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Cultural Heritage Protection and Low-Carbon Development in World Heritage Sites: Synergistic Mechanisms, Quantitative Assessment, and Practical Pathways

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Abstract: Against the backdrop of global "carbon peaking and carbon neutrality" goals and the rapid development of the digital economy, World Heritage Sites (WHSs) face the triple mission of cultural inheritance, ecological protection, and low-carbon transition. These goals are inherently synergistic, yet existing research remains limited in assessment methods, cross-case comparison, mechanism integration, and policy relevance. Based on 17 core studies, this study constructs a framework of "methodological integration–empirical validation–mechanism construction–path optimization" to examine the synergy between heritage protection and low-carbon development in WHSs. It integrates screening methods, Life Cycle Assessment (LCA), and spatial comparison models with digital economy indicators to build an ecological/carbon footprint assessment system tailored to WHSs. Using Huangshan, Taishan, Suzhou Pingjiang Road, and Gulangyu as cases, it verifies synergistic effects and identifies heterogeneous features through literature and field survey data. The study further proposes a four-dimensional synergistic mechanism of "cultural concept guidance–technical support–SME implementation–institutional guarantee" and advances optimization paths in cultural communication, technological innovation, agent cultivation, and institutional improvement. It provides both methodological support and practical reference for the sustainable development of WHSs.

Keywords: World Heritage Sites; Cultural heritage; Low-carbon transition; Synergistic mechanism; Digital economy; Ecological footprint; SMEs; Assessment framework

Introduction

Research background

Global climate change—characterized by rising temperatures and frequent extreme weather—poses severe threats to the survival and development of WHSs. For natural heritage, accelerated glacial melting in the Himalayan WHS disrupts ecosystems [8], and recurring droughts in the Amazon Rainforest WHS threaten biodiversity. For cultural heritage, sea-level rise intensifies erosion in coastal WHSs such as Venice and Gulangyu [7], while extreme rainfall and high temperatures increase the risk of damage to ancient buildings and cultural relics like the Forbidden City and the Mogao Grottoes [12]. Meanwhile, the growing global demand for tourism has made heritage tourism a key driver of regional economic development. However, the influx of tourists brings problems such as excessive energy consumption, soaring carbon emissions, overloaded environmental carrying capacity, and excessive commercialization of cultural heritage [5], exacerbating conflicts between heritage protection and economic development.

Guided by global "carbon peaking and carbon neutrality" goals, low-carbon transition has become an inevitable trend across industries, including WHSs. As core areas for ecological protection and cultural dissemination, WHSs embody profound ecological wisdom in their unique cultural connotations. For example, traditional Chinese ecological cultures emphasize "harmony between humans and nature" (symbiosis), "moderation in resource use" (sustainable exploitation), and "frugality and benevolence" (responsible consumption) [11]—concepts highly aligned with the sustainability, effi-

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ciency, and responsibility pursued by low-carbon development, laying a natural value foundation for synergizing heritage protection and low-carbon development.

The rise of the digital economy has injected new momentum into this synergy. Digital technologies such as big data, artificial intelligence (AI), VR/AR, and the Internet of Things (IoT) not only optimize the allocation of tourism resources in WHSs and reduce carbon emissions during operations [16] but also innovate cultural heritage dissemination methods and expand cultural influence [15]. As important micro-agents in the digital economy, SMEs—with their flexibility and adaptability—play an irreplaceable role in linking digital technologies with heritage tourism scenarios, bridging skill mismatches, and promoting the implementation of low-carbon technologies [17]. However, WHSs face practical dilemmas in practice: some managers lack awareness of the synergy between culture and low-carbon development, viewing heritage protection and low-carbon transition as conflicting tasks; scientific and unified tools for carbon emission quantification are lacking, hindering accurate identification of key carbon sources and emission reduction potential; digital technology applications remain superficial, failing to deeply integrate with heritage protection and low-carbon transition; SMEs lack motivation and capacity to participate in the low-carbon digital transition of WHSs; and relevant institutional policies lack systematicness and synergy, making it difficult to form long-term guarantees. Thus, there is an urgent need to construct a systematic research framework to explore the synergistic logic, quantitative methods, and practical pathways of cultural heritage protection and low-carbon development in WHSs, providing theoretical support and practical guidance for addressing these challenges.

