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Investment Decision Model for Local Government Waste Disposal Projects Based on Entire Life Cycle Cost Analysis

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Abstract: When investing in waste disposal projects, local government faces a critical dilemma: how to move beyond short-term cost evaluation to long-term environmental and economic benefits. Therefore, this research focuses on local government waste disposal projects, using a life cycle cost analysis to construct a comprehensive evaluation model that integrates energy, environment, and economy, and to analyze the system performance and comprehensive benefits of the proposed technological transformation plan. The results indicated that the total life cycle cost of processing one ton of tail vegetables was -97.05 Chinese Yuan (CNY), of which the internal cost was -85.04 CNY and the external environmental cost was -12.01 CNY. Sensitivity analysis revealed that government subsidies and processing benefits were the most sensitive factors affecting total costs. In terms of environmental impact, this technology route generated significant benefits across key indicators, including global warming potential and acidification potential, through biogas recovery and utilization. Its global warming potential reached -49.88 kg CO_2 eq/t, significantly better than that of the original project. The energy analysis confirms that the system is a net energy producer, but the amount of biogas generated is the most sensitive parameter for its energy performance. This model effectively evaluates the long-term operational efficiency of waste disposal projects, provides a quantitative basis for local governments in project planning, process comparison, policy formulation, and improves the accuracy and sustainability of public investment.

Keywords: Waste disposal, entire life cycle, cost analysis, energy consumption, environmental impact.

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1. Introduction

In the process of modernizing the environmental governance system, scientific investment in waste disposal projects is a key priority for local government to optimize public resources, thereby directly affecting the efficiency of public funds and the long-term environmental goals. Among the various types of garbage generated in cities, tail vegetables, as an important component of urban organic waste, require significant treatment. Tail vegetables have a tendency to decay quickly and have a high moisture content. Improper management during collection, transportation, and processing can easily cause secondary pollution and increase the burden on public finances (Sarker et al., 2024). Tail vegetable disposal is primarily achieved through resource utilization, turning waste into treasure. Treatment methods include organic fertilizer conversion, feed processing, and biomass energy development. Various models have been formed in practice in various regions. Therefore, promoting the scale and resource utilization of such garbage is not only an inevitable requirement for achieving sustainable urban and rural development, but also a key link for local governments to optimize public investment efficiency (Osman et al., 2024). At present, the Tail Vegetable Disposal Project (TVDP) that has been operated in China generally adopts resource utilization technologies such as anaerobic fermentation. However, in actual operation, it often faces bottlenecks such as insufficient system stability, low energy efficiency, and high operating costs. These challenge's have made it difficult for the project to continue stable operation, both economic and environmental benefits have not met expectations, directly affecting the long-term effectiveness of public investment (Kohli et al., 2024). Especially for local government, the lack of scientific decision-making tools that comprehensively consider construction costs, operational energy consumption, environmental benefits, and policy dependence in the early stages of projects often leads to insufficient investment decision-making basis and weak risk controllability (Duan et al., 2024).

Many researchers have adopted the Life Cycle Assessment (LCA) method to evaluate the environmental impacts and economic benefits in different fields. This plays a crucial role in economic decision-making. For example, Nordahl and Scown (2024) improved the LCA method by reconstructing the Functional Unit (FU), system boundaries, and alternative scenario assumptions to better achieve plastic recycling LCA. They have proposed that evaluating the number of recycled products could accurately and efficiently reflect the environmental benefits of the plastic circular economy. Results showed that this method was feasible (Nordahl and Scown, 2024). Atescan-Yuksek et al. (2024) used the LCA method to analyze the impact of various carbon fiber composite materials on the environment during the manufacturing, operation, and disposal stages. The break-even distance showed that carbon fiber composite materials were more effective (Atescan-Yuksek et al., 2024). Hübner et al. (2024) proposed a machine learning cloud service and LCA method to analyze the entire sales process and optimize it for predicting food. The return volume of this method has been reduced by an average of 30% (Hübner et al., 2024). Luthin et al. (2024) developed a life cycle sustainability assessment framework to identify trade-offs among the environmental, economic, and social aspects of circular economy strategies. The framework was evaluated using four dimensions: LCA, Life Cycle Cost (LCC), social LCA, and cycle assessment. The results of a systematic screening of material, product, and life cycle indicators confirmed the framework's practicality (Luthin et al., 2024).

In terms of waste disposal, many professionals have adopted different LCA methods and achieved good results. Among them, Ferronato (2024) used the LCA method, SimaPro software, and the Ecoinvest database to verify the effectiveness of black soldier fly larvae in treating organic household waste. They compared the environmental impacts of different schemes and identified key parameters through sensitivity analysis. The results showed that black soldier fly farming could achieve better environmental performance (Ferronato et al., 2024). Üstün Odabaşı and Laratte (2024) analyzed the potential environmental impacts of various solid waste management schemes across cities using the LCA method. The results showed that the scheme that did not support material recycling had the worst environmental performance, while the scheme that classified recyclables and organic waste at the source was the most environmentally friendly. Environmental impacts were highly sensitive to transportation emissions and raw material recovery rates. (Üstün Odabaşı and Laratte, 2024). Walker et al. (2024) combined LCA and actor network theory to enhance LCA's applicability in inter-enterprise networks, focusing on tableware use. The results show the method was sustainable. Cheng et al. (2025) conducted LCA analysis on the environmental impacts of four resource utilization pathways for kitchen waste and found that lactic acid fermentation can better reduce environmental impacts.

In summary, for local government waste disposal projects, although existing research has provided various technical solutions, it has not considered environmental, energy, and economic factors. Therefore, this study innovatively applies the LCC Assessment framework to this field by accounting for environment, energy, and economy, and uniformly quantifying multidimensional impacts. To ensure the transparency and reproducibility of the model input parameters, this study combined literature data and field research results to determine the following key benchmark parameters: the typical composition of tail vegetable waste is set as follows: moisture content of 85%, Volatile Solids (VS) accounting for 88% of Total Solids (TS), and Chemical Oxygen Demand (COD) of 250,000 mg/L. The biogas production potential during Anaerobic Digestion (AD) is measured at 100 m^3 of biogas per ton of wet waste, with a methane volume fraction of 60%. In the life cycle environmental impact assessment, the carbon emissions corresponding to electricity consumption are calculated based on the national regional power grid average emission factor of 0.5306 kg CO_2/kWh. The waste collection logistics system uses electric self-loading and unloading garbage trucks with a rated load of 35 tons, serving 30 fixed collection points, with an average collection and transportation distance of 38.5 km, achieving closed transportation throughout the entire process without leakage. The setting of the above benchmark parameters provides a unified and comparable accounting basis for the subsequent quantitative evaluation of LCC and LCA. The research aims to improve the efficiency of household waste disposal, such as tail vegetables, and provide an effective technical solution for the local government's green environmental management decisions.

