If $CR < 0.1$, then the consistency of the judgment matrix is acceptable.

$$CR = CI/RI \tag{5}$$

where RI is a random index determined by the indicator number of criteria (see Table S3).

3.3.2. Calculation of indicator weights using EWM

Entropy is a measure of the amount of information contained in the system (Shannon, 1948). The greater the degree of variation of the indicator, the smaller the entropy value and the greater the information quantity, which implies it would play a stronger role in the comprehensive evaluation and will be assigned a greater weight (Ma et al., 2019b; Tang et al., 2022).

The weight calculation processes are as follows.

$$P_{ij} = X_{ij} / \sum_{i=1}^{n} X_{ij} \tag{6}$$

where P_{ij} is the proportion of the value of the i^{th} technology in the j^{th} indicator, X_{ij} is the value of the i^{th} technology in the j^{th} indicator, and n is the number of technologies.

The entropy e_j and weighting factor of the j^{th} indicator (w_j) were calculated using Eqs. (7) and (8).

$$e_j = -(1/\ln n) \times \sum_{i=1}^{n} P_{ij} \ln(P_{ij}) \tag{7}$$

$$w_j = (1 - e_j) / (\sum_{1}^{m} 1 - e_j) \tag{8}$$

where m donates the number of indicators.

3.3.3. Determination of final weights of indicators

The core idea of GT is to seek a balance point between different weight vectors to minimize the deviation between the ideal comprehensive weight and the weight set to retain the information of all weighting vectors as much as possible (Liu et al., 2021; Wang et al., 2019).

The weight vectors obtained from AHP and EWM were integrated based on GT as follows:

Step 1. Assuming that the weight vectors obtained by the AHP and EWM are w_1 and w_2, respectively, the combined weight vector can be constructed through a linear combination as follows:

$$WI = \alpha_1 w_1^T + \alpha_2 w_2^T \tag{9}$$

where α_1 and α_2 are linear coefficients of the weight vector.

Step 2. The deviation of the comprehensive weight from the weight set was minimized to solve for the linear coefficients.

$$min\| \alpha_1 w_1^T + \alpha_2 w_2^T - w_q^T \|_2, q = 1, 2 \tag{10}$$

and the optimal condition for Eq. (10) is as follows.

$$\alpha_1 w_1^T w_q + \alpha_2 w_2^T w_q = w_q^T w_q \tag{11}$$

Linear coefficients α_1 and α_2 can be obtained by solving the linear equations in Eq. (12).

$$\begin{bmatrix} w_1^T w_1 & w_2^T w_1 \\ w_1^T w_2 & w_2^T w_2 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} = \begin{bmatrix} w_1^T w_1 \\ w_2^T w_2 \end{bmatrix} \tag{12}$$

Step 3. The comprehensive final weight vector WI^c was determined by normalizing the linear coefficients using Eqs. (13) and (14).

$$\alpha_q^c = \alpha_q / (\alpha_1 + \alpha_2) \tag{13}$$

$$WI^c = \alpha_1^c w_1 + \alpha_2^c w_2 \tag{14}$$

3.4. Evaluation of the utility performance based on utility theory

Utility theory can assist in risk-based decision making by incorporating the risk attitudes of the decision-makers. This is important because the risk attitudes of decision-makers have great influence when establishing their preferences (da Silva et al., 2022). Utility theory is divided into the following three steps:

3.4.1. Normalization of indicators

To ensure comparability, indicators with inconsistent measurement units must be normalized. A range transformation method was employed for this purpose.

For benefit indicators:

$$\sigma_{ij} = (V_{ij} - V_{ijmin}) / (V_{ijmax} - V_{ijmin}) \tag{15}$$

For cost indicators:

$$\sigma_{ij} = (V_{ijmax} - V_{ij}) / (V_{ijmax} - V_{ijmin}) \tag{16}$$

where V_{ijmax} and V_{ijmin} are the maximum and minimum value of the j^{th} indicator for the i^{th} technology, respectively.

3.4.2. Evaluation of the utility of the individual indicators

The utility function, determined according to the decision maker's risk attitudes, was used to calculated the utility values of the individual indicators. The decision-makers are divided into three categories based on their risk attitudes (ε) (da Silva et al., 2022): (A) risk-seeking decision-makers, who are sensitive to interests but slow to respond to losses; (B) risk-averse decision-makers, who are sensitive to losses but slow to interests; and (C) risk-neutral decision-makers, who have a risk-neutral attitude and directly make a decision according to the indicator value. The corresponding shapes are shown in Fig. S1.

Similar to Heravi's study (Heravi et al., 2017), each dimension of technology is treated as a decision-maker with a risk attitude during the decision-making process. Utility functions are employed to handle diverse preference orders and risk attitudes among decision-makers. This approach allows for the consideration of each criterion and its corresponding indicators as rational decision-makers with risk attitudes.

The following logarithm utility functions are selected to compute the utility values of the individual indicators (Ma et al., 2019a):

$$U_{ij} = 1 - \left| \beta_j + \alpha_j ln\{1 - \sigma_{ij} + (1 - \varepsilon^2)/(1 - 2(1 - \varepsilon))\} \right|, \varepsilon > 0.5 \tag{17}$$

$$U_{ij} = \beta_j + \alpha_j \ln(\sigma_{ij} + \varepsilon^2/(1 - 2\varepsilon)), \varepsilon < 0.5 \tag{18}$$

$$U_{ij} = \sigma_{ij}, \varepsilon = 0.5 \tag{19}$$

where U_{ij} is the utility value of indicators, σ is the normalized values of indicators, and ε is calculated by averaging the normalized values of indicators. Coefficients α and β are calculated using linear regression based on the special utility values and their normalized values.