Literature review

As a core indicator for measuring the impact of human activities on ecosystems, the ecological footprint has been widely used in evaluating the sustainability of heritage tourism [2]. Early studies focused on the application and validation of single methods: Li et al. (2019) developed a screening method for calculating the ecological footprint of heritage tourism, simplifying the calculation process and reducing data acquisition costs by identifying key carbon sources (e.g., transportation, accommodation, catering, and sightseeing), which was successfully applied to Taishan WHS [1]; Lenzen et al. (2018) confirmed through large-scale statistical analysis of global tourism carbon emissions that transportation (especially air travel) and accommodation are the main sources, providing key directions for carbon emission control in WHSs [3]; Kuo and Chen (2009) introduced the Life Cycle Assessment (LCA) method into island WHS research, covering the entire process from pre-trip preparation to post-trip activities, enabling full-chain quantification of environmental loads from tourist activities [7]; Zhang and Zhang (2020) compared the carbon footprints of the Himalayan and Huangshan mountain WHSs, identifying tourism scale, transportation modes, management measures, and geographical environment as key factors affecting carbon emission intensity [8].

With the development of the digital economy, some studies have begun to focus on carbon emissions from digital facilities, but existing quantitative assessment systems still have obvious deficiencies: first, they lack comprehensive consideration of the triple goals of "cultural protection-low-carbon development-digital empowerment" in WHSs, failing to include emerging carbon sources such as digital facility operation and digital content dissemination; second, the applicable scenarios of different methods are not clearly defined, and an integrated assessment tool that can be flexibly adjusted according to WHS types and tourism modes has not been formed; third, assessment indicators focus on total carbon emissions, with insufficient attention to the synergistic efficiency of cultural protection and low-carbon development, making it difficult to fully reflect the sustainable development level of WHSs.

Empirical research on synergy between heritage protection and low-carbon development

Existing empirical studies cover diverse WHS types (mountains, historical districts, islands) and explore synergistic development pathways in different scenarios. For mountain WHSs, Hu et al. (2022) found in a case study of Huangshan that scenic management measures (e.g., optimized transportation scheduling, energy structure adjustment) and tourist behavior guidance (e.g., low-carbon travel advocacy, green consumption promotion) significantly reduce carbon emission intensity [4]; Zhang and Zhang (2020) highlighted energy-saving renovations of transportation facilities such as cable cars and sightseeing vehicles as key emission reduction measures [8]. For historical district WHSs, Tweed and Sutherland (2007) explored pathways to improve energy efficiency in cultural heritage buildings through thermal insulation renovations, renewable energy utilization, and spatial layout optimization [6]; Suzhou Pingjiang Road integrated cultural experience and low-carbon development by promoting a "slow life" tourism model (encouraging walking and cycling) and green renovations of home stays and shops [13]. For island WHSs, Kuo and Chen (2009) quantified carbon emissions from transportation, accommodation, catering, and material transportation in the Penghu Islands using LCA, proposing measures such as material recycling, renewable energy promotion, and tourism capacity control [7]; Gulangyu effectively controlled carbon emissions while ensuring tourism experiences through optimized ferry scheduling, promotion of electric sightseeing vehicles, and development of a digital reservation and crowd-limiting system [15].

Notably, the role of the digital economy and SMEs in empirical practice is increasingly prominent. Gu et al. (2025) revealed the development mechanism of the digital tourism economy under environmental constraints, noting that digital technologies improve low-carbon transition efficiency through resource integration, tourist flow regulation, and carbon emission monitoring [16]; Gu and Lukin (2025) confirmed through empirical analysis that SMEs— as key providers of digital tourism services—bridge skill mismatches between digital technologies and heritage tourism scenarios through flexible skill training and service innovation, promoting the application of low-carbon technologies in ticketing, intelligent navigation, and cultural and creative (CC) product development [17]. However, existing empirical research remains fragmented: first, most studies focus on single WHSs, lacking comparative analysis and regularity extraction of synergistic effects across different types; second, the empowering role of digital technologies and SMEs is insufficiently explored, with unclear adaptation models and action boundaries in different WHS types; third, the evaluation of synergistic effects is mostly qualitative or based on single indicators, lacking systematic measurement of "cultural-ecological-economic" comprehensive benefits.