2. Methodology

2.1. TVDP Scheme Design

For tail vegetables, common disposal methods include composting, Anaerobic Digestion (AD), biotransformation, and incineration power generation (Ichinose, 2024). A TVDP scheme is designed with AD as the main focus. The energy system life-cycle process and environmental impact boundary diagram for this scheme are presented in Fig. 1. The scheme's life cycle comprises three stages: construction, operation, and demolition. Among the three main stages, there are ten steps (S1-S10). To clearly demonstrate the system boundary and material/energy flow, Fig. 1 specifically indicates the initial process stages S1-S3, operational stages S4-S9, and demolition stage S10, and shows the corresponding energy input, material consumption, and pollutant output paths for each stage. Specifically, during the construction phase, stages S1 to S3 involve sequential production, transportation, and construction. The auxiliary energy and building materials used for production, transportation, and construction provide a material foundation for the scheme. The operation phase includes raw material transportation (S4), pre-treatment (S5), anaerobic fermentation (S6), biogas power generation (S7), solid-liquid separation (S8), and aerobic treatment (S9). S4 performs preliminary treatment, such as sorting and crushing, on the collected garbage, and the pre-treated garbage enters the anaerobic fermentation stage to produce biogas (Wikurendra et al., 2024). The process involves transporting garbage and its intermediate products. Biogas is used for power generation and ultimately outputs electricity. During system operation, heat is also produced and can be used for energy utilization or process requirements. Following anaerobic fermentation, the products undergo solid-liquid separation into sludge and slurry. The sludge then proceeds to stage S9, ultimately producing a biogas slurry. This slurry is primarily used as an agricultural byproduct, with other uses as well. The demolition stage is the process of dismantling facilities. When the system reaches the end of its lifespan, facility dismantling will have an environmental impact. Pollutants generated throughout the entire life cycle include soil, water, and air pollutants, reflecting the potential environmental impact range of the system from construction to demolition (Kumari et al., 2024).

This research sets up 1 pre-treatment workshop, 1 anaerobic tank, 6 fermentation tanks, 1 solid-liquid separation workshop, 1 biogas utilization workshop, and 1 aerobic treatment tank. The Energy Consumption (EC) during the construction stage is the total EC E_{sum} generated in stages S1 to S3, as shown in Eq. (1) (Sharma et al., 2024).

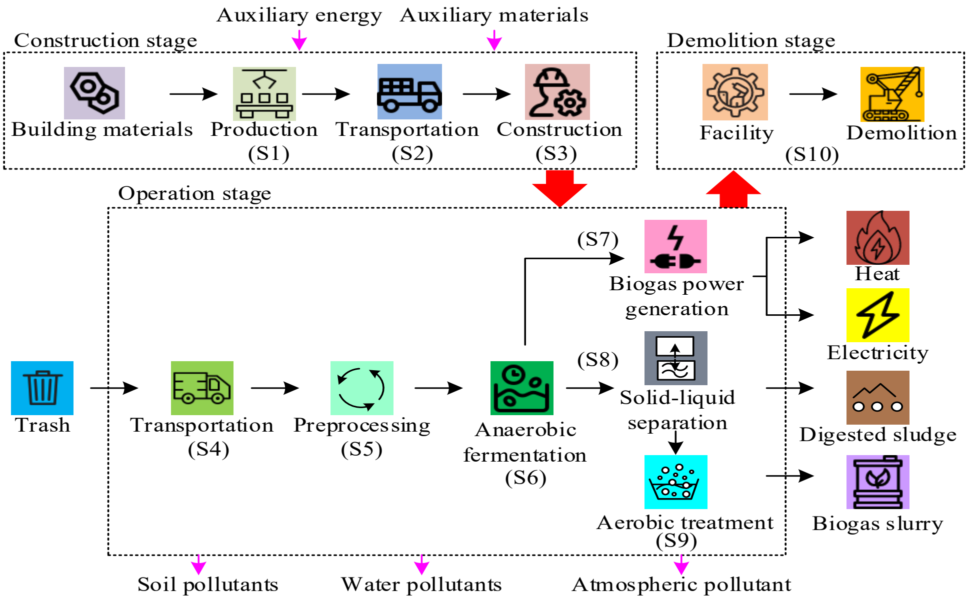


Fig. 1. Energy system life cycle process and environmental impact boundary diagram

$$\begin{cases} E_1 = \sum_{q=1}^{a} u_q^{\text{mat}} \times \left(1 + r_q/100\right) \times E_q^{\text{mat}} \\ E_2 = \sum_{q=1}^{a} u_q^{\text{mat}} \times \left(1 + r_q/100\right) \times E_q^{\text{tra}} \times D_q^{\text{tra}} \times 10^{-3} \\ E_3 = \sum_{w=0}^{b} q_w^{\text{con}} \times E_w^{\text{con}} \times 10^{-3} \\ E_{\text{sum}} = E_1 + E_2 + E_3 \end{cases} \tag{1}$$

In Eq. (1), E_1, E_2, and E_3 are the EC generated by the three stages S1 to 3, respectively. a is the number of types of building materials q. u_q^{mat} is the usage amount of building material q. r_q is the proportion of waste generated by q during the construction process. E_q^{mat} is the unit EC for producing q. E_q^{tra} is the unit EC for the selected transportation method. D_q^{tra} is the transportation distance, and $D_q^{\text{tra}} = 38.5\text{km}$. b is the number of main types involved in the S3. E_w^{con} signifies the unit EC for a certain construction type w. q_w^{con} is the workload for a certain construction type w. In fields such as LCA and cost analysis. FU is the core tool used, and the research employs it to treat 1 ton of garbage (Bachmann et al., 2024). During operation, the S4 stage uses an electric self-loading and unloading garbage truck with a 35-ton cargo capacity. The truck compartment has been sealed to prevent any pollutant leakage during transportation. The transportation route is fixed and covers 30 local vegetable warehouses, with an average transportation distance of 38.5km. The S5 section is equipped with spiral feeders, chain plate machines, iron removers, crushers, and belt conveyors, with 3 sets of each type. The system's processing capacity under full-load operation is 3,000 t/day, with a daily operating time of 12 hours. The total installed power of the equipment reaches 355.5kW (Duong and Nga, 2024). The S6 stage is insulated with waste heat from the biogas internal combustion engine generator set. The effective volume of the fermentation tank is 4.8×10^4 m^3, the temperature is set at 35±2°C, the hydraulic retention time is 24 days, the pH is 7.2, and the stirring rate is 50 r/min. Before entering the power generation stage, the S7 stage biogas needs to undergo desulfurization and decarbonization treatment. The generator set has a rated power of 204 kW and operates continuously for 24 hours. The biogas leakage rate is stable when controlled within 2% (Suwarto et al., 2024). The daily operation time is 12 hours, and the equipment's total power is 666 kW.