3.4.3. Calculation of total utility value

The distance-based merging rule (Zwickl, 2019) was employed to calculate the utility value of the criteria level (four dimensions) and the total utility value U_T of solid waste recycling technologies.

$$U_T(i) = 1 - \sqrt{\sum_{j=1}^{m} [WI_{ij}(1 - U_{ij})]^2} / \sqrt{\sum_{j=1}^{m} {WI_{ij}}^2} \tag{20}$$

3.5. Uncertainty analysis

Uncertain elements, such as the lack of data, the selection of sub-indicators, and choice of normalization methods, weighting methods, and aggregation methods, affect the ranking results of the comprehensive evaluation (Dunn, 2020). Therefore, it is essential to analyze these factors to avoid misleading or non-robust policy messages in technology assessment.

The range transformation method was used to normalize the indicators owing to the limitations of the equation coefficient calculation based on specific points in utility theory (see Section 3.3.2). Therefore, weighting and the aggregation methods are the focus of uncertainty analysis. Detailed elements considered in the uncertainty analysis are summarized in Table S4.

The Monte Carlo method was used to perform the uncertainty analysis through a four steps process:

(1) Determine the input variables X_i, $i = 1,2$ and specify the probability density function of the variables.
(2) Randomly generate N combinations of input variables using the random sampling method (each combination is called a sample X^l).
(3) Compute the computational models for each sample.
(4) Generate the total utility values of all computation models or the rank assigned by the total utility values for each technology.

3.6. Data and software

This study analyzed 15 types of PG recycling technologies, including 29 practices and representing a comprehensive range of industrialized technologies in China. Data for the resource, economic, and social dimensions were gathered from the environmental impact assessment reports, feasibility studies, annual reports, published literature, and consultations with technical experts. When necessary, additional measures were taken to handle confidential data. The environmental dimension indicators were primarily assessed using the LCA method, whereas the energy and material background data were sourced from the GaBi and the Ecoinvent databases. The technology evaluation was based on the average values for each technology type.

The LCA in this study was carried out using GaBi 10 software. The remaining tasks, including technology evaluation, mapping (except Fig. 2, created using Microsoft office), uncertainty analysis, and sensitivity analysis, were executed using a custom package developed in R software.

4. Results

4.1. The weights of the dimensions and the indicators

Fig. 2 shows the weights of the dimensions and indicators within their dimensions computed using the weighting method described in Section 2.2.

Fig. 2 highlights the significantly differences in the indicator weights obtained from the AHP and EWM methods owing to their distinct underlying principles. However, the GT method achieves a more balanced weight distribution by integrating the data from both approaches. For example, when considering the solid waste recycling rate (R2), where all technologies have a recycling rate of 100 %, the EWM weight becomes zero owing to the infinite entropy in the dataset. By contrast, the AHP assigns a dominant weight to this indicator in the resource dimension based on expert experience. The GT method calculated a final weight of 0.28 by leveraging data from the AHP and EWM, representing a balanced compromise between the AHP and EWM weights.

An in-depth analysis of the GT weight results revealed that within the resource dimension, R5 (solid waste recycling rate) and R2 (comprehensive energy consumption) had similar weights, which were double that of R4 (land occupation). This emphasizes the significance of resource utilization and energy efficiency in assessing overall technology performance. From an environmental perspective, R1 (carbon emissions) has a substantial weight, equivalent to the combined weight of other indicators, indicating its prominent role in evaluating the environmental performance of PG recycling technology. S1 (employment opportunities) and ECO3 (Net Present Value) receive increased attention in social and economic aspects, reflecting social fairness and project feasibility considerations.

The GT method produced well-balanced weighting results for the four dimensions, as listed in Table 2. The weight assigned to the environmental dimension surpasses that of the others, underscoring its pivotal roles in overall performance. Economy, society, and resource criteria had weights of 0.25, 0.22, and 0.20, respectively, indicating comparable significance.

4.2. Utility performance of PG recycling technologies

4.2.1. Utility values of the individual indicators

The normalized indicator results (see Table S6) were calculated using Eqs. (15) and (16) and the indicator values (see Table S5, calculated

Table 2
The weights of the dimensions in different weighting methods.

Dimension	Resource	Environment	Economy	Society
AHP	0.29	0.50	0.15	0.06
EWM	0.09	0.14	0.37	0.40
GT	0.20	0.33	0.25	0.22

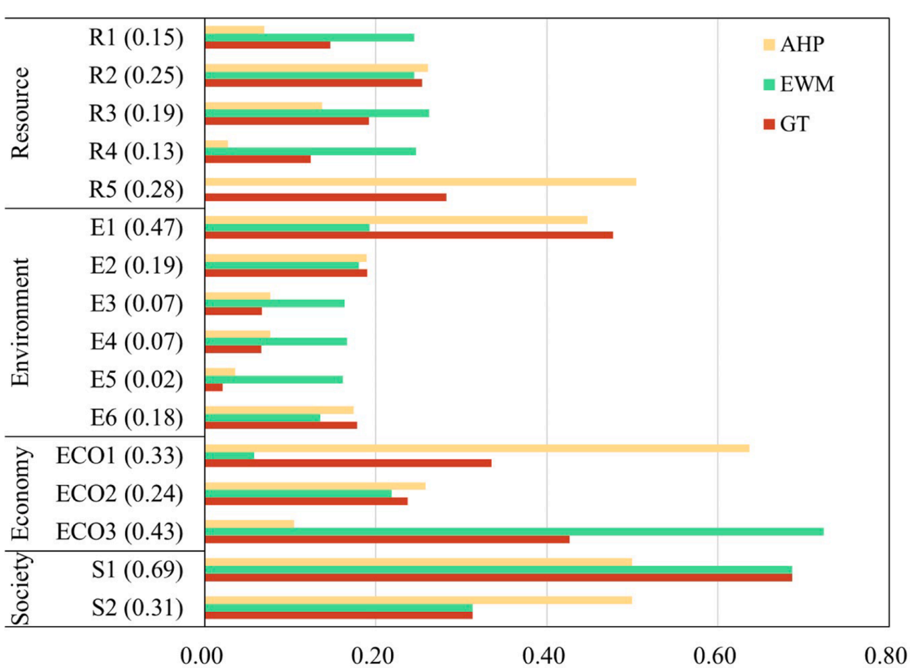


Fig. 2. The weights of the indicators in different weighting methods.

according to the methods listed in Table 1 and the collected raw data information). The utility values (a larger utility value implies a better performance) of the individual indicators and coefficients of the utility function (see Table S7) can be further measured by combining normalized results and Eqs. (17) and (19), as listed in Table 3.

