Innovation and Development Policy

Available online at http://idp-journal.casisd.cn/

Comprehensive Benefit Evaluation of Biobanks based on Cost-benefit Analysis

Ang Li*

School of Public Policy and Management, University of Chinese Academy of Sciences, Beijing 100049, China

Abstract

The study constructs a comprehensive benefit evaluation system for biobanks based on cost-benefit analysis, aiming to provide decision support for the scientific management of biobanks and the effective utilization of national strategic resources. By using the grounded theory method, key concepts are extracted, with two core categories of cost and benefit identified. A comprehensive benefit evaluation indicator system is constructed, including construction and operation costs, regulatory costs, strategic benefits, scientific benefits, economic benefits, and social benefits. The cost-benefit analysis method is used to construct an evaluation model. The Germplasm Bank of Wild Species in China is empirically studied as a case study to comprehensively evaluate its performance in key dimensions of cost and benefit. Using the Monte Carlo simulation, the development trend of the Germplasm Bank of Wild Species is predicted for 2035 and 2050. The results show that the biobank has achieved significant results in preservation, scientific research, and talent cultivation, and has made important contributions to biodiversity conservation and sustainable development. However, the biobank still has shortcomings in terms of preservation gains, external scientific benefits, achievement transformation, and market-oriented commercialization. It is necessary to optimize the cost structure and continue to explore its scientific and economic benefits. The evaluation system of this study provides a scientific and comprehensive tool for the comprehensive benefit evaluation of biobanks, and offers important decision support for the construction and management of biobanks.

Key words

Biobank; Comprehensive benefits; Evaluation; Grounded theory; Cost-benefit analysis

* Corresponding author. E-mail address: liang201@mails.ucas.ac.cn

10.20046/j.cnki.2096-5141.2024.0004

1. Introduction

Biobanks as part of the strategic research infrastructure play a crucial role in advancing fields such as regenerative medicine, personalized medicine, and biotechnology, and are an integral component of the emerging bioeconomy. Their establishment and operation are not only vital for scientific research endeavors but also serve as a key component in the national strategic framework. Biobanks must showcase their value through tangible contributions to research so as to secure funding support and engage researchers. The comprehensive benefit evaluation of biobanks not only quantifies the contribution of biobanks to scientific research and innovation, but also helps to assess their economic and social impacts, thereby providing the basis for continued funding and policy support. China is currently in the initial stages of developing a biobank evaluation system, highlighting the pressing need for the creation of scientific evaluation methods and frameworks to enhance the efficient establishment and management of biobanks. Despite of the efforts made, the existing evaluation system for biobanks is fragmented and lacks standardized criteria, hindering collaboration and communication among biobanks. There is an urgent requirement to establish a comprehensive indicator system to ensure the effective and sustainable support for the innovative research ecosystem.

This study adopts a comprehensive definition of biobanks, which is a structured system that utilizes controlled environments to standardize the collection, processing, storage, and distribution of biological materials in anticipation of future demand and global advancements. These biobanks support scientific research by providing access to relevant biological materials, data, and information. Biological materials encompass living entities such as plants, animals, fungi, viruses, and their components. Currently, biobanks predominantly focus on storing human-derived biomaterials, with primary research on benefit evaluation revolving around these human-derived biobanks. The suitability of existing evaluation indicators for non-human-derived biobanks, such as microorganisms and plants, requires further examination. Moreover, most evaluation indicators and models for biobanks remain theoretical (Slušná and Balog, 2023) and are seldom applied in practice due to methodological limitations and implementation challenges. The cost-benefit analysis (CBA) method, widely used to assess the socio-economic benefits of research infrastructure (Bastianin *et al*., 2023; Florio *et al*., 2016; Florio and Sirtori, 2016; Morretta *et al*., 2023), can quantify resource allocation efficiency and the economic value of outputs. This approach aids decision-makers in achieving an optimal balance between scientific considerations, available personnel, infrastructure, and financial resources, ultimately maximizing economic and social benefits in infrastructure operations.

This study develops a comprehensive benefit evaluation system and model for biobanks using the CBA conceptual framework. The objective is to offer decision support for the scientific management of biobanks and the efficient utilization of national strategic resources. The study addresses the two key questions of what and how to evaluate the comprehensive benefits of biobanks. To achieve this, the study first examines the evaluation indicators and methods used in previous research on biobanks and research infrastructure, laying the groundwork for a comprehensive benefit evaluation of biobanks. Subsequently, a comprehensive benefit indicator system for biobanks is established through grounded theory, and a biobank comprehensive benefit evaluation model is developed based on the CBA conceptual framework. The study then takes the Germplasm Bank of Wild Species as a case to validate the usability and applicability of the evaluation system and model. Finally, the study draws conclusions and provides targeted recommendations for the future development of the biobank.

2. Literature Review

The Chinese Academy of Sciences categorizes research infrastructure (also known as large research infrastructure, large-scale research infrastructure, research facilities and so on, and here collectively refers to as research infrastructure) into three groups: dedicated research infrastructure, public experimental platforms, and public infrastructure. Biobanks fall under the category of public infrastructure, with the objective of offering fundamental data and information services to meet national development requirements. Evaluating the benefits of biobanks should integrate with the evaluation methods used for research infrastructure benefits to ensure a comprehensive and scientific evaluation process. Therefore, this study reviewed the comprehensive benefit indicators of biobanks and the benefit evaluation methods of research infrastructure.

2.1. Benefit evaluation indicators for biobanks

As part of the key research infrastructure, biobanks provide essential biological samples and data resources that support a wide range of research endeavors. Despite the high costs associated with their establishment and maintenance, a variety of quantitative and qualitative indicators, such as the quantity and quality of data and samples (Brown *et al*., 2017; Hofman *et al*., 2013; Rush *et al*., 2020), data and sample allocation (Bledsoe *et al*., 2021; Meredith *et al*., 2015), costs and human resources (Hofman *et al*., 2013; Rush *et al*., 2020, 2024), and subsequent publication results (Henderson *et al*., 2019; Hofman *et al*., 2013; Rodriguez Llorian *et al*., 2023; Rush *et al*., 2024; Tarling *et al*., 2017), as well as research and business collaborations (Henderson *et al*., 2019; Hofman *et al*., 2013; Matharoo-Ball and Thomson, 2014), can showcase the significant contributions of biobanks to scientific research. This demonstration of value is crucial for securing support from funding agencies and ensuring ongoing continued engagement from both funders and researchers. However, challenges exist in evaluating the comprehensive benefits and long-term impacts of biobanks, as these indicators primarily focus on outcomes rather than impacts, which often require an extended period of time to materialize and be fully evaluated.