Research on synergistic mechanisms and policies

Theoretical exploration of the synergistic logic between heritage protection and low-carbon development has yielded multi-dimensional results. At the cultural concept level, Dickinson et al. (2011) proposed the "slow tourism" concept, emphasizing reduced travel frequency, longer stays, and in-depth cultural experiences—achieving both low-carbon goals (reducing transportation emissions) and enhanced cultural heritage understanding [9]; Loulanski and Loulanski (2011) constructed an integrated model of cultural heritage and sustainable tourism, emphasizing the coordination of cultural value inheritance with ecological protection and economic development [11]. At the technical support level, Bec et al. (2019) suggested that digital technologies such as VR/AR reduce carbon emissions from physical tourism through virtual heritage experiences while expanding cultural dissemination [15]; Gu et al. (2025) expanded application scenarios, noting that big data and IoT enable real-time carbon emission monitoring, and AI optimizes resource allocation and energy efficiency [16]. At the institutional policy level, the joint report *World Heritage and Tourism in a Changing Climate* by UNESCO, UNEP, and UCS [12] analyzed climate change threats to global WHSs and advocated integrating climate adaptation and low-carbon goals into protection plans; scholars proposed policy recommendations such as financial subsidies for low-carbon transition enterprises and the construction of a "government-scenic area-community" collaborative governance system [4][11].

At the agent participation level, Gu and Lukin (2025) filled the research gap on SMEs' role in synergistic mechanisms, noting that SMEs not only provide digital tourism services but also act as carriers for low-carbon technology implementation, promoting the deep integration of digital and low-carbon technologies in heritage tourism through skill mismatch bridging [17]. However, existing research on synergistic mechanisms still has limitations: first, it focuses on single dimensions (e.g., culture, technology, or institutions), failing to form a systematic four-dimensional framework integrating "concept-technology-agent-institution"; second, the interaction between dimensions is insufficiently explored, lacking clarification of the circular reinforcement logic—"concepts guide technological direction, technologies empower agent participation, agents promote institutional implementation, and institutions guarantee concept inheritance"; third, policy research remains macro-level, lacking precise design for different WHS types and development stages, and insufficiently addressing SME support and digital technology incentives.

Research gaps

Synthesizing existing research, three core gaps are identified: first, quantitative assessment systems lack integration and adaptability, failing to form a comprehensive tool that balances the triple goals of cultural protection, low-carbon development, and digital empowerment while adapting to different WHS types, with insufficient indicators for synergistic efficiency; second, empirical research is fragmented, lacking cross-case comparison of synergistic effects across WHS types and in-depth exploration of the digital economy and SMEs, making it difficult to form replicable and scalable practical models; third, synergistic mechanism research is single-dimensional, failing to construct a four-dimensional framework of "cultural concept guidance-technical support-SME implementation-institutional guarantee," and policy recommendations lack pertinence, operability, and long-term effectiveness. Based on this, this study focuses on four core questions: How to construct a quantitative assessment system adapted to the triple goals of WHSs? How to verify synergistic effects and heterogeneous rules across different WHS types? How to build a four-dimensional integrated synergistic mechanism? How to propose precise and effective optimization pathways?

Research significance

Theoretical significance

First, this study constructs a comprehensive research framework of "quantitative assessment-empirical validation-mechanism construction-path optimization," integrating cultural heritage protection, low-carbon development, digital economy, and SMEs, filling the systematic research gap at the intersection of cultural heritage studies and environmental economics. Second, it integrates multiple methods (screening, LCA, spatial comparison) and incorporates emerging indicators (digital facility emissions, digital empowerment coefficient, SME participation) to form a quantitative assessment system tailored to WHSs' triple goals, enriching methodologies for WHS sustainability evaluation. Finally, it reveals the four-dimensional synergistic mechanism and its circular reinforcement logic, expanding the application boundaries of sustainable development theory, cultural economics, and digital economy theory.

Practical significance

First, the quantitative assessment system provides WHS managers with scientific carbon accounting tools and synergistic efficiency standards, facilitating accurate identification of key carbon sources, emission reduction potential, and differentiated strategies. Second, empirical comparison of mountain, historical district, and island WHSs extracts scenario-specific synergistic development models—especially the application pathways of digital technologies and SMEs—offering replicable practical experience. Third, the optimization pathways based on the four-dimensional mechanism cover cultural communication, technological innovation, agent cultivation, and institutional improvement, providing policy references for governments to promote the triple win of "improved cultural protection, efficient low-carbon transition, and increased economic growth," contributing Chinese wisdom to global WHS sustainable development.