The utility performance of the individual indicators in the resources and environment was generally better and utility values were centrally distributed from 0.678 to 1. However, the utility performance of individual indicators in terms of economic and social aspects was poor. In particular, the average utility values of ECO2, ECO3, and S1, were only 0.455, 0.342, and 0.436, respectively.

The best-performing indicators are further analyzed to provide valuable information. In the resource dimensions, R1 (raw and auxiliary materials consumption), R2 (comprehensive energy consumption), and R4 (land occupation) of T8 (PG-based lightweight plastering gypsum technology) were significantly better than other technologies. T1 (PG-based subgrade materials technology) performed best in R3 (freshwater consumption), which means it may consume less freshwater to process equal amounts of PG. Within the environment, T8 (PG-based lightweight plastering gypsum technology) was optimal for all indicators owing to its lower material and energy consumption, which directly lowered the environmental burden compared to other technologies. In the economic dimension, T12 (co-production of sulfuric acid and fertilizer of calcium silicon magnesium potassium technology) and T13 (hollow-core slabs) had better utility performance in ECO1 (investment cost) and ECO2 (net profit margin on sales), respectively, because of low investment and high value-added products. T10 (PG-based polymer material) had the highest net present value, implying that this technology can reap a high investment benefit. From a societal perspective, T6 (PG-based gypsum composite board technology) performed the best in terms of S1 (employment opportunity) and S2 (exposure risk) owing to its excellent capacity to provide jobs and a healthy work environment.

From the perspective of PG recycling technologies, it can be summarized that T1, T2, T5, T6, T7, T8, and T9 have better performance for most indicators while T4, T12, and T13 had lower performances.

4.2.2. Utility values of the criteria

Fig. 3 shows the utility values of the four criteria aggregated using the distance-based merging rule and their distribution characteristics. The utility performance of the criteria was determined by the values and weights of the individual indicators.

Fig. 3a shows that for the resources and environment criteria, T8 performs the best, with utility values of 0.999 and 1, respectively. Conversely, T12 exhibits the worst performance, with utility values of 0.318 and 0.067, respectively. The utility performance of the technologies in the environmental criterion was generally consistent with that in the resource criterion. This may be because the environmental performance of technologies was closely related to R1, R2, and R3, which play an important role in resource performance because the sum of their weights exceeds 0.5. Owing to the excellent performance of ECO1 and ECO2, which are the dominant economic performance variables, T12 performed the best in the economy, with a utility value of 0.64. Although the utility performance of T4 in ECO2 and ECO3 was at a medium level (see Table 3), its utility value of 0.25 still indicated poor economic performance, which was attributed to its low performance in ECO1, with a utility value of zero. Similarly, T6 and T4 showed excellent and poor performances in the social dimension, respectively, owing to their extreme performances in the decisive variable of society (S1). Notably, T14 performed worse in environmental and economic criteria compared to T1, which contrasts the findings of Tsioka and Voudrias (2020). These contrasting results can be attributed to two factors. First, unlike previous studies (Cai et al., 2018; Tsioka and Voudrias, 2020), this study did not consider material substitution in the environmental assessment. Second, multiple indicators beyond cost were included in this study to identify the economic performance of the technologies. These factors underline the challenges associated with directly comparing the results of different studies.

Fig. 3b reveals that the utility values of the PG recycling technology exhibited distinct patterns for different criteria. Specifically, the resource and environment criteria showed a concentrated distribution and high-level characteristics, indicating strong performance. However, the performance of technology in terms of economic and social criteria was generally dispersed and poor. This was evident from the notably lower median utility values of 0.367 and 0.351 for economic and social criteria, respectively, compared to the resource and environment criteria, at 0.943 and 0.972.

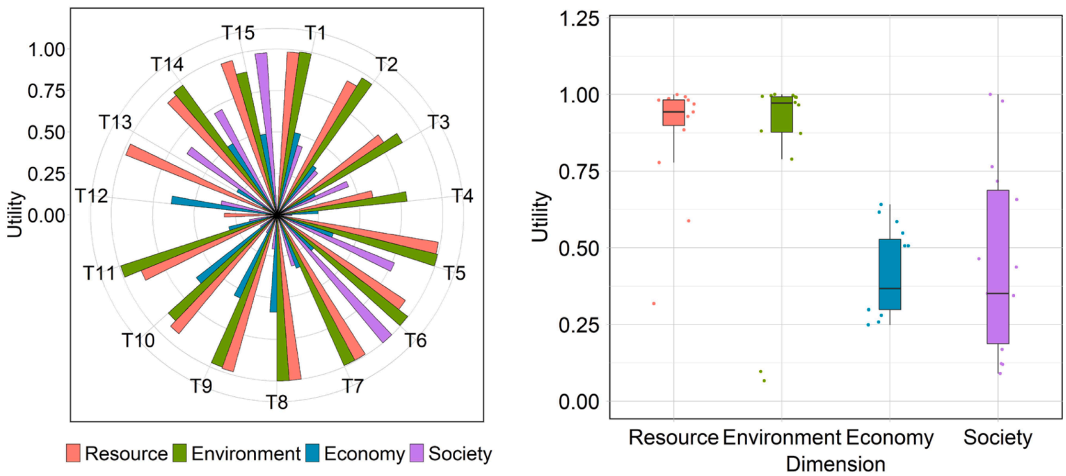
4.2.3. Comprehensive utility values of PG recycling technologies

The comprehensive utility performance was obtained by merging the utility values of the four dimensions, as shown in Fig. 4.