2.2. Benefit evaluation methods for research infrastructure

Research infrastructure utilizes a combination of qualitative and quantitative research methods in benefit evaluation. Qualitative evaluation methods involve operational reports, on-site inspections, and user feedback. While these methods are effective in handling complex outputs, there is a risk of subjectivity impacting the objectivity of the evaluation. For instance, Bianchi-Streit *et al*. (1985) evaluated the operational efficiency of CERN through interviews and surveys, and Qiao *et al*. (2016) evaluated China's research infrastructure using a multi-case study approach.

Quantitative evaluation methods, such as facilitymetrics (Hallonsten, 2013, 2014), primarily focus on the quantitative analysis of published papers and patent outputs, providing an objective evaluation approach. However, most of them focus on assessing the scientific effects of research infrastructure (Li *et al*., 2022; Zhang *et al*., 2019b), and these methods may not be adequate for comprehensively evaluating structurally complex and functionally diverse facilities like biobanks. Input-output, logit and probit econometric models evaluate project costs and benefits through mathematical and economic perspectives (Caliari *et al*., 2020; Suslov *et al*., 2021; Zhang, 2022) but may overlook long-term and indirect benefits. The cost-benefit analysis (CBA) framework developed by Florio and his team (2016) integrates technological, economic, social, and cultural factors, having the potential to combine quantitative and qualitative methods to provide comprehensive decision support for research infrastructure (Bastianin *et al.*, 2023; Ecchia *et al.*, 2021; Florio *et al.*, 2024; Morretta *et al.*, 2022). This study chooses CBA framework to evaluate the multidimensional comprehensive benefits of biobanks. To overcome the limitation of CBA method in evaluating the limited content (Xu *et al.*, 2021), the impact modes and channels of biobanks on social and economic development were clarified through desk research and interviews, and a comprehensive benefit evaluation system for biobanks was constructed from the theoretical level. Indicators were monetized by using quantitative and qualitative methods.

3. Construction of Comprehensive Benefit Evaluation System and Model for Biobanks

3.1. Construction of evaluation indicator system based on grounded theory

3.1.1. The grounded theory method

Grounded theory is a qualitative research method that builds theories from the ground up through open coding, spindle coding, and selective coding. It emphasizes deriving theories from empirical data to deeply reflect and explain the essence of social phenomena (Chen, 1999). Data collection and coding are fundamental steps in grounded theory, with the coding process involving open coding, spindle coding, and selective coding. And research findings are derived through theoretical sampling. In this study, comprehensive benefit evaluation indicators for biobanks are identified using the grounded theory, and the specific research approach is illustrated in Fig. 1.

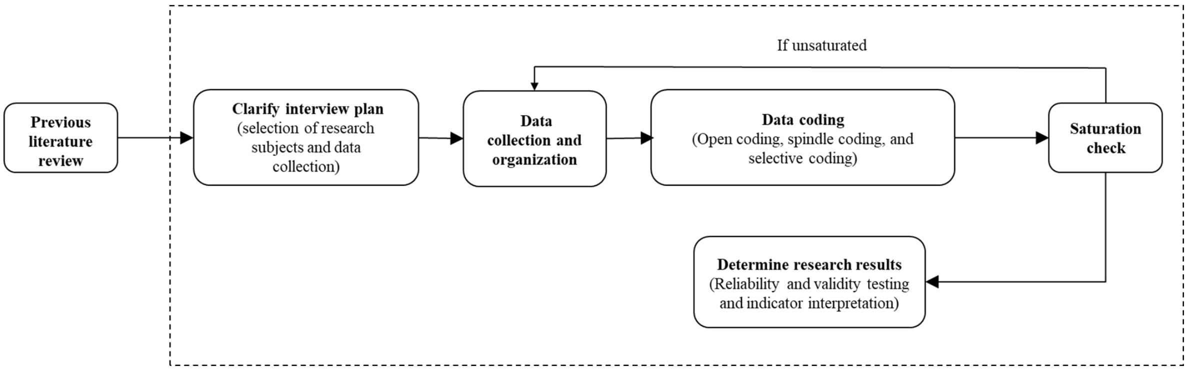

Fig. 1. The research framework of this paper.

3.1.2. Research sample selection and data collection

(1) Data collection methods

This study is based on grounded theory and utilizes in-depth interviews as the primary method of data collection to ensure the depth and relevance of the data, thereby enhancing the robustness of the theory. Meanwhile, considering the shared and unique aspects of the target, function, and features of the biobank, to guarantee the precision and comprehensiveness of the indicators, this study also collects pertinent official, literary, and online data and materials. The sources and contents of the original data are presented in Table 1.

Table 1
Source and content of original data.

Data category	Data type	Data content	Sources
First-hand	Interview	Benefits, impacts, and development plans related to biobanks	Experts, scholars, construction units, and the public
	Official	Development and strategic planning of domestic and international biobanks, management and governance policies, management regulations for large research infrastructure of the Chinese Academy of Sciences, progress in the construction of public infrastructure of the Chinese Academy of Sciences, scientific research achievements, international collaboration, etc.	Official websites of governmental bodies, domestic and international biobanks, and the Chinese Academy of Sciences
Second-hand	Literature	Relevant literature on the evaluation of benefits of large-scale research infrastructure and biobanks	China National Knowledge Infrastructure (CNKI), Web of Science, etc.
	Online	Application cases, technology promotion, science popularization activities, etc. of biobank achievements	Social media coverage, related conferences or lectures, WeChat tweets, etc.

(2) Selection of research subjects

Grounded theory emphasizes the breadth and depth of data sources, requiring interviews to encompass all stakeholders. This study selects interviewees from the perspective of research infrastructure stakeholders, including core, potential, and peripheral stakeholders. Taking into account various phases such as construction and ongoing maintenance operations (Wang *et al*., 2020), the following five types of interviewees are chosen:

A. Experts involved in research concerning biobanks and biological samples, including representatives from collaborative institutions such as enterprises and institutions, who have unique insights into the scientific value and application potential of biobanks.

B. Graduate and doctoral students trained in the biobank, who can provide intuitive insights and underlying data information about the social benefits of the biobank.

C. The personnel of the construction unit, who have practical experience and profound understanding in the construction and operation of the biobank, and can provide constructive suggestions for comprehensive benefit evaluation.

D. Professionals engaged in the operation and management of biobanks, who have a more objective understanding of the costs and benefits of biobanks.

E. The general public, who as potential beneficiaries of biobanks, has direct feelings and opinions on the protection and utilization of biological resources, which is equally crucial for comprehensive benefit evaluation.

(3) Interview data collection

Data collection is conducted through face-to-face interviews, discussions, or remote video interviews via Tencent Meeting. The interview period spans from January to March 2024, with 93% of the participants holding a master's degree or higher. Additionally, 63% hold senior professional titles or above, and 60% are experts from germplasm bank and gene bank, all of whom have worked for more than 3 years. A set of broad open-ended questions are designed in advance, and then the interview questions are focused so that they can trigger detailed discussions for developing an interview outline. After that, the interviews are conducted with the selected interviewees from experts, students, the public, and other individuals based on the interview outline. The sample distribution is shown in Table 2, resulting in a 179,000-word interview data.