2.2. Entire Life Cycle Investment Decision Model

After clarifying the TVDP plan, an integrated investment decision-making model is developed to quantitatively analyze and comprehensively evaluate the environmental, economic, and energy aspects of the TVDP plan. The study uses LCA software eBalance to integrate dispersed energy input, material consumption, and pollutant emissions data across the entire life cycle of TVDP on a single platform. By establishing system boundaries and process relationships, the software can automatically calculate the resource and environmental load of each link, avoiding manual accounting errors. This software converts different impact characteristics into a unified environmental impact indicator, namely Characteristic Indicators (CI). CI has six potential categories: eutrophication, acidification, global warming, photochemical oxidation, human toxicity, and fossil energy consumption potentials (Li et al., 2024). The indicator information is presented in Table 1.

Table 1. Characteristic Indicators

CI number	CI	Unit	$V_{\text{bas}}(t)$	$f_{\text{wei}}(t)$
CI-1	Eutrophication potential	kg PO43- eq	4.8×10^7	30.9×10^2
CI-2	Acidification potential	kg SO_2 eq	5.9×10^7	5.1×10^2
CI-3	Global warming potential	C_2H_4 eq	4.6×10^7	6.27×10^2
CI-4	Potential for photochemical oxidation	kg 1,4-DB eq	3.8×10^7	7.88×10^2
CI-5	Human toxicity potential	kg CO_2 eq	6.4×10^7	23.7×10^2
CI-6	Fossil energy consumption potential	MJ	6.0×10^7	4.42×10^2

In Table 1, the normalized benchmark values and weight coefficients for each CI are set based on the internationally mainstream LCA framework. The specific determination method is as follows: the normalized benchmark value is sourced from the China Life Cycle Basic Database (CLCD), and the national annual per capita environmental impact is used as a reference to convert the characterization results into dimensionless relative impact potential values (Lu et al., 2024). The weight coefficients are determined using a comprehensive weighting method that combines the entropy method and the expert survey method. This method considers both the objective differences of each indicator's data itself and the subjective judgments of domain experts on the importance of different environmental impact categories. The CI is shown in Eq. (2).

$$\begin{cases} V_{\text{pot}}(t) = \sum M_{\text{emi}}(t)_{p,z} \times F_{\text{cha}}(t)_{p,z} \\ V_{\text{nor}}(t) = V_{\text{pot}}(t) / V_{\text{bas}}(t) \\ V_{\text{wei}}(t) = V_{\text{nor}}(t) \times f_{\text{wei}}(t) \end{cases} \tag{2}$$

In Eq. (2), $V_{\text{pot}}(t)$ signifies the characteristic latent value of the t-th type of influence. $M_{\text{emi}}(t)_{p,z}$ signifies the substance z emitted by process p causing t impact type. $F_{\text{cha}}(t)_{p,z}$ is the characteristic factor of $M_{\text{emi}}(t)_{p,z}$. $V_{\text{nor}}(t)$ and $V_{\text{bas}}(t)$ are the normalized latent value and baseline value for the t-th type of influence, respectively. $V_{\text{wei}}(t)$ and $f_{\text{wei}}(t)$ are the weighted value and weighting factor for the t-th type of influence, respectively. The study uses LCC as the economic evaluation index for the system's life cycle. The internal and external costs of the k-stage of the life cycle are C_k^{int} and C_k^{ext}, respectively. The expressions for the two are shown in Eq. (3) (Chopra et al., 2024).

$$C_k^{\text{sum}} = \sum_k \left(C_k^{\text{int}} + C_k^{\text{ext}}\right), \quad C_k^{\text{ext}} = \sum_k \left(P_k + V_k^{\text{env}}\right) \tag{3}$$

In Eq. (3), C_k^{sum} is the total cost consumed by the entire design of the system until its completion. P_k is the monetization parameter for the k-class environmental impact potential. V_k^{env} is the environmental impact potential of the k-class environmental impact category. Due to the need for large amounts of data in the evaluation process, combined with the existing data from field research, the sensitivity of the results obtained using commonly used uncertainty analysis methods in LCA is evaluated. The sensitivity coefficient c_s of the evaluation result R_{res} to the undetermined parameter R_{cha} is shown in Eq. (4) (Salimi and Taherkhani, 2024).

$$c_s = \frac{\Delta R_{\text{res}}}{\Delta R_{\text{cha}}} \tag{4}$$

In Eq. (4), ΔR_{cha} represents the rate of change of R_{cha}. ΔR_{res} is the rate of change of R_{res} when R_{cha} changes ΔR_{cha}. The information on environmental impact factors is presented in Table 2.