Fig. 4 shows that the comprehensive utility values for PG recycling technologies range from 0.26 to 0.74, where a larger utility value indicates more excellent performance. The comprehensive utility performance of T15 (PG-based dry-mix mortar technology) and T14 (PG-based organic fertilizer technology) were the first and second highest, at 0.74 and 0.73, respectively. This was because both technologies performed better in all four dimensions, especially in the economic and social dimensions, where the utility performance of all technologies varied significantly. This finding is consistent with that of Cao (2022) that PG-based dry-mix mortar exhibited the best comprehensive performance among four building materials produced from PG. Despite having the best performance in the economic dimension, T12 (PG-based co-production of sulfuric acid and fertilizer) had the worst comprehensive utility performance. The main reason for this may be that T12

Table 3
Utility values of the individual indicators for PG recycling technologies.

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15
R1	0.973	0.875	0.879	0.000	0.993	0.983	1.000	1.000	0.998	0.944	0.891	0.990	0.961	0.936	0.947
R2	1.000	0.997	0.999	1.000	1.000	1.000	0.999	1.000	0.996	0.994	0.997	0.000	1.000	0.979	1.000
R3	1.000	0.813	0.468	0.981	0.998	0.876	0.997	0.998	0.979	0.991	0.740	0.000	0.996	0.999	0.975
R4	0.946	0.954	0.999	0.000	0.950	0.816	0.973	1.000	0.939	0.739	0.905	0.970	0.949	0.804	0.908
R5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
E1	0.990	0.975	0.899	0.787	0.997	0.996	0.995	1.000	0.979	0.886	0.992	0.000	0.126	0.982	0.914
E2	0.993	0.950	0.878	0.820	0.999	0.997	0.988	1.000	0.963	0.861	0.991	0.168	0.000	0.957	0.831
E3	0.992	0.975	0.678	0.830	0.999	0.992	0.994	1.000	0.926	0.902	0.989	0.000	0.282	0.789	0.621
E4	0.996	0.983	0.959	0.902	0.999	0.999	0.995	1.000	0.983	0.889	0.994	0.218	0.000	0.993	0.949
E5	0.990	0.978	0.993	0.631	0.971	0.996	0.980	1.000	0.923	0.753	0.988	0.000	0.965	0.849	0.276
E6	0.997	0.995	0.777	0.759	0.999	0.999	0.994	1.000	0.972	0.892	0.997	0.595	0.000	0.987	0.849
ECO1	0.994	0.983	0.969	0.000	0.998	0.948	0.989	0.990	0.919	0.558	0.948	1.000	0.985	0.977	0.947
ECO2	0.468	0.517	0.000	0.468	0.516	0.335	0.476	0.589	0.792	0.274	0.216	0.107	1.000	0.468	0.594
ECO3	0.383	0.164	0.134	0.383	0.149	0.099	0.133	0.472	0.387	1.000	0.131	0.974	0.000	0.383	0.333
S1	0.381	0.336	0.472	0.000	0.741	1.000	0.299	0.128	0.072	0.033	0.208	0.441	0.624	0.830	0.976
S2	1.000	0.429	0.429	1.000	1.000	1.000	0.429	1.000	0.429	1.000	0.000	0.000	1.000	0.429	1.000



(a) (b)

Fig. 3. Utility performance of PG recycling technologies in four dimensions. (a) Utility values. (b). Distribution of utility values.

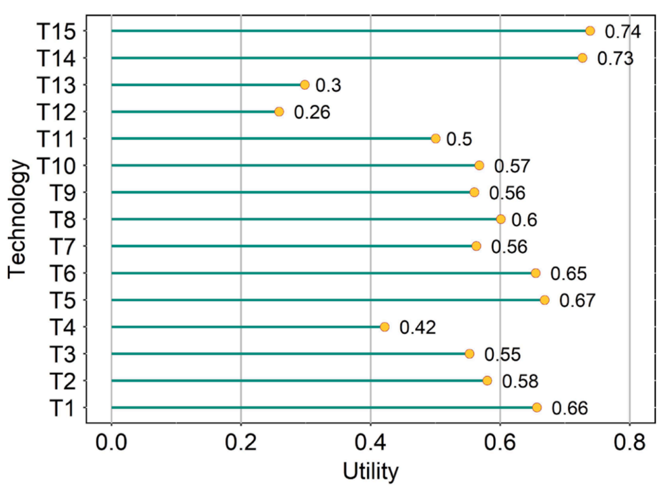
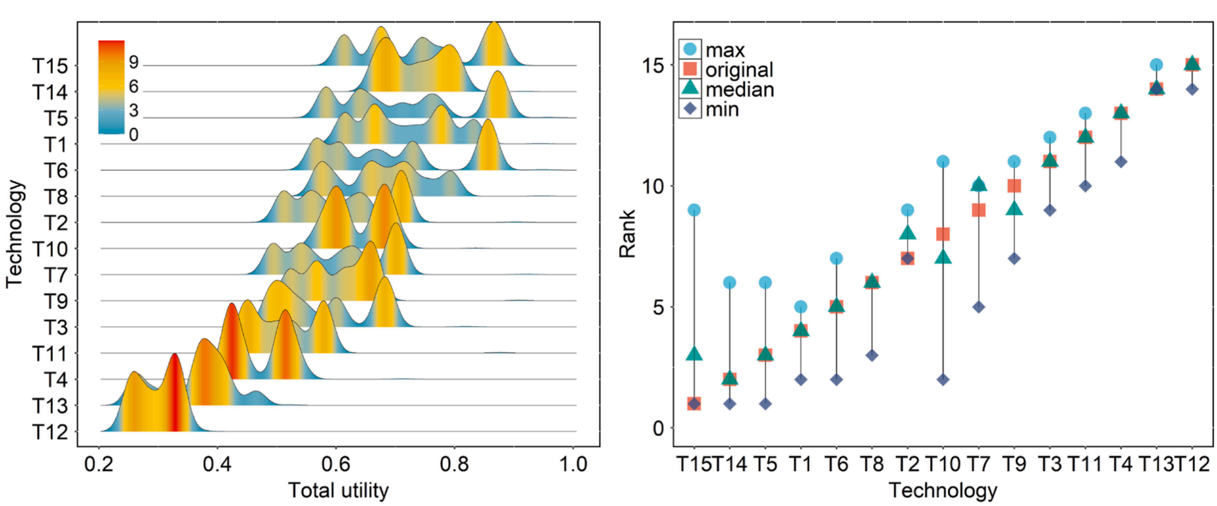