Table 2
Basic information of the interviewees.

Interviewees	Work engaged in	Number	Percentage
Experts conducting related research	Research related to biological samples, research in research institutions, and university teachers	26	56%
Graduate and doctoral students trained in the biobank	Research in universities or research institutions	3	7%
Construction units	Construction of large-scale research infrastructure, biobanks	4	9%
Operation and management personnels of the biobank	Administrative, financial, management, or maintenance work	5	11%
General public	Public officers, teachers, and students	8	17%

3.1.3. Data coding

(1) Open coding

Open coding is a crucial stage in the research process, involving a thorough analysis and organization of the raw textual data collected. This process includes a systematic categorization and summarization of pertinent literature and textual content derived from interviews. By employing this method, researchers are able to pinpoint key ideas within the text and further distill them into more abstract, higher-level theoretical constructs. This study obtains a total of 156 textual materials, including 46 interview transcripts, 75 domestic and international literature pieces, and 35 materials sourced from relevant lectures and online searches. Through the analysis of the primary data and the arrangement of recurring and irrelevant statements, relevant concepts pertaining to the comprehensive benefits of biobanks are preserved. These concepts are then summarized and categorized, resulting in 22 initial concepts, with the corresponding original statements for some of these concepts presented in Table 3.

Table 3
Open coding.

Representative statements of the original data	Categorization
"The national gene bank is constructed in two phases, with the first phase investing 780 million CNY." "The construction of the germplasm bank database and artificial intelligence platform is also worth 10 million CNY. Currently, we have spent over 7 million CNY in the first phase of equipment procurement, mainly for storage and computing power, in order to build a big platform for artificial intelligence data." … …	A1 Platform construction investment A2 Construction period investment
"The operating expense plan mainly includes the basic operating expenses or those required for daily operation, including direct consumption, indirect consumption, equipment maintenance, etc." "We are the information center of the institute, mainly responsible for IT support	A3 Equipment maintenance A4 Support investment

Table 3. (continued)

services for the germplasm bank." … …	
The Chinese National Gene Bank has established strategic partnerships with over 100 organizations and research institutions, including the Consultative Group on International Agricultural Research, the American Museum of Natural History, the International Association of Biobanks and Sample Banks, the Norwegian Apocalypse Seed Bank, and the Food and Agriculture Organization of the United Nations, to conduct collaborative research in areas such as human health, biodiversity, agricultural development, and biological evolution mechanisms (Cui, 2016). … …	A5 Collaborative network
According to the reports by the Biobanking and Biomolecular Resource Research Infrastructure (BBMRI), the management and biobank expertise account for 60% to 80% of the cost (Yuille *et al*., 2017). "Our germplasm bank requires approximately 1.5 million CNY in electricity consumption for one year of operation." "The operating expenses of the germplasm bank account for almost 70% of the total expenses, including the labor and maintenance costs involved in sample collection, processing, storage, etc." … …	A6 Operation and management overheads
Due to the significant initial investment and long capital recovery cycle of the biobank, it is also necessary to pay attention to its financial management, including that during the construction and operation periods, financial management on project investment, internal value (profit) distribution management, and daily operation financial management (Wu *et al*., 2022). … …	A7 Financial management
China National Gene Bank … provides database services for precision medicine in maternal and child health (Cui, 2016). The China Marrow Donor Program still has significant room for development in the overall scale, technological level, and application fields, which can play a greater role in maintaining people's life, health, and safety (Shu, 2022). "Collection and preservation services for national germplasm security." Only by diversifying the means of protecting species can humans make conservation more reliable. What should we do if a nature reserve encounters a fire, frost disaster, or pest infestation? The germplasm resource bank can effectively solve the problems of natural disasters and germplasm degradation (Wang *et al*., 2021). On January 24, 2020, the National Pathogen Resource Center released the information of the first virus strain in China successfully isolated by the Institute of Viral Disease Prevention and Control of the Chinese Center for Disease Control and Prevention, its electron microscope image, the nucleic acid detection primer and probe sequence of novel coronavirus, and other important authoritative information first released in China, and provided shared services (Tian and Wang, 2020). … …	A8 Maintain germplasm safety A9 Maintain life, health, and safety A10 Public health and safety
Ethical codes need to be considered for biobanks, especially when dealing with privacy issues of individual sample sources (Yuille *et al*., 2017). Biobanks should comply with the requirements of the "Regulations on the Management of Human Genetic Resources" for the collection, preservation, utilization, and external provision of human genetic resources, such as obtaining permits and approvals for collection or preservation (Wang *et al.*, 2023). The design of the biobank laboratories should ensure that the level of protection against biological, chemical, radiation, and physical hazards is controlled at an evaluated acceptable level to prevent harm to the environment (Wang *et al*., 2023). … …	A11 Risk and environmental management
The Australasian Biospecimen Network Biorepository Protocols outlined issues related to principles such as consent, privacy, access, processing, storage, collection, and data management (Catchpoole *et al*., 2007). "Biobanks need to comply with relevant laws and regulations, such as the General Data Protection Regulation (GDPR) and other regional data protection laws." … …	A12 Data supervision

Table 3. (continued)