Table 2. Environmental impact factors

Environmental impact factors number	Environmental impact factors	Input values during the construction phase	Input values during the demolition phase
F1	Electricity	1.41 kW·h	1.18 kW·h
F2	Natural gas	2.16×10^{-2} Nm^3	3.18×10^{3} Nm^3
F3	Raw coal	18.68 g	5.31 g
F4	Crude oil	90.35 g	22.41 g
F5	Lime	7.19×10 kg	/
F6	Brick	1.28 kg	/
F7	Timber	1.19 kg	/
F8	Stone	2.64 kg	/
F9	Sand	2.12 kg	/
F10	Reinforced steel	1.17 kg	/
F11	Cement	1.46 kg	/

The evaluation indicators for the entire life cycle EC are the energy efficiency ratio and energy utilization, expressed as Eq. (5) (Marrucci et al., 2025).

$$R_{\text{ee}} = \sum_j \sum_m E_{jm}^{\text{out}} - \sum_j \sum_m E_{jm}^{\text{in}} \tag{5}$$

In Eq. (5), j represents different stages in the system. E_{jm}^{in} and E_{jm}^{out} are the input and output quantities of energy in the m-th category for link j. The study constructs an evaluation model based on the designed TVDP scheme and uses the LCA model to comprehensively evaluate the system LCC from three dimensions: economy, energy, and environment, as shown in Fig. 2. Fig. 2 clearly relates the corresponding relationships between the stages S1 to S10 and internal costs (costs 1-9), external benefits (costs 10-13), characterization indicators (CI-1-6), and energy utilization efficiency. Among them, economic costs are related to the economic inputs and outputs of the entire life cycle at two levels: external and internal costs, spanning all stages, to assess economic feasibility and cost-effectiveness. Internal costs include construction, equipment, installation, transportation, depreciation, maintenance, energy, labor, and demolition, and are replaced by costs 1-9. LCA also needs to consider handling benefits, government subsidies, product benefits, and environmental costs, with costs ranging from 10 to 13. The environmental cost is evaluated through various environmental impact indicators, including CI-1-6. These indicators are associated with stages S1 to S10 and quantify the potential impacts of the system on various environmental factors, including the greenhouse effect, acidification, and emissions of pollutants (Htoo et al., 2024).

Taking energy utilization R_{eu} as the core, the energy-related links throughout the entire life cycle are associated, including S1-10, and the energy input, output, and consumption efficiency of these links are evaluated.

To enhance the transparency and reproducibility of cost accounting, this study summarizes the specific composition, benchmark values, measurement units, and data sources of internal and external costs, as shown in Table 3. This table also specifies the three key economic parameters: the project calculation period, social discount rate, and residual value rate. The project calculation period is set to 20 years, including a construction period of 1 year and an operation period of 19 years (Guo et al., 2024). The social discount rate is set at 8% per the “Methods and Parameters for Economic Evaluation of Construction Projects (Third Edition)” and is used to calculate the present value of life cycle costs (Tajani et al., 2024). The various cost data come from project feasibility reports, equipment supplier quotations, local market price research, and relevant government subsidy documents. The monetization parameters of environmental costs are determined based on the “Technical Guidelines for Identification and Assessment of Ecological Environment Damage in the People’s Republic of China” and the current carbon market trading prices (Deng et al., 2024).

3. Results and Analysis

3.1. Analysis of Economic Cost Results

From Eq. (3), the internal cost is calculated to be 49.63 CNY. The internal and external costs of TVDP are displayed in Fig. 3. Fig. 3(a) presents the internal cost proportion. Therefore, cost 4 (transportation cost) had the highest proportion at 56.84%, totaling 28.21 CNY. The proportions of costs 3, 6, and 9 (installation, maintenance, and labor) were relatively small at 1.01%, 1.15%, and 1.22%, respectively. These three costs were 0.50 CNY, 0.57 CNY, and 0.61 CNY, respectively. In Fig. 3(b), the external cost of CI-5 was the highest, at -6.59 CNY/t. Negative numbers indicate that the system has significantly reduced human health risks in the region through measures such as source reduction and end-of-pipe treatment, and has reduced hidden costs, such as medical expenses and labor losses, at the societal level. The external costs of CI-2, CI-4, and CI-6 were -1.28 CNY/t, -2.01 CNY/t, and -2.85 CNY/t, respectively. The external costs of CI-1 and CI-3 were 0.64 CNY/t and 0.08 CNY/t, respectively, both of which were positive. During operation, there are minimal emissions of nitrogen and phosphorus pollutants. These pollutants can cause eutrophication of water bodies, but because of their minimal emissions, there is no need to invest large amounts of manpower and funds in their treatment. Therefore, the corresponding social governance cost is relatively low. In addition, the plan also strictly controls greenhouse gas emissions, ultimately achieving the requirements of green and low-carbon development.

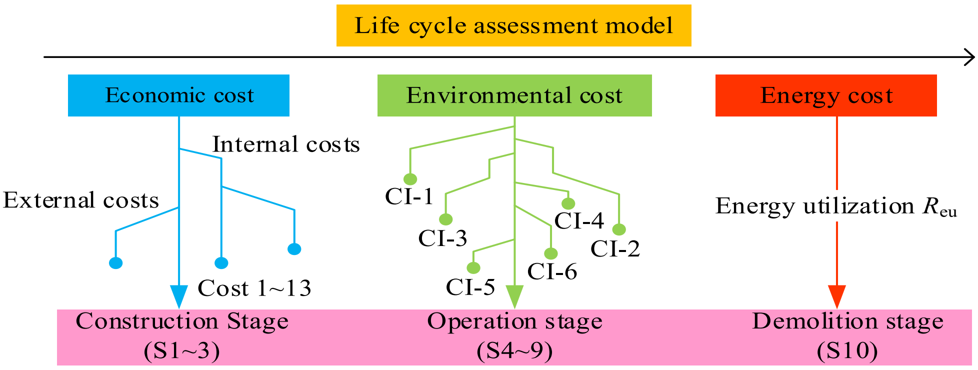


Fig. 2. LCA model

The total cost and sensitivity analysis of LCC are shown in Fig. 4. In Fig. 4(a), the total internal and external costs of the life cycle calculated were -85.04 CNY/t and -12.01 CNY/t, respectively. Therefore, the total cost was -97.05 CNY/t. In Fig. 4(b), the slope of cost 11 (government subsidy) was the largest, and its impact on LCC was the most significant, with a sensitivity of 0.596. Next was cost 10 (processing benefit), with a sensitivity of 0.498. The sensitivities of costs 4 and 7 were 0.401 and 0.156, respectively, while the sensitivities of costs 12 and 13 were 0.045 and 0.148, respectively.

The internal costs during the TVDP scheme construction phase are presented in Table 4. In Table 4, S6 had the highest cost, totaling 3,282.75×104 CNY for construction, equipment procurement, and installation required for anaerobic fermentation. The total investment for the construction of the TVDP scheme includes construction engineering costs (3,250.50×10^4 CNY), equipment purchase cost (3,750.33×10^4 CNY), and installation engineering cost (712.65×10^4 CNY), totaling 7,713.48×10^4 CNY. Therefore, the construction cost allocated to each ton of tail vegetables was 1.961+2.310+0.462=4.733 CNY/t.