Fig. 4. Comprehensive utility performance of PG recycling technologies.

performed poorly in the other three dimensions. In particular, for the resource and environmental dimensions, the utility performance of T12 was far lower than that of the other technologies (see Fig. 3a). The comprehensive utility performance of T13 (PG-based hollow-core slabs) was close to that of T12 because of its poor utility performance in the environment and economy. These findings indicate that the PG used for the co-production of fertilizer, sulfur acid or other by-products is unsustainable, which agrees with the literature (Mohammed et al., 2018). Similarly, T4 (PG-based urban comprehensive pipe gallery) exhibits the worst behavior in terms of economy and society, resulting in a relatively low ranking. The comprehensive utility values of the remaining technologies were concentrated from 0.53 to 0.67 and decreasing in the order of T5 (PG-based cement retarder), T1 (PG-based subgrade materials), T6 (PG-based gypsum composite board), T8 (PG-based lightweight plastering gypsum), T2 (PG-based gypsum block), T10 (PG-based polymer materials), T7 (PG-based gypsum powder), T9 (PG-based high-strength gypsum), T3 (PG-based ammonium sulfate), and T11 (PG-based co-production of sulfuric acid and cement).

4.3. Uncertainty analysis results

Based on the Monte Carlo method, the utility values of the PG



(a) (b)

Fig. 5. Distribution results of PG recycling technologies. (a) Probability density curves of utility values of PG recycling technologies. (b) Rank variation of PG recycling technologies considering uncertain elements.

recycling technologies and their ranking changes under different weight methods and aggregated rules were analyzed, as shown in Fig. 5.

Fig. 5 presents the probability density curve of the utility values obtained via uncertainty analysis with a sampling number of 1000. The darker the color, the higher the frequency of the resulting value falling into the interval. The probability density curve, representing the likelihood of different values occurring within a given range, exhibits a multimodal distribution for the total utility value of the PG recycling technology, mainly because the samples obtained in this study are discrete values. Although the sampling methods and uncertain factors considered were the same, the result distribution of the technologies was significantly different, indicating that other factors (such as the indicator raw data) affect the distribution. Further analyses of these elements are required in subsequent studies.

The median of the ranking results obtained through uncertainty analysis was consistent with the original ranking, indicating that the overall impact of the uncertain factors on the ranking results was small and that the MCDA methods proposed in this study was robust. However, for individual technologies, uncertain factors had different degrees of effect on the ranking. For example, the uncertain factors considered in this study had a significant effect on T10 and T15, causing the ranking results to fluctuate from 2–11 and 1–9, respectively. Uncertain factors only had a slight effect on the ranking of T12 and T13, which remained at 14–15.

5. Discussion

5.1. Importance of evaluation of PG recycling technologies in China

The Chinese government implemented a range of mandatory and encouraging policies to address PG reduction, as shown in Table S8. Provinces, such as Guizhou, Hubei, Yunnan, and Sichuan, where PG generation is prevalent, have established strict policies to promote PG reduction (Cui et al., 2022; Luo et al., 2017). These policies incentivize PG-generating enterprises to treat their waste and attract more enterprises to participate in PG recycling. For example, Guizhou province has enforced a mandatory policy called "recycling determines the production" which links the production quantity of the main product (phosphoric acid) to the amount of PG recycled by the enterprise (Guizhou Provincial People's Government, 2018). Consequently, PG-generating enterprises are compelled to recycle PG individually or in collaboration with other enterprises. Statistics show that local governments provided financial subsidies to approximately 80 enterprises between 2018 and 2021 as incentives for PG recycling. The technologies adopted by these enterprises encompass more than ten categories. As policies continue to improve and be promoted, more enterprises are expected to engage in PG recycling, leading to the adoption of additional technologies.

Although national policies in China prioritize PG reduction and comprehensive utilization, the recent regional regulations have explicitly emphasized the importance of safe use. For example, Hubei province issued the "Technical Regulations for Harmless Treatment of Phosphogypsum (Trial)" to address the safe disposal and recycling of PG (Hubei Provincial Department of Economy and Information, 2022). When PG is used as a soil amendment, it must undergo pretreatment to meet GB18599 standards before being recycled, and the properties of the resulting soil amendment should adhere to HG/T 4219 and GB 38400 standards. Therefore, ensuring environmental safety (identified based on human toxicity and ecotoxicity for the current study) of PG recycling is imperative.

In summary, identifying the overall performance of PG recycling technologies is crucial for the sustainable development of the PG recycling industry, particularly in China, where the industry is rapidly growing. Existing enterprises utilizing PG recycling technologies must address concerns regarding potential environmental impacts, evaluate the performance of the adopted technologies in various aspects such as the environment and economy, and identify measures to address any technological shortcomings. Additionally, prospective entrants to the PG recycling industry should consider environmentally safely, economically feasible, and sustainable technologies. Therefore, it is necessary to develop a research methodology to comprehensively evaluate the performance of PG recycling technologies. The evaluation results can assist enterprises in making informed decisions regarding technology selection and promote the sustainable development of the PG recycling industry as PG reduction efforts continue to strengthen in China.