"Support for young researchers returning from overseas to establish companies and engage in research and development in the field of biotechnology, as well as encouraging them to accelerate their research pace and produce results as soon as possible to promote the transformation and application of scientific and technological achievements." "The cell culture technology of Rhodiola rosea demonstrates the enormous potential of extracting and transforming traditional Chinese medicine components into an efficient industrial production process." The marine biobank is an institution that supports the marine biological industry by excavating and transferring useful materials that can be industrialized from marine biological resources, and providing relevant information (Han Hai's Perspective, 2020). "The adoption of the "PPP model" by the National Gene Bank clearly makes the industrialization and commercialization of genetic technology one of its core functions, indicating its commitment to promoting the market-oriented application and development of genetic science." … …	A13 Market-oriented commercialization A14 Industrialization
"Our germplasm bank also develops some technical methods and tools." "I would like to highlight the achievements of our team in intellectual property. We hold 10 invention patents and 30 utility model patents. These patents not only represent our innovation capabilities, but also an important component of our germplasm bank assets. We are committed to transforming these patents into actual assets." Haier Biomedical provides a biological sample bank solution for China Bone Marrow Bank (Haier Biomedical, 2008). … …	A15 Technological innovation A16 Patented technology
"We have recruited nearby villagers for simple germplasm screening, processing, and other work." Standardized and high-quality biobanks play an irreplaceable role in the development of the bioeconomy (Qingdao High-tech, 2022). … …	A17 Economic growth, driving employment
"Seeds are distributed to universities, research institutions, and enterprises for research and development, with the contribution being generally acknowledged in the acknowledgements section in the generated research papers and other achievements." "We also make some research achievements in our own projects in the germplasm bank." European and American institutions pay higher attention to biobanks and have achieved more research results, with those highly cited research laying a foundation for sustainable development of biobank research (Gao *et al*., 2021). … …	A18 Research achievements
In addition to open to scientists around the world for scientific research, this "national treasure"-level research infrastructure is also the best for science popularization and education. Starting from the trial operation stage, these facilities and platforms will be systematically opened to the public for "science tourism" (Beijing Daily, 2021). … …	A19 Promoting tourism
"The organization of public science popularization and science and technology dissemination have been done well, with 80 interviews and news reports on the germplasm bank from central media, plus 30 videos from China Central Television." "We have also published popular science books, such as Seed Ark: The Germplasm Bank of Wild Species, and other popular science articles." "The 'Fuli Palace' has established a seed museum for visitors to learn and tour. … …	A20 Science popularization promotion
"We also conduct some external training at our germplasm bank." The innovation ability of the graduate students in the biobank has been continuously improved after training, and they have achieved remarkable results in various competitions. They have undertaken various innovative training projects, and the	A21 Talent training and development

Table 3. (continued)

students have strong working competence and are greatly accepted by employers (Jiang *et al.*, 2020). … …	
By the end of 2017, The China Marrow Donor Program had stored 2.42 million samples of Chinese hematopoietic stem cells, making it the largest, most diverse, and geographically largest health donor blood sample bank in China (Haier Biomedical, 2024). Storing even a single seed is no simple task; it must adhere to the so-called "3E" criteria, that is, the seed must be endangered, endemic, and economically valuable (Wang *et al.*, 2021). "After seed collection, it needs to undergo a series of processes to test and ensure its viability." … …	A22 Value of stored samples

Note: The data are sourced from interviews, literature, or online materials, with interview content indicated by quotation marks (" ").

(2) Spindle coding

The main function and purpose of spindle coding is to analyze the relationships between relational categories, sort and summarize them, and merge several relational categories into a main category. In this part, the study analyzes and organizes the 22 relationship categories obtained from Table 3, and further abstract them to obtain 6 main categories eventually. The specific relationship categories and their corresponding main categories are shown in Table 4.

Table 4
Spindle coding.

No.	Main categories	Relationship categories
1	**Construction and operation investment**	A1-2 Infrastructure construction investment
		A3-4 Maintenance and support investment
		A6 Operation and management overheads
2	**Supervision investment**	A7 Financial management
		A11 Risk and environmental management
		A12 Data protection and compliance
3	**Strategic value**	A8-10 Safety impact
		A22 Preservation value
4	**Scientific benefits**	A5 Collaborative network
		A18 Research achievements
5	**Economic benefits**	A13-14 Development of industrial services
		A15-16 Value of spin-off products
		A17 Economic growth, driving employment
6	**Social benefits**	A19 Promoting tourism
		A20 Science popularization promotion
		A21 Talent training and development

(3) Selective coding

The main purpose of selective coding is to integrate the main categories, extract the core categories, and initially form a theoretical model. This study repeatedly refines the original text to extract the two core categories of cost and benefit, and describes the corresponding relationship categories according to cost and benefit. The structural dimensions of comprehensive benefit evaluation indicators for biobanks are shown in Fig. 2. The comprehensive benefit indicator system of the biobank maximizes the scientific, economic, and social benefits through balancing construction and operation costs, while ensuring compliance and sustainable development of the biobank through regulatory costs. These indicators are interdependent and collectively reflect the long-term contribution of biobanks in promoting scientific innovation, economic growth, and social welfare.

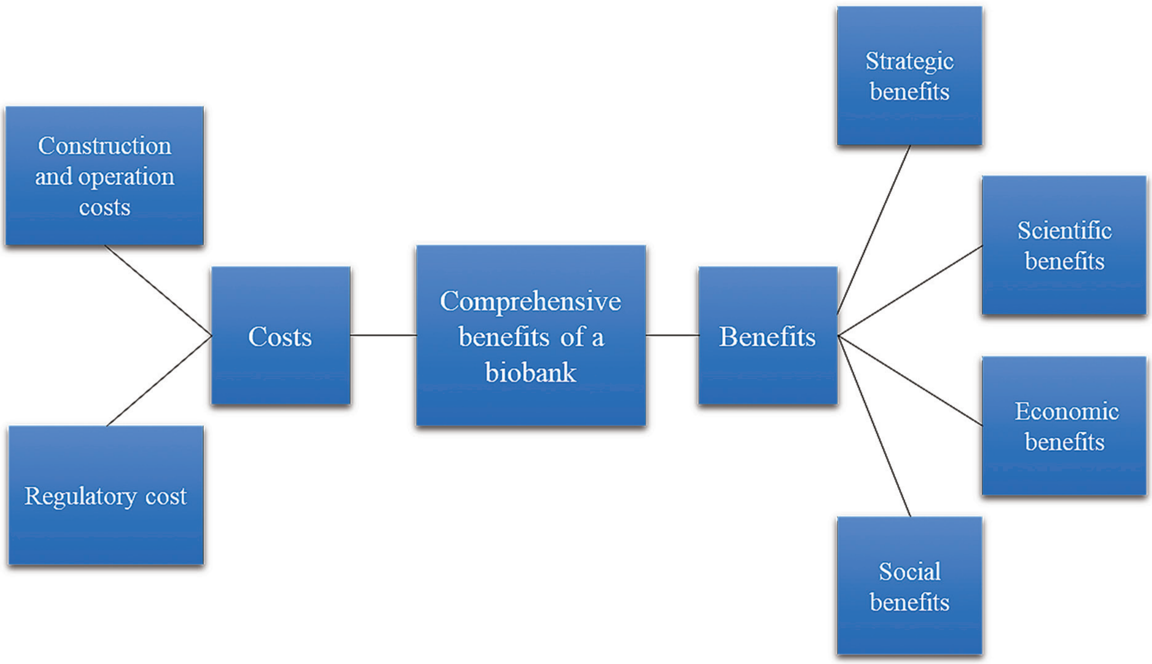

Fig. 2. Structural dimensions of comprehensive benefit evaluation indicators for biobanks.