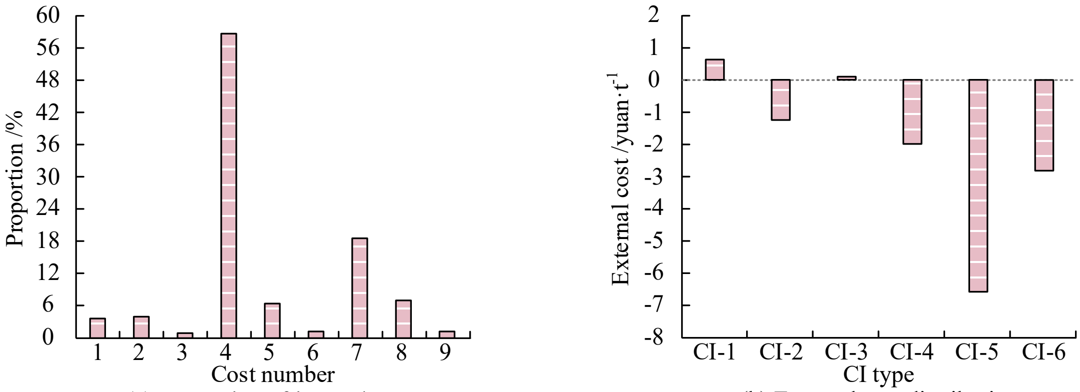
3.2. Analysis of Environmental Cost Results

To analyze the impact of the TVDP scheme on the environment during its life cycle, the study obtained environmental impact potential values using eBalance software, calculated potential values for each environmental indicator at the construction, operation, and demolition stages, and the total life cycle impact value. The quantified results for the six types of environmental impacts caused by processing 1 ton of garbage at different stages are shown in Table 5. In Table 5, the CI-1 and CI-4 values for the entire life cycle were positive, at 5.72×10^{-3} and 9.37×10^{-4}, respectively. Positive values indicate environmental costs that negatively impact the environment. This is because the plan's process for returning biogas slurry to the field involves partial losses of nitrogen and phosphorus, which can slightly exacerbate eutrophication of the water body. The transportation vehicles, generator sets, and other sources of exhaust emissions in the plan have increased photochemical smog pollutants. The CI-2, CI-3, CI-5, and CI-6 values throughout the entire life cycle were all negative. Negative values indicate environmental benefits, that is, having a positive impact on the environment. The entire life cycle value of CI-3 was -3.58×10^1. The biogas in this plan is collected and utilized, and it is used to generate electricity instead of fossil fuels, avoiding significant greenhouse gas and pollutant emissions. Therefore, during the operation phase, except for CI-1, all five indicators were negative.

The comparison of environmental impacts during the construction and demolition phases is shown in Fig. 5. The TVDP scheme contributed the most to CI-1, CI-3, and CI-4, with F10 (steel reinforcement) accounting for 29.6%, 41.2%, and 54.3%, respectively. The scheme contributed the most to F1 (electricity) for CI-2, CI-4, CI-5, and CI-6, accounting for 38.5%, 34.6%, 43.8%, and 24.1%, respectively. The impact of CI-3 and CI-4 during the demolition phase was less than 10%, accounting for 7.5% and 6.4%, respectively.

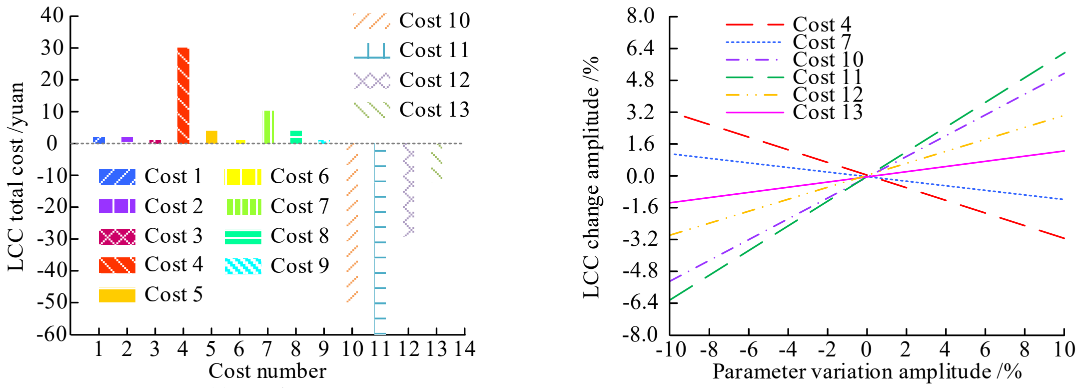
Table 3. LCC Accounting benchmark table

Cost number	Cost category	Unit	Calculation equation/reference value	Data source
1	Construction project cost	CNY	Based on design plan engineering quantity × local quota unit price	Project feasibility study report: code of valuation with bill quantity of construction works
2	Equipment purchase and installation cost	CNY	Equipment supplier quotation + installation rate (usually 5%~10% of equipment price)	Equipment supplier quotation: industry installation rate standard
3	Construction period transportation cost	CNY	Σ(transportation volume × distance × unit freight rate)	Logistics company market quotation: project site traffic distance survey
4	Fixed asset depreciation	CNY/year	(Fixed asset original value - salvage value) / depreciation period (19 years)	Accounting standards for business enterprises: project investment budget table
5	Operation and maintenance labor cost	CNY/year	Staffing quota × average annual salary per person	Local human resources and social security bureau issued industry wage guidelines: project staffing plan
6	Energy consumption cost	CNY/year	(Outsourced electricity volume × electricity price) + (outsourced heat power × heat price)	Local power grid and heat power company commercial charging standards: project energy balance calculation
7	Maintenance and repair cost	CNY/year	Usually take 2%~3% of equipment purchase cost as annual repair rate	Industry maintenance rate, empirical data, equipment maintenance manual
8	Chemical reagents and material cost	CNY/year	Based on design material balance to calculate consumption × market unit price	Chemical product market price: process design manual
9	Demolition and disposal cost	CNY	Estimated engineering quantity × demolition comprehensive unit price	Local demolition project market quotation: subsidy standard for treatment of waste electrical and electronic products (for reference)
10	Environmental cost (externality)	CNY/year	Σ(type environmental impact value × the impact monetization factor)	Monetization factor refers to technical guidelines for identification and assessment of ecological and environmental damage of the people's republic of China, carbon trading price, etc.
11	Government operation subsidy income	CNY/year	Processing volume × per ton subsidy price + grid-connected electricity × electricity price subsidy difference	Local government waste disposal subsidy documents: national renewable energy power generation subsidy policy
12	Product sales income	CNY/year	Grid-connected electricity × grid-connected electricity price + fertilizer sales volume × sales unit price	Local power grid purchase price: organic fertilizer market price research
13	Resource recovery benefit (avoided cost)	CNY/year	Avoided landfill volume × landfill disposal unit price + substitute fertilizer volume × fertilizer unit price	Local waste landfill disposal fee standard: fertilizer market price
Key economic parameters	Project calculation period	Year	20 years	Typical project lifespan in the industry: Equipment design service life
	Social discount rate	%	8%	Refer to "Methods and Parameters for Economic Evaluation of Construction Projects (Third Edition)"
	Residual value rate	%	5%	Common accounting treatment conventions in the industry