5.2. Sensitivity analysis

The global sensitivity analysis method, which has been widely used in the field of ecological environment (Groen et al., 2017), can quantitatively analyze the contribution of input parameters to the output and identify whether there is an interaction between the input parameters (Tian, 2013). This study employed a global sensitivity analysis method based on a tree-shaped Gaussian process (Gramacy, 2007) to analyze the sensitivity of the input indicators to the performance of the PG recycling technology.

The six most sensitive factors were identified (Fig. S2) as E1 (carbon emission), S1 (employment opportunities), ECO1 (investment and construction cost), ECO3 (net present value), E2 (acidification), R2 (comprehensive energy consumption), and E6 (human body Toxicity), which made contributions to the result variation of 79.42 %, 6.99 %, 3.97 %, 2.37 %, 1.78 %, 1.77 %, and 1.72 %, respectively. Improving the data quality of such parameters in a targeted manner may be an effective way to enhance the reliability of the output results. The main and total effect of the sensitivity analysis were approximately the same, indicating that the indicators did not interact.

5.3. Recommendations

The evaluation results showed that the performance of PG recycling technology generally presented a relatively high level in terms of resources and environment, while that of the economy and society was at a lower level. Therefore, optimizing the performance of a technology in terms of economic and social criteria is key to improving its overall performance level. Improvements in the indicators that contribute significantly to changes in technological performance, such as carbon emissions and employment opportunities, can effectively enhance the overall performance of a technology in a short time.

From the perspective of performance of PG recycling technologies, T15 and T14 may be the best choices for enterprises that recycle PG. Thus, it is crucial to intensify the efforts to promote these technologies. Effective measures, such as enhancing public awareness, providing subsidies for recycled products, investing in technological advancements, and implementing synergistic approaches, have been proven to yield positive outcomes (Cui et al., 2022; Wu et al., 2022). Moreover, poorly performing technologies may need to be replaced by well-performing technologies to help enterprises gain more benefits from PG recycling and facilitate the sustainable development of the PG recycling industry.

5.4. Limitations and future improvements

In this study, data derived from the enterprise's annual report were used to calculate ECO2 (net profit margin on sales) and ECO3 (net profit value) of T12 (co-production of sulfuric acid and fertilizer). However, this type of data, which is currently the best available data, better reflects economic performance at the enterprise level rather than at specific technology or product. In addition, because of the lack of local data on some materials, such as urea and paraffin, global-scale data or similar process data in other regions were used in the LCA to fill in the missing data. Therefore, these data should be collected and updated to improve the accuracy of results.

Risk attitudes were determined by averaging the normalized values of the indicators. This approach can quantify the risk attitude of decision-makers to some extent and has been adopted in MCDA research because of its high applicability. However, the risk attitudes determined using this method changed when new PG recycling technologies were added. The utility curve is also influenced, which may further affect the ranking results of the technologies (see Section 2.3). More measures, such as covering as many types of technologies as possible, may be required to reduce the fluctuations caused by increasing the number of samples.

This study mainly evaluated the PG recycling technologies that have been industrialized in China and technologies at other scales (such as laboratory scale, pilot plant, and full scale) were not considered. This may result in some technologies that perform well and have the potential for industrial application not being identified in time for adopting. Therefore, it may be necessary to focus on evaluating these technologies in subsequent studies to provide more comprehensive information for enterprise technology selection.

6. Conclusions

This study introduced utility theory to assess the performance of PG recycling technologies and support decision-making. GT was employed to reasonably weight individual indicators and dimensions. Uncertainty analysis was conducted to validate the robustness of the methods. The main conclusions were as follows:

GT achieves balanced weighting of the criteria and indicators by minimizing the deviation between the ideal weight and weight set derived from AHP and EWM. The environmental criterion had a higher weight (0.33) than resource, economy, and society. GT is an ideal method in scenarios where trade-offs between different weight strategies are necessary.

The utility of PG recycling technologies in the resource and environmental criteria (median value of 0.943 and 0.972, respectively) outperformed the economic and social criteria (median value of 0.367 and 0.351, respectively). Therefore, enhancing economic and social performance, particularly focusing on indicators such as carbon emissions (contributing up to 79.42 % of the variation in utility), is crucial for the overall improvement in PG recycling technology.

The utility values of PG recycling technologies ranged from 0.26 to 0.74. T15 and T14 performed exceptionally well, with utility values above 0.70, while T12 and T13 underperformed, with values below 0.30. Prioritizing the optimization or substitution of these poorly performing technologies with well-performing alternatives is crucial for fostering the sustainable development of the PG recycling industry.

The median ranking results from the uncertainty analysis aligned with the original ranking, demonstrating the robustness of the proposed MCDA method in evaluating the performance of PG recycling technologies. This suggests that the MCDA method can be a reliable and robust approach for decision-making for other solid-waste recycling technologies.

Further improvements are required to enhance the credibility of evaluation method and results. These improvements involve addressing the data representativeness of technical processes and the economic benefits of specific products and technologies. Additionally, evaluating the utility function uncertainty and incorporating more emerging PG recycling technologies will enable better-informed decision-making.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgement

This work was supported by the National Key R&D Program of China (2018YFC1903601).

Appendix A. Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.wasman.2023.09.029.