3.1.4. Saturation check

Jia and Tan (2010) propose that when newly collected data no longer elicits new concepts, categories, or relationships, and the extracted concepts can fully explain both existing and new data, the research of grounded theory has reached a state of theoretical saturation. Based on this theory, this study, on the basis of existing literature, selected five experts and scholars with in-depth research in the field of biobanks for in-depth interviews. Through the organization and analysis of these interview materials, and processing them according to the aforementioned coding procedures, we find that no new categories are generated, and the results are consistent with previous analyses. This indicates that the "comprehensive benefit evaluation indicators for biobanks" constructed in this study have met the requirements of theoretical saturation, and its scientificity and applicability have been verified.

3.1.5. Reliability and validity testing

In order to ensure the objectivity and reliability of the coding process, this study adopted a dual coding strategy, that is, two independent researchers coded the interview data back to back. This dual coding method helps to reduce the influence of individual subjectivity on coding results, and improves the consistency and accuracy of data coding. In addition, we also carried out the reliability test among coders, and ensured the reliability of the coding results by calculating the coding consistency ratio, which reached more than 90%.

This study uses a questionnaire survey to verify the rationality of the above evaluation indicators. The survey mainly targets practitioners, experts, scholars, and students in the field of biobanks. A sample of 81 participating people are surveyed, of whom 66.67% (or 54) are biobank research and technical personnel, 87.66% (71) have a master's degree or above, 48.15% (39) are research scientists, 34.57% (28) are technical personnel, 12.35% (10) are administrative management personnel, 74.07% (60) have intermediate or senior professional titles, and 82.72% (67) have worked for 3 years or more.

The questionnaire adopts a 5-level scale of "unimportant, generally important, important, relatively important, and very important" with corresponding score from 1 to 5, and participants score each indicator one by one. Statistical analysis is conducted on the questionnaire, and the final scores are shown in Table 5. The importance of the indicators in the evaluation system is relatively high. To further demonstrate the rationality of the indicator system, an analysis of the questionnaire reliability and validity is conducted, resulting in a Cronbach's alpha coefficient of 0.917, which is greater than 0.8, indicating that the indicator system has good internal consistency. The Kaiser-Meyer-Olkin (KMO) value is obtained as 0.771, greater than 0.7, which indicates that there is no significant difference in the degree of correlation between variables, and the data is very suitable for extracting information. Additionally, the p-value of the Bartlett's sphericity test is less than 0.001, suggesting that the questionnaire has good structural validity. In summary, based on the aforementioned analysis, the evaluation indicators derived from grounded theory have good reliability and validity and can be applied to the research on the comprehensive benefit evaluation of biobanks.

Table 5
Average score of indicators.

Evaluation indicator	Indicator score
Construction and operation costs	4.51
Regulatory costs	4.45
Strategic benefits	4.66
Scientific benefits	4.48
Economic benefits	3.95
Social benefits	4.12

In the existing biobank comprehensive benefit evaluation practice, most of the research focuses on quantitative analysis, and the theoretical basis and deep influencing factors of the evaluation system are insufficient. Through the application of grounded theory, this study deeply discusses the theoretical basis of the construction of evaluation indicator system, emphasizes the internal relationship and interaction between evaluation indicators, and provides a more comprehensive perspective for evaluation practice. Especially in the context of the rapid development of biobanks, the evaluation system of this study not only reveals the complex relationship between evaluation indicators and biobanks' benefits, but also points out the possible blind spots in the existing evaluation practices in terms of risk management, ethical considerations and data supervision. At the same time, strategic benefits are considered, and it provides strategic guidance and decision support for the long-term development of biobanks. In addition, the evaluation system of this study also provides a new theoretical framework and research direction for the comprehensive benefit evaluation of biobanks in the future, especially in the aspects of promoting biodiversity conservation, promoting scientific and technological innovation, and strengthening international cooperation.

3.2 Construction of evaluation model

3.2.1. Evaluation methods

The comprehensive benefit indicator system structure for biobank evaluation is consistent with the cost-benefit analysis (CBA) method. This study referred to the framework of social cost-benefit analysis (Florio, 2019), and based on the theoretical construct results, additional regulatory compliance costs are added to the cost side, strategic benefits are considered in the benefit side, and the content and method of the original measurement are improved, such as considering the cooperative network effect in scientific benefits.

The CBA is widely used by governments and economists to evaluate the socio-economic impact of investment projects. It requires predicting inputs, outputs, and their marginal social value (MSV) to determine the expected net present value (NPV) of the project. The NPV, as a core indicator for assessing the economic rationality of research infrastructure projects, evaluates the net contribution of the project to social welfare over the entire time horizon by adjusting the future benefits and costs for the time value based on the social discount rate. Generally speaking, the condition for investment projects to pass the CBA test is NPV=0.

The expected NPV of the biobank within a given time domain j is:

$$E(NPV_j) = E[DB_j\text{-}DC_j] \tag{1}$$

where DB_j and DC_j are the cumulative sum of discounted social costs and benefits over the lifespan of a biobank, respectively. Social costs (DC_j) include not only construction and maintenance expenses (CM_j), but also regulatory compliance costs (RC_j).

According to the comprehensive benefit evaluation indicator system of the biobank constructed earlier, the benefits of the biobank include four parts: strategic benefits (ST_j), scientific benefits (SC_j), economic benefits (EC_j), and social benefits (SO_j).

By incorporating costs and benefits, equation (1) can be rewritten as:

$$E(NPV_j) = E[(ST_j+SC_j+EC_j+SO_j) - (CM_j+RC_j)] \tag{2}$$

3.2.2. Cost evaluation

(1) Construction and maintenance costs

Construction and maintenance costs (CM_j) are defined as the cash outflows directly paid by the management agency of a biobank for the design, construction, operation, maintenance, and updating of the biobank, including fixed and variable costs. Fixed costs generally include depreciation, amortization, repair, maintenance, wages and benefits (excluding piece-rate wages), and other expenses. Typically, all interest incurred during the operational period is also considered as a fixed cost. Variable costs mainly include purchased raw materials, fuel and power costs, piece-rate wages, and other expenses.

(2) Regulatory compliance costs

The regulation of policy environment will limit the income and expenditure of biobanks, resulting in regulatory compliance costs (RC_j), including management and ethical costs. The management cost of a biobank includes human and material resources invested in sample and data quality, intellectual property protection, risk control, and other aspects to ensure the quality and safety of operations. The ethical cost of human biobanks includes the investment of ethical resources such as informed consent, privacy protection, and ethical review, ensuring the rights of sample donors and the ethical compliance of research projects.

3.2.3. Benefit evaluation

(1) Strategic benefits

Strategic benefits (ST_j) emphasize the long-term benefits and value obtained from a national strategic perspective, reflecting the long-term contribution of biobanks to promoting scientific research, technological innovation, and industrial development, as well as their importance in strategic resource reserves and knowledge accumulation, including biodiversity conservation, ecological security maintenance, and support for medical and health progress.