(a) Proportion of internal costs (b) External cost distribution

Fig. 3. Internal and external costs



(a) Total cost (b) Sensitivity analysis

Fig. 4. LCC total cost and sensitivity analysis

Table 4. Internal costs during the construction stage

Process name	Construction engineering cost ($\times 10^4$ CNY)	Construction engineering cost (FU/CNY)	Equipment purchase cost ($\times 10^4$ CNY)	Equipment purchase cost (FU/CNY)	Installation engineering cost ($\times 10^4$ CNY)	Installation engineering cost (FU/CNY)
S5	543.80	0.328	564.80	0.348	99.45	0.065
S6	2,261.70	1.364	866.10	0.533	154.95	0.101
S7	113.00	0.068	999.48	0.616	215.50	0.140
S8	238.00	0.144	1,305.00	0.804	240.10	0.156
S9	94.00	0.057	1,495.00	0.921×10^{-2}	2.65	0.172×10^{-2}
Total	3,250.50	1.961	3,750.33	2.310	712.65	0.462

The environmental impact results of the six CI during the operation phase are shown in Fig. 6. Fig. 6(a), the CI-1 of the original project and TVDP in S7 were 1.3×10^{-3} kg PO_4^{3-} eq and -10.1×10^{-3} kg PO_4^{3-} eq. At this stage, there was a negative eutrophication potential, which could reduce it, while the original project generated a small amount of eutrophication potential. The original project had a CI-1 of 37.9×10^{-3} kg PO_4^{3-} eq in S9, while the TVDP was only 1.4×10^{-3} kg PO_4^{3-} eq. TVDP significantly reduced the eutrophication potential of the biogas slurry treatment process. Fig. 6(b), the CI-2 of the original project and TVDP in S7 were 0.6×10^{-2} kg SO_2 eq and 16.3×10^{-2} kg SO_2 eq, respectively. TVDP significantly optimized the acidification potential and reduced the acidification risk in the treatment and utilization of biogas slurry. In Fig. 6(c), TVDP had a particularly outstanding effect on mitigating global warming in the S7 stage. The CI-3 of the original project was 7.99 kg C_2H_4 kg CO_2 eq, and the new system was -49.88 kg CO_2 eq. TVDP significantly reduced global warming potential during the S7 and S9 stages. In Fig. 6(d), TVDP reached -2.99×10^{-2} kg C_2H_4 eq in CI-4 of S7, while the original project was -0.44×10^{-2} kg C_2H_4 eq. TVDP had a particularly outstanding effect on reducing photochemical smog at this stage. In Fig. 6(e), TVDP reached -9.64 kg C_2H_4 eq at CI-5 in S7. In Fig. 6(f), TVDP exhibited better resource consumption performance in stages S5, S6, S7, and S9. The potential for resource conservation in the S7 stage (-561.08 MJ) was significantly higher than that of the original project (-182.49 MJ).

Table 5. Quantitative results of six types of environmental impacts at different stages

Type	Construction stage	Operate stage	Demolition stage	Entire life cycle
CI-1	8.51×10^{-4}	4.86×10^{-3}	9.30×10^{-5}	5.72×10^{-3}
CI-2	5.91×10^{-3}	-4.58×10^{-2}	5.87×10^{-4}	-4.21×10^{-2}
CI-3	2.94×10^{2}	-2.10×10^{1}	2.53×10^{-1}	-3.58×10^{1}
CI-4	4.83×10^{-4}	-3.15×10^{4}	3.49×10^{-5}	9.37×10^{-4}
CI-5	2.79×10^{-1}	-4.77×10^{2}	3.77×10^{-2}	-4.74×10^{2}
CI-6	2.50×10^{1}	-2.27×10^{2}	3.67×10^{2}	-2.28×10^{2}

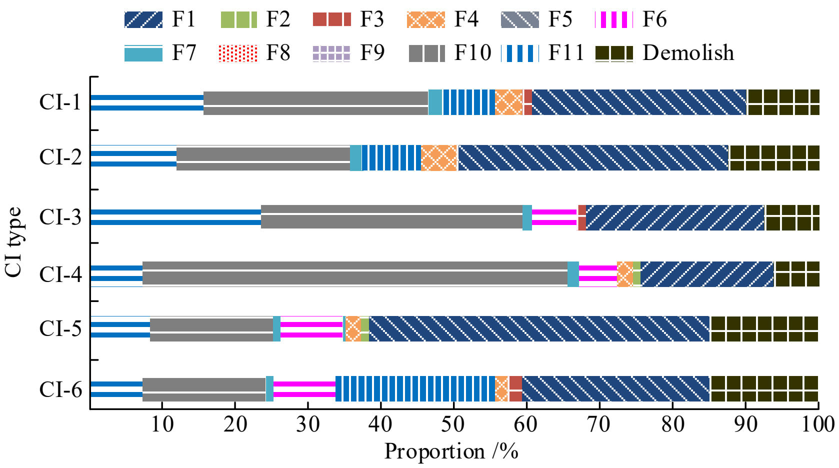


Fig. 5. Comparison of environmental impact between construction and demolition stages