References

Abdullah, L., Zulkifli, N., Liao, H.C., et al., 2019. An interval-valued intuitionistic fuzzy DEMATEL method combined with Choquet integral for sustainable solid waste management. Eng. Appl. Artif. Intel. 82, 207–215.
Biluca, J., de Aguiar, C.R., Trojan, F., 2020. Sorting of suitable areas for disposal of construction and demolition waste using GIS and ELECTRE TRI. Waste Manag. 114, 307–320.
Cai, W., Liu, C.H., Zhang, C.X., et al., 2018. Developing the ecological compensation criterion of industrial solid waste based on emergy for sustainable development. Energy 157, 940–948.
Cao, J.Z., Wang, Z.Y., Ma, X.H., et al., 2022. Promoting coordinative development of phosphogypsum resources reuse through a novel integrated approach: A case study from China. J. Clean. Prod. 374, 134078.
Cao, W.X., Yi, W., Li, J., et al., 2021. A facile approach for large-scale recovery of phosphogypsum: an insight from its performance. Constr. Build. Mater. 309.
Chadderton, C., Foran, C.M., Rodriguez, G., et al., 2017. Decision support for selection of food waste technologies at military installations. J. Clean. Prod. 141, 267–277.
Chen, C., Wen, Z.G., Wang, Y.H., et al., 2022. Multi-objective optimization of technology solutions in municipal solid waste treatment system coupled with pollutants cross-media metabolism issues. Sci. Total Environ. 807.
China Association of Circular Economy, 2022. T/CACE 050—2022: Technical specification for multi-dimensional performance evaluation of solid waste recycling technology.
China Standardization Administration, 2013. General principles of stipulating the assessment indicator frame of cleaner production (to try out).
China Standardization Administration, 2015. GB/T 32326-2015: Assessment guidelines for integrated utilization technology of industrial solid waste.
Coban, A., Ertis, I.F., Cavdaroglu, N.A., 2018. Municipal solid waste management via multi-criteria decision making methods: a case study in Istanbul, Turkey. J. Clean. Prod. 180, 159–167.
Cui, Y., Chang, I.S., Yang, S., et al., 2022. A novel dynamic business model to quantify the effects of policy intervention on solid waste recycling industry: a case study on phosphogypsum recycling in Yichang, China. J. Clean. Prod. 355.
da Silva, L.B.L., Alencar, M.H., de Almeida, A.T., 2022. Exploring global sensitivity analysis on a risk-based MCDM/A model to support urban adaptation policies against floods. Int. J. Disast. Risk Sci. 73.
Dodgson, J.S., Spackman, M., Pearman, A., et al., 2009. Multi-criteria analysis: a manual. Economic History Working Papers 12761. London School of Economics and Political Science, Department of Economic History.
Dunn, J. 2020. Handbook on constructing composite indicators: methodology and user guide.
Fu, L.M., Yang, Q., Liu, X.X., et al., 2021. Three-stage model based evaluation of local residents' acceptance towards waste-to-energy incineration project under construction: a Chinese perspective. Waste Manag. 121, 105–116.
Garcia-Garcia, G., 2022. Using multi-criteria decision-making to optimise solid waste management. Curr. Opin. Green Sust. 37, 100650.
Gettu, R., Patel, A., Rathi, V., et al., 2019. Influence of supplementary cementitious materials on the sustainability parameters of cements and concretes in the Indian context. Mater. Struct. 52 (1).
Gramacy, R.B., 2007. tgp: an R package for Bayesian nonstationary, semiparametric nonlinear regression and design by treed Gaussian process models. J. Stat. Softw. 19 (9), 1–46.
Groen, E.A., Bokkers, E.A.M., Heijungs, R., et al., 2017. Methods for global sensitivity analysis in life cycle assessment. Int. J. Life Cycle Assess. 22 (7), 1125–1137.
Guizhou Provincial People's Government, 2018. Opinions on Promoting the Comprehensive Utilization of Phosphogypsum. http://www.guizhou.gov.cn/zwgk/zfgb/gzszfgb/201804/t20180404_70523317.html (accessed 15 December 2022).
Heravi, G., Fathi, M., Faeghi, S., 2017. Multi-criteria group decision-making method for optimal selection of sustainable industrial building options focused on petrochemical projects. J. Clean. Prod. 142, 2999–3013.
Huang, A., 2017. A Framework and Metrics for Sustainable Manufacturing Performance Evaluation at the Production Line, Plant and Enterprise Levels. University of Kentucky.
Huang, Y.B., Qian, J.S., Lu, L.C., et al., 2020. Phosphogypsum as a component of calcium sulfoaluminate cement: hazardous elements immobilization, radioactivity and performances. J. Clean. Prod. 248.