Based on the grounded theory findings, strategic benefits include preservation benefits and security benefits, among which preservation benefits include indicators such as sample diversity and rarity, representativeness and coverage, data availability and integrity. Security benefits include food security, public health security, etc. The benefits from preservation can be measured in three ways. First, it can be discounted to present value by converting the expected future scientific discoveries and commercial applications into current value using the discounted cash flow method. The second is to evaluate the value of biological samples such as rare species and flagship species, and obtain willingness to pay (WTP) based on expert views and questionnaire survey (Li *et al*., 2024). Third, according to the idea of Echia *et al*. (2021) to estimate the time cost of data resource users, the storage benefit can be estimated by using the product of the average salary of biological resource users and the collection time saved.

Considering the importance of human samples and non-human biological samples, security benefits include food security benefits and public health security benefits. A country's food security depends on germplasm resources (Zhang *et al*., 2021). Since the social benefits of food security are difficult to measure with specific data, it is usually chosen to measure the benefits of food security with farmers' income from grain production related to grain yield (Dai, 2015; Long and Su, 2007). In this study, the food security benefits of the biobank are the increased income of farmers who receive support from the biobank resources (biological resources, technical support, professional guidance, etc.).

Drawing on the relevant research of Farla *et al*. (2016), Giffoni and Vignetti (2019), STFC (2018), and Wang *et al*. (2020), this study examines the benefits of public health safety from two aspects: (1) the ability to handle and respond to public health safety issues, represented by data such as medical staff allocation, number of public health incidents, and response situations; (2) The ability to collect and forecast information on public health events is characterized by the number of emergency plans for public health events and the corresponding forecast situation. Security benefits can be evaluated through "willingness to pay" surveys.

(2) Scientific benefits

Scientific benefits (SC_j) are mainly reflected in the contribution of biobanks to scientific research. Building upon the coding results of grounded theory, this study predominantly assessed the spillover effects of research outcomes and the collaborative network. Among them, research outcomes include scientific achievements generated by the biobank through its own research activities and by providing resources to support external research. The internal and external achievements are identified using authorship institutions and acknowledgements. Spillover benefits are measured by the yearly value of citations and secondary citations, which depend on two variables: the number of primary and secondary citations and the value of citations. According to the marginal cost method, this value represents the opportunity cost of the time the researcher spends reading the cited paper (Morretta *et al*., 2022).

By establishing a collaborative network, the biobank promotes scientific exchange and collaboration, enhances scientific value and sustainability. By increasing the number and quality of collaborative institutions, as well as boosting network influence, it enhances its scientific research status and sustainable resource supply capacity, reflecting its indirect contribution in scientific collaboration. Papers published inside and outside biobanks were collected, and quantitative and qualitative methods were combined to measure the impact of teamwork and institutional cooperation on the scientific outcomes of biobanks (Zhang *et al*., 2019a). Interviews were used to explore specific cooperation patterns and contribution values, and time cost savings were estimated through improved efficiency.

(3) Economic benefits

Economic benefits (EC_j) refer to the direct and indirect economic activities and returns created by a biobank on a certain scale. Economic benefit indicators can be selected from indicators such as revenue promotion, innovation, entrepreneurship, direct and indirect employment, and can be specifically divided into spin-off product benefits and industrial service benefits. The revenue of spin-off products is measured by evaluating the value of patents, software, and other assets. The revenue from industrial services is calculated using the contract amounts of commissioned services provided by the biobank to the industry.

(4) Social benefits

From the results of grounded theory analysis can be inferred, social benefits (SO_j) encompass the contributions of biobanks in enhancing public scientific literacy, popular science promotion, and talent cultivation. This includes organizing science popularization activities, opening on-site visits for science popularization, enhancing public awareness and interest in biological science, and cultivating professional talents in the field of biological science through training and educational projects, which can be specifically divided into science popularization benefits and talent cultivation benefits. The focus of science popularization benefits is on the exhibition benefits of biobanks and their spillover effects, which are calculated by applying the travel cost method (Brown and Mendelsohn, 1984; Carson, 2012).

The benefits of talent cultivation are estimated by comparing the expected salary of early career researchers who work or study in the upstream and downstream activities of the biobank with the counterfactual expected income without such practical experience. This framework allows the expected present value of human capital and social accumulation benefits to be defined as the total expected increase in income for early career researchers from departure from the program to the end of their career (Catalano *et al*., 2021).

3.2.4. Cost and benefit forecast

The Monte Carlo method is the standard method for economic evaluation of infrastructure projects (Bastianin *et al*., 2023; European Commission, 2014; Florio *et al*., 2016; Salling and Leleur, 2011), because it allows for estimating the expected value of the variables of interest, provided that the residual error of the probability density function (PDF) of the input variables is assumed and the limit of the Monte Carlo error is zero in the case of infinite sampling.

Generally speaking, for past data and minor items, the baseline is considered deterministic. While for key predictions, a PDF is assigned based on sample information or expert evaluation of the possible range of values around the baseline. In practice, only some key variables need to be considered random (European Commission, 2014). For 2 costs and 4 benefits given, the hypothetical PDF can be evaluated based on expert data. To simplify calculations, it is usually assumed that a normal distribution is adequately represented by a triangular PDF (with maximum, minimum, and model values, but not always with a symmetrical tail). But in other cases, this study suggests that using different distributions are more appropriate. This study has tested that using truncated normal distributions or other continuous PDFs within a fixed range does not significantly alter the results. Finally, by running a Monte Carlo simulation with 10,000 random variable conditions, a PDF with the same net present value (NPV) as expressed by equation (2) is obtained.

4. Case Study

Germplasm resource banks play a key role in biodiversity conservation, highlighting their importance in ensuring ecosystem health and human well-being, as well as their central position in achieving the United Nations Sustainable Development Goals and national biodiversity conservation strategies, particularly in the strategic significance of promoting ecological civilization and safeguarding public health in China.

The Germplasm Bank of Wild Species (hereinafter referred to as the Germplasm Bank) is a national major scientific project construction plan, which is jointly built by the Chinese Academy of Sciences (CAS) and Yunnan Province, relying on the Kunming Institute of Botany under CAS. The Germplasm Bank project has a total investment of 148 million CNY and started construction in March 2005. It was initially completed and put into trial operation in 2007 and passed the national acceptance in November 2009. The overall scientific goal of the construction of the Germplasm Bank is set in line with the comprehensive benefit evaluation indicators of the biobank. Therefore, this study selects the Germplasm Bank as the empirical object for case study to analyze its annual trend and scale of the indicators since operation through adjusting and improving the evaluation indicator system based on its characteristics.