Quantitative Assessment System for Ecological/Carbon Footprints in WHSs

Combining methodological achievements from existing literature and core characteristics of WHSs—"cultural protection priority, intensive tourism activities, ecological sensitivity, accelerated digital technology penetration, and increased SME participation"—this study constructs a "three-in-one" quantitative assessment system, including assessment dimension definition, core method integration, and indicator system design, to achieve comprehensive, accurate, and dynamic evaluation of WHS ecological/carbon footprints.

Definition of assessment dimensions

Focusing on the full-chain carbon emissions from WHS tourism and protection activities—covering direct and indirect emissions, traditional and emerging carbon sources—three core assessment dimensions are defined to fully align with the triple goals of "cultural protection-low-carbon development-digital empowerment":

- Direct carbon emissions: Emissions directly generated by tourists during on-site activities, including transportation (cable cars, sight seeing vehicles, ferries, excluding walking), accommodation (hotels, homestays), catering (energy consumption and food waste), and sightseeing (entertainment facilities, experience programs).
- Indirect carbon emissions: Emissions indirectly generated to support WHS tourism operations and cultural protection, including energy consumption (administrative facilities, cultural exhibition venues), building maintenance (heritage restoration, tourism facility upkeep), material procurement (production and transportation of operational supplies), and digital facility operation (intelligent navigation devices, data centers, virtual experience platforms).
- Cultural protection-related carbon emissions: Emissions from specialized activities to ensure the authenticity and integrity of cultural heritage, including heritage restoration (ancient building renovation, cultural relic restoration), cultural relic protection (storage environment regulation, pest control), and cultural exhibition (lighting, constant temperature/humidity equipment in museums). This dimension balances protection effectiveness and emission reduction goals, avoiding compromises to cultural heritage quality for absolute emission reduction.

Integration of core quantitative methods

To adapt to different WHS types and assessment scenarios, three core methods—screening, Life Cycle Assessment (LCA), and spatial comparison models—are integrated into a "basic method + supplementary method + comparison method" system:

Basic calculation method: Screening method

Adopting the screening method proposed by Li et al. (2019) [1] as the core, and optimizing the process to reflect the digital economy and SME participation:

- Carbon source identification and classification: Comprehensive identification of WHS carbon sources through field surveys, scenic management data, and tourist interviews, classified into the three dimensions above, with emphasis on emerging sources such as digital facility operation and SME digital services.
- Key carbon source screening: Prioritizing carbon sources accounting for over 1% (e.g., transportation, accommodation, energy consumption, digital facilities) for detailed calculation; simplifying minor sources to balance accuracy and efficiency.
- Data collection: Multi-source data acquisition, including scenic energy consumption reports, transportation logs, accommodation/catering revenue data, digital facility operation records, heritage protection project files, and SME operational data; supplementing missing data with industry averages or interpolation.
- Quantitative calculation: Using industry-standard emission factors (e.g., recommended values in *Provincial Greenhouse Gas Inventory Compilation Guidelines*) adjusted for WHS-specific conditions:
    - Total carbon emissions = Σ (Activity level of a carbon source × Corresponding emission factor)
    - Digital facility carbon emissions = Operation time of digital devices × Unit time energy consumption × Power emission factor
    - SME carbon emissions = Scale of SME services × Unit service carbon emission coefficient
- Result verification: Validating results through comparison with historical WHS emission data and peer WHS levels to ensure reliability.

Supplementary method: Life cycle assessment (LCA)

Introducing the LCA method by Kuo and Chen (2009) [7] for complex scenarios with long industrial chains (e.g., island WHSs, historical districts):

- Scope definition: Expanding to the full life cycle of "pre-trip preparation-during trip-post-trip activities," covering tourist transportation, digital reservation experiences, on-site visits, waste disposal, and digital content dissemination; including the "production-use-disposal" cycle of heritage buildings and digital facilities.
- System boundary division: Clarifying geographical (WHS administrative area and surrounding associated regions), temporal (usually 1 year), and functional units (e.g., "per tourist visit," "per unit area heritage protection").