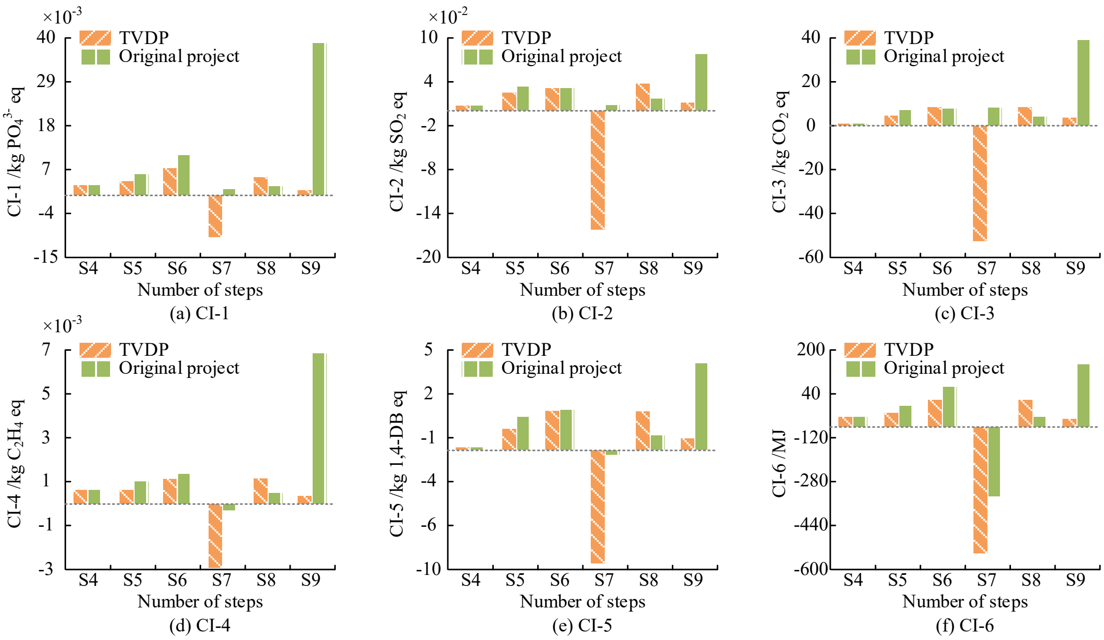


Fig. 6. Environmental impact results during the operational phase

3.3. Analysis of Energy Cost Results

The input and output substances, including the quantitative results for different stages of the TVDP scheme, are shown in Table 6. The main environmental burden of the S4 stage was the exhaust gases, such as CO, HC, and NOx, generated by diesel combustion. The main environmental burden of S5 and S8 was the production of odorous gases, such as NH_3 and

H_2S. In the S7 stage, 2.14 kW·h of electricity were input, 34.37 kW·h of electricity, and 65.63 MJ of heat were output, demonstrating the economic and environmental benefits of the project. Pollutants include various combustion exhaust gases such as CO, HC, NOx, unburned CH_4, and H_2S impurities contained in raw materials. The emission of CH_4 reached 150g.

Table 6. Input and output substances and their quantitative results in different stages of operation

Process name	Status	Name	Result	Process name	Status	Name	Result
S4	Input	Diesel	0.62kg	S7	Input	Electricity	2.14kW·h
	Output	CO	18.22g		Output	Electricity	34.37kW·h
		HC	1.25g			Heat	65.63MJ
		NOx	6.38g			CO	152.40g
S5	Input	Electricity	2.47kW·h			NOx	119.36g
	Output	NH_3	4.77g			H_2S	3.38g
		H_2S	1.30g			CO_2	270.10g
S6	Input	Electricity	4.72kW·h			CH4	150.10g
S8	Input	Electricity	4.54kW·h			O_2	0.75g
	Output	NH_3	2.77g			H_2	3.25g
		H_2S	0.90g			N_2	3.60g
S9	Input	Electricity	1.45kW·h				
	Output	NH_3	1.10g			HC	18.95g
		H_2S	0.90g				

To fully illustrate the mass-energy balance relationships of the system, this study summarizes the key energy parameters as follows: biogas production from tail vegetable AD is 100 Nm^3/t wet garbage, the methane volume fraction in biogas is 60%, and the lower heating value is 21.5 MJ/Nm^3. In the energy conversion process, the power generation efficiency of biogas generators is set at 40%. The total thermal efficiency of the cogeneration systems is 85%, with power generation efficiency of about 40% and heating efficiency of about 45%. The system's self-consumption mainly comes from pre-treatment, feeding and discharging, mixing, desulfurization and other processes, totaling about 35 kWh/t of garbage. The difference in operating time between process units is determined based on their continuity and start-stop characteristics: anaerobic fermentation and power generation units need to operate continuously and stably. Preprocessing, solid-liquid separation, and other processes can be operated in batches. By configuring intermediate storage tanks for material and energy buffering, the differences in operating timing can be effectively adjusted to ensure the overall stable operation and energy balance of the system.

The study compares the proportions of energy input between TVDP and the original project at 10 steps across three stages. In Fig. 7(a), the total energy input of TVDP and the original project accounted for 6.97% and 5.59%, respectively. The two had the highest proportion of energy input in S1, with TVDP and the original project accounting for 5.03% and 4.15% respectively, in this step. The proportions of the two in S2 were extremely low, at 0.35% and 0.26% respectively. The proportions of the two in S3 were 1.59% and 1.18%, respectively, with a difference of 0.41%. In Fig. 7(b), the total energy input of TVDP and the original project accounted for 91.58% and 93.42%, respectively. The proportion of energy investment in S7 for TVDP and the original project was not significantly different, at 8.05% and 9.2% respectively. The proportion of S9 in the original project (31.40%) was significantly higher than that of TVDP (7.10%). In Fig. 7(c), the TVDP and original project were 1.45% and 0.99%, respectively.