Based on the comprehensive benefit evaluation indicator system and evaluation model of the biobank, this study evaluated the costs and benefits of the Germplasm Bank. Due to factors such as the applicability of indicators, availability of data, difficulty in quantifying indicators, and limitations in research scope, this study mainly evaluates the construction and maintenance costs, as well as scientific benefits, preservation benefits in strategic benefits, industrial service benefits in economic benefits, and talent cultivation and science popularization benefits in social benefits. The data required for cost and preservation, industrial service and talent cultivation benefits are obtained from the financial management, human resources, science and technology management, germplasm collection and other departments of the germplasm bank; the data required for scientific benefits are from the Web of Science database; and the data required for science popularization benefits are from the Fuli Palace.

Specifically, regarding the conservation benefits, this study conducted a systematic survey and interviews with frontline staff, revealing that collection costs account for a significant proportion of the costs in the Germplasm Bank, while the costs for subsequent processing and storage are relatively low. Given the specific conditions of the empirical research and the availability of data, the calculation of conservation benefits was not further subdivided into diversity, rarity, representativeness, and availability benefits. Instead, a more direct and operational approach is adopted. That is, the human labor cost incurred in collecting germplasm resources is estimated as a savings in the user's time cost to calculate the preservation benefit. The industrial service benefits are primarily reflected in the indirect technical guidance and support provided by the Germplasm Bank to industries and the economy, and are mainly represented by the total annual value of service contracts undertaken by the biobank for enterprises. The science popularization benefits are considered in light of the fact that the statistics on visitors to the Fuli Palace began in 2023, resulting in a lack of historical data from previous years. Therefore, only the science popularization benefits of the Germplasm Bank for 2023 are calculated to provide a reference for future research discussions. In this study, the cost and four benefits are calculated respectively according to cost and benefit evaluation (for the details see 3.2.2 and 3.2.3), and the subsets of benefits (such as the benefits of science popularization and talent cultivation) are added and calculated, and then the net present value are calculated according to formula 2. The specific evaluation results of costs and benefits are shown in Table 6.

Table 6
Comparative cost-benefit analysis of the Germplasm Bank.

Year	Cost (10 kCNY)	Strategic benefits (10 kCNY)	Scientific benefits (10 kCNY)	Social benefits (10 kCNY)	Economic benefits (10 kCNY)	Net present value (10 kCNY)
2010	997.00	196.73	102.97	94.60	0.00	-602.70
2011	1331.32	229.33	98.93	132.00	0.00	-871.06
2012	1727.40	244.68	103.65	297.00	302.60	-779.47
2013	1890.98	173.56	120.04	215.05	32.90	-1349.43
2014	1937.08	205.45	240.23	389.58	500.00	-601.82
2015	1995.99	159.24	218.56	310.81	255.40	-1051.98
2016	1933.06	221.74	251.94	352.26	310.80	-796.32
2017	1872.53	225.17	265.29	364.32	257.00	-760.75
2018	1863.40	327.46	259.31	495.00	90.20	-691.43
2019	1711.84	229.89	404.02	443.33	141.88	-492.72
2020	2300.87	299.08	662.62	806.08	160.79	-372.30
2021	2151.67	442.94	398.85	1024.20	272.13	-13.55
2022	2575.19	774.19	655.86	1676.76	2223.50	2755.12
2023	2826.26	1190.69	612.03	1493.57	610.84	1080.87

The results show that the Germplasm Bank has achieved a balance between preservation benefits and cost inputs during its initial construction phase, and the benefits have demonstrated exponential growth as they scale up, far exceeding costs. However, the strategic benefits mainly manifest as potential value, which still needs to be further transformed into scientific, economic, and social benefits in the future. Meanwhile, the scientific and economic benefits of the biobank have not shown significant growth in the past five years. In terms of scientific benefits, the output of external research results accounts for a relatively small proportion compared to internal scientific benefits, comprising only 18% of scientific benefits as of 2023. This reflects practical difficulties in areas such as tracking external results and maintaining relationships with high-quality users, as well as issues like a lack of specialized personnel and lagging digital infrastructure. Additionally, there is insufficient systematic planning in terms of collaborations on commercialization and result transformation. Although the Germplasm Bank has a positive impact on popular science services and contributions to the economy and society, the quantification and inclusion of these non-direct economic benefits still face challenges. There is a need to further explore market-oriented operational models to achieve stable growth in economic benefits.

At the same time, this study uses Monte Carlo simulations to predict the development trends of the Germplasm Bank up to 2050 (Fig. 3), with forecasts specifically aimed at 2035 and 2050 (Figs. 4-5). According to the investigation of the current situation of the Germplasm Bank, the collection of germplasm is nearing saturation. Thus, it is assumed that costs and benefits follow a triangular distribution, and the simulation suggests that conservation benefits peaks in 2023, after which the focus of development will shift towards value creation rather than scale expansion. In the future, the cost inputs of the Germplasm Bank are expected to remain stable, while the exploration of its scientific and economic benefits will become crucial for maximizing the utilization and value transformation of conserved resources. Additionally, after 2023, to achieve sustained growth in conservation benefits, efforts should be made to enrich conservation resources through promoting international collaboration and overseas collection, as well as building strategic alliance networks.

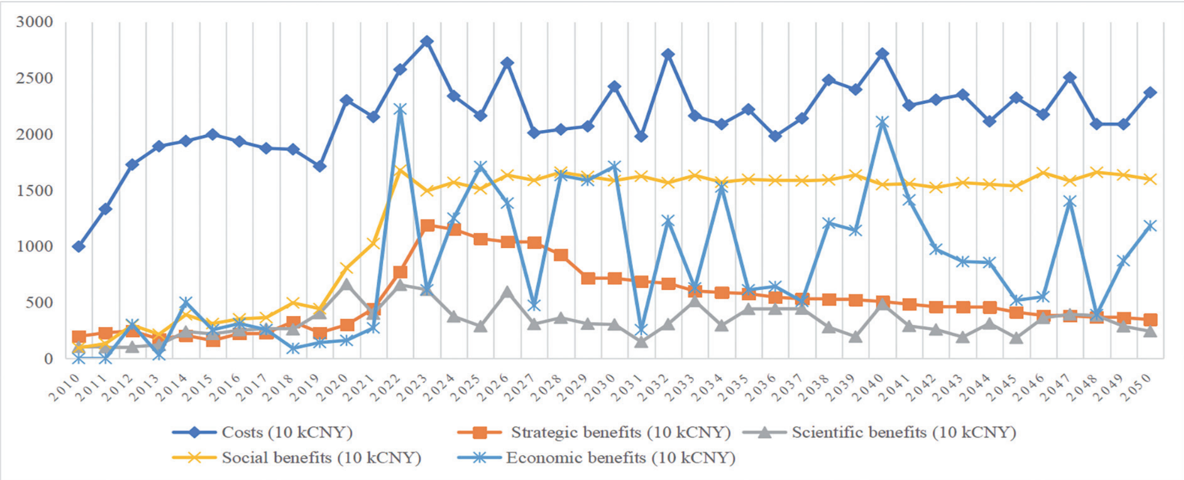

Fig. 3. Cost-benefit simulation of future development of the Germplasm Bank.