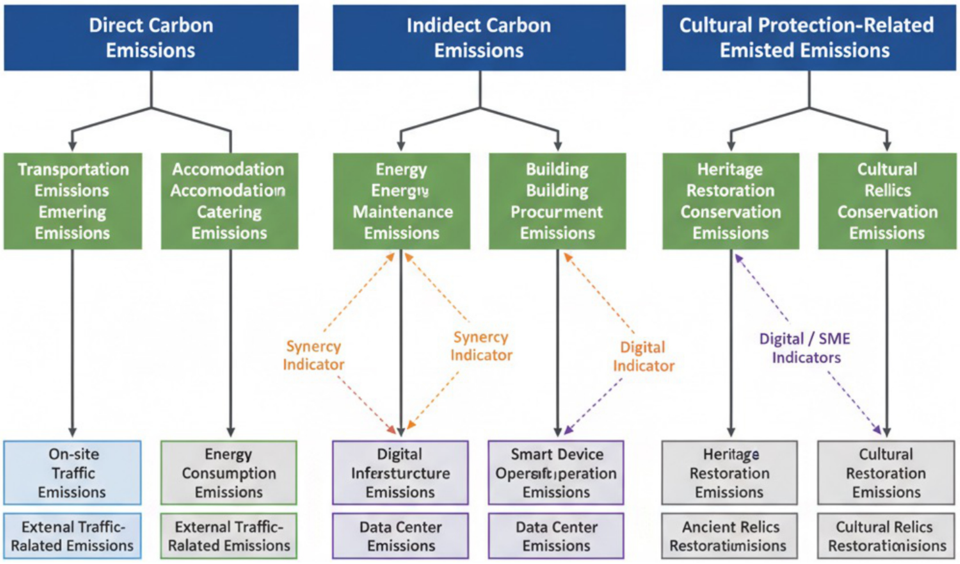

Figure 1 | World Heritage Sites Ecological / Carbon Footprint Tertiary Evaluation Index System

- Inventory analysis: Detailing all inputs (energy, materials, water) and outputs (CO_2, SO_2, solid waste) within the system boundary to establish a complete life cycle inventory.
- Impact assessment: Using midpoint or endpoint methods to evaluate the comprehensive impact of carbon emissions on climate change and ecosystems, identifying key emission reduction links.
- Interpretation: Proposing optimization schemes balancing minimal environmental impact and maximal cultural value.

Comparative analysis method: Spatial comparison model

Drawing on the spatial comparison approach by Zhang and Zhang (2020) [8], a cross-WHS comparison model is constructed to reveal heterogeneous carbon emission characteristics and synergistic efficiency:

Control variable selection: Key variables including WHS type (mountain, historical district, island), tourism scale (annual tourist volume), geographical location (eastern/central-western, coastal/inland), digital economy development level (digital facility coverage, share of digital tourism services), and SME participation (number of relevant SMEs, revenue share) to ensure scientific comparison.

Comparison dimension design: Four core dimensions—carbon emission intensity (per capita, per unit area, per tourism revenue), synergistic efficiency (cultural protection satisfaction per unit carbon emission, low-carbon transition effect per cultural protection cost), digital empowerment coefficient (digital technology-induced emission reduction/total emission reduction, digital technology-induced cultural dissemination increment/total dissemination), and SME contribution (SME-induced emission reduction/total emission reduction, share of digital tourism services provided by SMEs).

Model construction: Panel data models or difference-in-differences models to control individual and time fixed effects, quantifying the impact of different factors on carbon emission intensity and synergistic efficiency, and extracting key drivers of synergistic development.

Indicator system design

Based on assessment dimensions and core methods, a "three-level indicator system" is constructed, covering carbon emission accounting, synergistic effect evaluation, and digital empowerment/SME participation assessment, balancing scientificity, systematicness, and operability (Table 1 and Figure 1).

Empirical Validation: Synergistic Effect Analysis of Typical WHSs

Four typical WHSs—mountain heritage (Huangshan), mixed mountain-cultural heritage (Taishan), historical district heritage (Suzhou Pingjiang Road), and island heritage (Gulangyu)—are selected as case studies. Using the quantitative assessment system, combined with literature data, scenic annual reports, field surveys, tourist interviews, and SME surveys, this study systematically verifies the synergistic effects of heritage protection and low-carbon development, analyzes heterogeneous carbon emission characteristics and synergistic efficiency, and highlights the empowering role of the digital economy and SMEs.