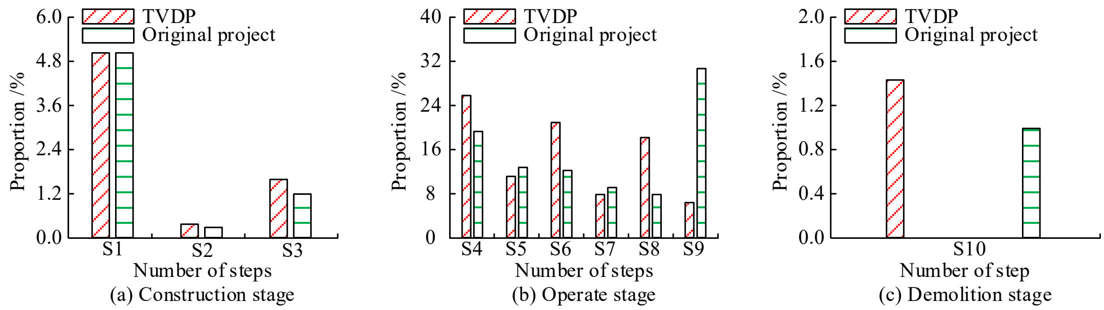


Fig. 7. Proportion of energy investment in different projects

The evaluation results for energy and LCC are presented. Fig. 8(a) displays the sensitivity for the three types of energy consumption: biogas power generation capacity, transportation fuel consumption, and aerobic treatment power consumption. The sensitivity of these three factors was 3.359, 0.429, and 0.265, respectively. Biogas power generation was the most sensitive factor affecting energy use. When the power generation decreased by 10%, the system's energy utilization decreased by 12.5%. The impact of aerobic treatment on electricity consumption was minimal. When electricity consumption decreased by 10%, the energy utilization decreased by 0.8%. In Fig. 8(b), the changes in environmental, energy, and transportation costs were 1.5%, -1.5%, and 3.1%, respectively. Product revenue, government subsidies, and processing income showed significant upward trends with increasing parameter variation amplitude, increasing by 2.6%, 6.5%, and 5.3%, respectively.

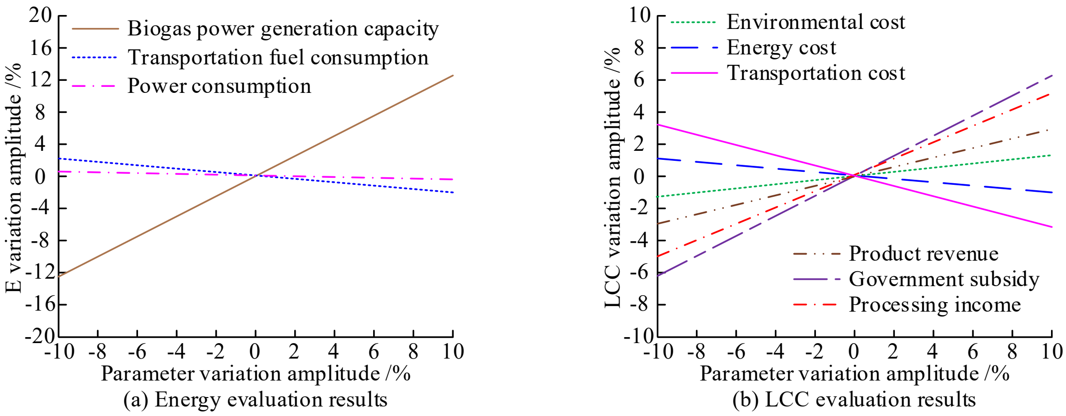


Fig. 8. Evaluation results of energy and LCC

4. Conclusion

To comprehensively evaluate local government waste-disposal projects, a TVDP scheme was designed, and a comprehensive evaluation framework was developed from the perspectives of environment, economy, and energy. The results showed that the internal cost per unit of waste disposal was 49.63 CNY, with transportation costs accounting for the largest share at 56.84% (28.21 CNY). Installation (0.50 CNY), maintenance (0.57 CNY), and labor (0.61 CNY) costs accounted for less than 2%, indicating that transportation was the key to internal cost control. In contrast, Nordahl and Scown (2024) had a single environmental dimension, whereas Ferronato et al. (2024) faced greater limitations in evaluating environmental and economic fragmentation. This study incorporated proportions of transportation costs, external health costs, and energy conversion efficiency into a single decision-making framework, and the resulting quantitative results were more aligned with the collaborative decision-making needs of local governments. To further clarify the quantitative impact of key variables on decision-making, this study conducted the following scenario deduction based on sensitivity analysis results: If the transportation distance is shortened by 10% (i.e. the average transportation distance is reduced from 38.5km to about 34.7km), the net LCC per unit of waste treatment will improve by about 2.8%, from 97.05 CNY/ton to about 99.8 CNY/ton. The improvement mainly stems from reduced diesel consumption and transportation-related vehicle depreciation costs. In addition, changes in government subsidy policies have shown a more significant impact. If the subsidy standard for grid connected electricity price of biogas power generation is increased by 0.10 CNY/kWh, the net LCC can be improved by about 6.5%, from 97.05 CNY/ton to about 103.4 CNY/ton. This change is attributed to the high sensitivity coefficient for cost item 11 (reaching 0.596). The above quantitative results indicate that, during project optimization, the two key ways to improve the economic feasibility and financial sustainability of the project are to plan the collection network layout rationally to shorten transportation distances and to actively pursue local electricity price subsidies and carbon trading benefits.

In terms of external costs, CI-5 was -6.59 CNY/t, while CI-2 (-1.28 CNY/t), CI-4 (-2.01 CNY/t), and CI-6 (-2.85 CNY/t) were all negative values. This plan reduced hidden social expenditures through source reduction and end-of-pipe treatment. Only CI-1 (0.64 CNY/t) and CI-3 (0.08 CNY/t) were positive, indicating a slight eutrophication risk in water from a small amount of nitrogen and phosphorus emissions, and the social governance cost was extremely low. Throughout the entire life cycle, CI-1 and CI-4 were positive, while CI-2, CI-3, CI-5, and CI-6 were negative. The core benefits come from biogas recycling to replace fossil fuel power generation. During the operation phase, except for CI-1, all showed positive environmental benefits that exceeded the single-link emission reduction effect (Ferronato et al., 2024). Unlike Üstün Odabaşı and Laratte (2024), who identified sensitive parameters, this study further clarified the specific proportions of each cost item across different stages (such as transportation costs exceeding 50%) and the primary source of environmental benefits (biogas power generation), providing actionable targets for project optimization. Cheng et al. (2025) compared the LCA of the resource utilization pathways for kitchen waste and expanded the quantitative analysis of energy input and output, filling the gap in the energy efficiency-cost linkage evaluation of existing waste disposal projects. The practicality is better than that of the universal framework proposed by Hübner et al. (2024).

However, the study does not consider other potential impacts, such as soil and noise pollution. Compared to the full-scenario evaluation based on actor-network theory by Walker et al. (2024), the scenario coverage in this study requires improvement. In the future, different regional differentiation parameters can be combined to analyze multiple influencing factors, thereby further enhancing applicability across different scenarios.

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Institutional Review Board Statement

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Declaration of Artificial Intelligence (AI) Tools

The author confirmed that no AI tools were used in the preparation of this manuscript.

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