Hubei Provincial Department of Economy and Information, 2022. Technical Regulations for Harmless Treatment of Phosphogypsum (Trial).
Kulczycka, J., Kowalski, Z., Smol, M., et al., 2016. Evaluation of the recovery of Rare Earth Elements (REE) from phosphogypsum waste - case study of the WIZOW Chemical Plant (Poland). J. Clean. Prod. 113, 345–354.
Liu, W.T., Han, M.K., Meng, X.X., et al., 2021. Mine water inrush risk assessment evaluation based on the GIS and combination weight-cloud model: a case study. ACS Omega 6 (48), 32671–32681.
Liu, H., Nie, C., Li, H., et al., 2022. Hydrophobically modified phosphogypsum and its application in polypropylene composites. Constr. Build. Mater. 347, 128500.
Luo, Z.B., Ma, S.J., Hu, S.Y., et al., 2017. Towards the sustainable development of the regional phosphorus resources industry in China: a system dynamics approach. Resour. Conserv. Recy. 126, 186–197.
Ma, Y., Shi, T.Y., Zhang, W., et al., 2019b. Comprehensive policy evaluation of NEV development in China, Japan, the United States, and Germany based on the AHP-EW model. J. Clean. Prod. 214, 389–402.
Ma, Q., Wang, Z.C., Pan, X.P., et al., 2019a. Evaluation method of power grid investment decision based on utility function under new electricity reform environment. Electric Power Automation Equipment 39 (12), 198–204.
Meskini, S., Samdi, A., Ejjaouani, H., et al., 2021. Valorization of phosphogypsum as a road material: stabilizing effect of fly ash and lime additives on strength and durability. J. Clean. Prod. 323.
Mir, M.A., Ghazvinei, P.T., Sulaiman, N.M.N., et al., 2016. Application of TOPSIS and VIKOR improved versions in a multi criteria decision analysis to develop an optimized municipal solid waste management model. J. Environ. Manage. 166, 109–115.
Mohammed, F., Biswas, W.K., Yao, H.M., et al., 2018. Sustainability assessment of symbiotic processes for the reuse of phosphogypsum. J. Clean. Prod. 188, 497–507.
Pathak, H., Wassmann, R., 2007. Introducing greenhouse gas mitigation as a development objective in rice-based agriculture: I. Generation of technical coefficients. Agr. Syst. 94 (3), 807–825.
Saadé-Sbeih, M., Feraille, A., Soulimani, A.A., 2019. Life cycle assessment of alternative road base materials: the case of phosphogypsum. In: Paper Presented at the IOP Conference Series: Earth and Environmental Science.
Shannon, C.E., 1948. A mathematical theory of communication. Bell Syst. Tech. J. 27 (4), 623–656.
Sharma, M., Joshi, S., Govindan, K., 2021. Issues and solutions of electronic waste urban mining for circular economy transition: an Indian context. J. Environ. Manage. 290.
Soltani, A., Hewage, K., Reza, B., et al., 2015. Multiple stakeholders in multi-criteria decision-making in the context of Municipal Solid Waste Management: a review. Waste Manag. 35, 318–328.
Soni, A., Das, P.K., Hashmi, A.W., et al., 2022. Challenges and opportunities of utilizing municipal solid waste as alternative building materials for sustainable development goals: a review. Sustain. Chem. Pharm. 27, 100706.
Stankovic, J.J., Jankovic-Milic, V., Marjanovic, I., et al., 2021. An integrated approach of PCA and PROMETHEE in spatial assessment of circular economy indicators. Waste Manag. 128, 154–166.
Tang, S., Jiang, J., Shamseldin, A.Y., et al., 2022. Comprehensive optimization framework for low impact development facility layout design with cost-benefit analysis: a case study in Shenzhen city, China. ACS ES&T Water 2 (1), 63–74.
Tian, W., 2013. A review of sensitivity analysis methods in building energy analysis. Renew. Sust. Energ. Rev. 20, 411–419.
Torkayesh, A.E., Malmir, B., Asadabadi, M.R., 2021. Sustainable waste disposal technology selection: the stratified best-worst multi-criteria decision-making method. Waste Manag. 122, 100–112.
Tsioka, M., Voudrias, E.A., 2020. Comparison of alternative management methods for phosphogypsum waste using life cycle analysis. J. Clean. Prod. 266.
Uek, L., Kleme, J.J., Kravanja, Z., 2015. Chapter 5 - Overview of environmental footprints. In: Klemes, J.J. (Ed.), Assessing and Measuring Environmental Impact and Sustainability. Butterworth-Heinemann, Oxford, pp. 131–193.
Vlachokostas, C., Michailidou, A.V., Achillas, C., 2021. Multi-criteria decision analysis towards promoting waste-to-energy management strategies: a critical review. Renew. Sust. Energ. Rev. 138.
Wang, H., Xu, C., Xu, Z.S., 2019. An approach to evaluate the methods of determining experts' objective weights based on evolutionary game theory. Knowl.-Based Syst. 182.
Wang, C.Q., Wang, Z.Y., Huang, D.M., et al., 2023. Recovery and recycling core of phosphogypsum: characteristic hazardous elements risk assessment and analysis. Process Saf. Environ. 170, 738–756.
Wood, D.A., Khosravanian, R., 2015. Exponential utility functions aid upstream decision making. J. Nat. Gas Sci. Eng. 27, 1482–1494.
Wu, Y.N., Chen, K.F., Zeng, B.X., et al., 2016. Cloud-based decision framework for waste-to-energy plant site selection - a case study from China. Waste Manag. 48, 593–603.
Wu, F.H., Ren, Y.C., Qu, G.F., et al., 2022. Utilization path of bulk industrial solid waste: a review on the multi-directional resource utilization path of phosphogypsum. J. Environ. Manage. 313.
Wu, S., Yao, Y.G., Yao, X.L., et al., 2020. Co-preparation of calcium sulfoaluminate cement and sulfuric acid through mass utilization of industrial by-product gypsum. J. Clean. Prod. 265.
Xi, H., Li, Z.H., Han, J.Y., et al., 2022. Evaluating the capability of municipal solid waste separation in China based on AHP-EWM and BP neural network. Waste Manag. 139, 208–216.
Xu, L., Fang, K.N., Bi, Y.X., et al., 2023. Preparation of anhydrous micron CaSO4 with different morphologies from phosphogypsum and its reinforcing in polyvinyl chloride. Constr. Build. Mater. 365.
Zhang, H., Liping, M.A., Jianhong, H.U., et al., 2013. LCA study on the preparation of cement clinker by the phosphogypsum decomposition under different decomposition process. Mater. Rev. 27 (S1), 302–305.
Zhang, J., Wei, C., Ran, J., et al., 2022. Properties of polymer composite with large dosage of phosphogypsum and it's application in pipeline. Polym. Test. 116, 107742.
Zhou, B., Zhu, H.Y., Xu, S.Y., et al., 2021. Effect of phosphogypsum on the properties of magnesium phosphate cement paste with low magnesium-to-phosphate ratio. Sci. Total Environ. 798.
Zwickl, K., 2019. The demographics of fracking: a spatial analysis for four US states. Ecol. Econ. 161, 202–215.