Case overview and data sources

Huangshan (Mountain heritage)

Core characteristics: A mixed natural and cultural WHS in Huangshan City, Anhui Province, renowned for its "four wonders" (peculiar pines, strange rocks, sea of clouds, hot springs). Tourism focuses on natural scenery appreciation, with transportation relying on cable cars and sightseeing vehicles. Digital technologies are mainly applied in intelligent monitoring, ticketing, and navigation. Relevant SMEs primar-

Table 1 | Indicator System Design

Primary Indicator	Secondary Indicator	Tertiary Indicator	Calculation Method	Data Source
Direct Carbon Emissions	Transportation Carbon Emissions	On-site transportation emissions	Number of tourists × Average on-site travel distance × Unit distance emission factor	Scenic ticketing data, tourist surveys, transportation logs
		External transportation-related emissions	Number of tourists × Average round-trip external distance × Unit distance emission factor	Tourist surveys, transportation statistics
	Accommodation Carbon Emissions	Hotel accommodation emissions	Hotel stays × Average stay duration × Unit time emission factor	Hotel check-in data, energy consumption statistics
		Homestay accommodation emissions	Homestay stays × Average stay duration × Unit time emission factor	Homestay operational data, field visits
	Catering Carbon Emissions	On-site catering emissions	Number of tourists × Per capita catering consumption × Catering carbon emission coefficient	Catering revenue data, industry reports, tourist surveys
	Sightseeing Carbon Emissions	Experience program emissions	Number of participants × Unit program carbon emission factor	Program operation records, facility energy consumption data
Indirect Carbon Emissions	Energy Consumption Carbon Emissions	Administrative facility emissions	Administrative facility electricity/heat consumption × Corresponding emission factor	Scenic energy bills, energy consumption reports
		Exhibition venue emissions	Exhibition venue electricity/heat consumption × Corresponding emission factor	Venue operation logs, energy consumption statistics
	Building Maintenance Carbon Emissions	Heritage building maintenance emissions	Maintenance area × Unit area maintenance carbon emission factor	Maintenance contracts, material procurement records
		Tourism facility maintenance emissions	Maintenance workload × Unit workload carbon emission factor	Maintenance project files, construction records
	Material Procurement Carbon Emissions	Operational material emissions	Operational material procurement volume × Unit material carbon emission factor	Procurement contracts, supplier data
		Cultural and creative (CC) product emissions	CC product sales volume × Unit product carbon emission factor	CC sales data, manufacturer reports
	Digital Facility Carbon Emissions	Intelligent device operation emissions	Number of intelligent devices × Average operation time × Unit time energy consumption × Emission factor	Digital facility operation logs, energy monitoring data
		Data center emissions	Data center electricity consumption × Power emission factor	Data center energy consumption statistics
Cultural Protection-Related Carbon Emissions	Heritage Restoration Carbon Emissions	Ancient building restoration emissions	Maintenance area × Unit area restoration carbon emission factor + Equipment operation energy consumption × Emission factor	Restoration project files, construction records, energy consumption data
		Cultural relic restoration emissions	Number of restored cultural relics × Unit cultural relic restoration carbon emission factor	Cultural relic restoration reports, material consumption records
	Cultural Relic Protection Carbon Emissions	Storage environment regulation emissions	Storage facility operation time × Unit time energy consumption × Emission factor	Cultural relic warehouse operation logs, energy consumption statistics
		Protection treatment emissions	Number of protected cultural relics × Unit treatment carbon emission factor	Protection treatment records, material consumption data
	Cultural Exhibition Carbon Emissions	Exhibition lighting emissions	Exhibition area × Average lighting duration × Unit area lighting energy consumption × Emission factor	Exhibition operation logs, energy consumption data
		Interactive exhibition emissions	Interactive device operation time × Unit time energy consumption × Emission factor	Interactive device operation records, energy monitoring data
Synergistic Effect Indicators	Carbon Emission Reduction Effect	Carbon emission reduction rate	(Baseline carbon emissions - Current carbon emissions)/Baseline carbon emissions × 100%	Multi-period monitoring data comparison, historical statistics
		Carbon emission intensity reduction rate	(Baseline carbon emission intensity - Current carbon emission intensity)/Baseline carbon emission intensity × 100%	Multi-period assessment results comparison
	Cultural Protection Effect	Heritage protection satisfaction	Expert score × 0.6 + Tourist score × 0.3 + Resident score × 0.1	Expert reviews, tourist surveys, community interviews
		Cultural dissemination coverage	Number of people aware of heritage culture/Total surveyed population × 100%	Public surveys, digital dissemination data
	Synergistic Efficiency	Synergistic efficiency index	Cultural protection satisfaction/Unit carbon emission	Comprehensive calculation
		Economic-ecological synergy index	Tourism revenue growth rate/Carbon emission growth rate	Tourism revenue statistics, carbon emission assessment data
Digital Empowerment and SME Participation Indicators	Digital Empowerment Coefficient	Digital emission reduction contribution	Digital technology-induced emission reduction/Total emission reduction × 100%	Technology application assessment reports, emission reduction calculation data
		Digital dissemination contribution	Digital channel cultural dissemination volume/Total cultural dissemination volume × 100%	Digital platform operation data, dissemination effect monitoring
	SME Participation	Quantity participation rate	Number of SMEs participating in WHS-related businesses/Total number of relevant enterprises × 100%	Enterprise directory surveys, industry statistics
		Revenue contribution	SME-related business revenue/Total relevant business revenue × 100%	Enterprise surveys, revenue statistics
		Skill adaptability	Number of SMEs with qualified digital low-carbon skills/Total employees × 100%	Enterprise surveys, skill training records