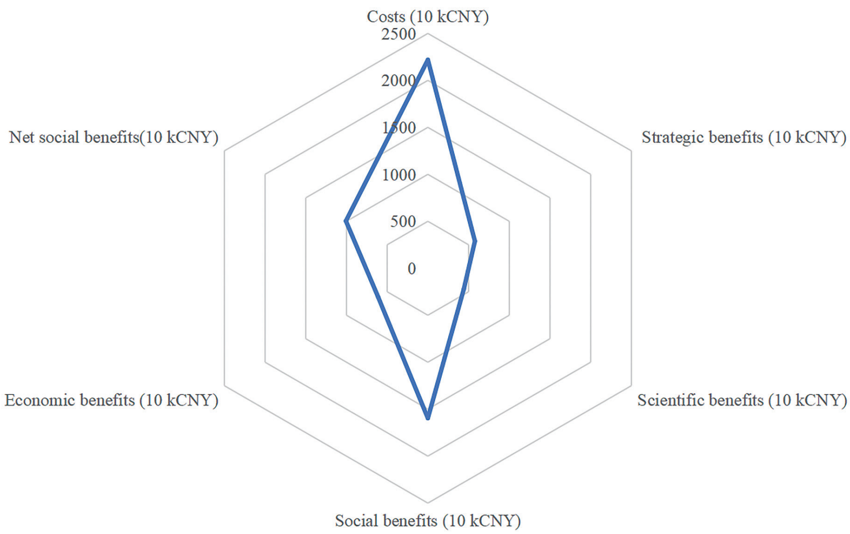

Fig. 4. Radar chart of cost-benefit distribution of the Germplasm Bank for 2035.

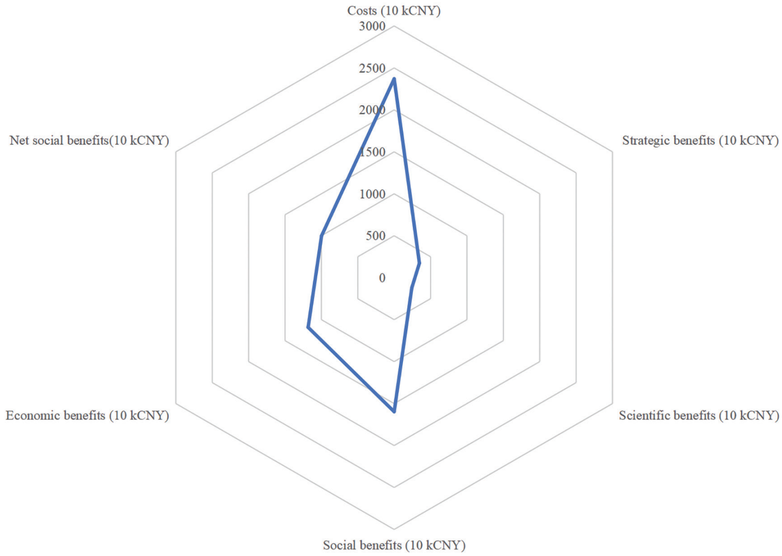

Fig. 5. Radar chart of cost-benefit distribution of the Germplasm Bank for 2050.

5. Conclusion and Suggestions

This study constructed a comprehensive benefit evaluation system for biobanks based on the cost-benefit analysis, aimed at providing decision support for the scientific management of biobanks and the effective utilization of national strategic resources. The application of grounded theory extracts key concepts from actual data and constructs an indicator system that includes construction and operation costs, regulatory costs, strategic benefits, scientific benefits, economic benefits, and social benefits. The Germplasm Bank of Wild Species is taken for empirical research as a case study to comprehensively evaluate its performance in key dimensions of cost and benefit, and predict its development trends in 2035 and 2050 through Monte Carlo simulations.

The results show that although the biobank has achieved significant achievements in preservation, scientific research, talent cultivation, and made important contributions to biodiversity conservation and sustainable development, it still has shortcomings in preservation gains, external scientific benefits, achievement transformation, and market-oriented commercialization. It thus needs to optimize its cost structure and continue to explore its strategic, scientific, economic, and social benefits.

In response to the problems identified in the comprehensive benefit analysis of the biobank, this study proposes three improvement strategies, namely, preserving capital while enhancing efficiency, increasing both capital and efficiency, and reducing costs while enhancing efficiency, in order to optimize the overall benefits of the biobank. First, in terms of capital preservation and efficiency improvement, it is recommended to maintain cost stability by optimizing resource allocation and improving operational efficiency, while enhancing the core scientific research and educational functions of the biobank. This requires sorting out existing processes, eliminating inefficient links, and improving automation levels through technological upgrades.

Second, in order to achieve increasing both capital and efficiency and reducing costs while enhancing efficiency, it is recommended to adopt a dual-track strategy. On the one hand, it is necessary to increase investment in scientific research and technological innovation, especially in international collaboration, by establishing partnerships with global research institutions and biobanks, sharing resources, and conducting joint research. It can not only reduce research and development costs, but also accelerate the international application of scientific research results. On the other hand, by strictly controlling costs and improving the conversion rate of results, unnecessary expenses can be reduced while increasing efficiency. This includes strengthening intellectual property protection, ensuring that biobanks receive due returns from their scientific research achievements, and increasing public participation through science education to enhance social awareness of biodiversity conservation.

Through the implementation of these comprehensive measures, the biobank can more effectively utilize existing resources while enhancing its contribution to scientific research and social development. This will not only help enhance the sustainable development capability of the biobank itself, but also bring broader economic and social benefits to society.

This study still has some limitations: the current research validates the effectiveness of the proposed indicator system through empirical analysis of only one single case, which may limit the generalization of results for broader applications. Future research needs to expand the depth and breadth of the empirical study through employing multiple case studies, including evaluating different types of biobanks. In addition, the sample selection bias and data accessibility issues encountered in data collection in this study suggest that future research needs to improve data acquisition strategies to enhance the accuracy and universality of the research results. In terms of cost estimation, especially the insufficient evaluation of regulatory compliance costs, it indicates the need for further development and improvement of cost structure evaluation models. Finally, based on the completed research results, future studies shall systematically investigate international regulatory policy experiences to improve the biobank regulatory system in China and promote the high-quality development of biobanks. At the same time, it is needed to conduct in-depth analysis of the operating costs and benefits of the biobank as well as the dynamic transformation mechanism between them, and explore scale economy effects to guide the rational layout and scale expansion of the biobank. It is also needed to explore the sustainable development path of the biobank from multiple perspectives to promote the implementation of sustainable development concepts for biobanks.

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