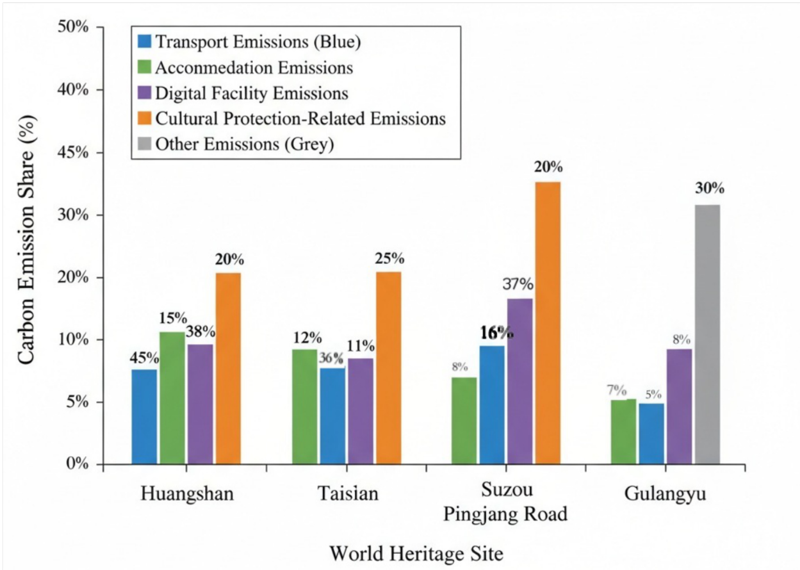

Figure 2 | Comparison Bar Chart of Carbon Emission Structures of Four Major Heritage Sites

ily provide tourism transportation, catering, and accommodation services [8][4].

Data sources: *Huangshan Scenic Area Annual Work Report (2018-2023)*, Huangshan carbon emission monitoring data, tourist questionnaires (800 distributed, 723 valid), interviews with 15 on-site SMEs, and relevant literature [8][4].

Taishan (Mixed mountain-cultural heritage)

Core characteristics: A mixed natural and cultural WHS in Tai'an City, Shandong Province, combining magnificent natural scenery with profound religious and historical culture. Tourism includes natural sightseeing, religious pilgrimages, and cultural experiences. Transportation combines cable cars, sightseeing vehicles, and walking. Digital technologies are applied in virtual research, intelligent navigation, and cultural dissemination. Relevant SMEs—with strong skill adaptability and service innovation capacity—focus on digital CC products, intelligent services, and tourism reception [1][5][17].

Data sources: *Taishan Scenic Area Annual Operation Report (2018-2023)*, archives of Taishan Cultural Heritage Protection Center, tourist questionnaires (900 distributed, 815 valid), operational data and interviews with 20 on-site SMEs, and relevant literature [1][5][17].

Suzhou Pingjiang Road (Historical district heritage)

Core characteristics: A cultural heritage extension project in Suzhou City, Jiangsu Province, preserving the most intact ancient urban area of Suzhou. Core tourism resources include Ming-Qing ancient buildings, canals, and folk culture. Tourism modes focus on walking, in-depth experiences, and homestay stays. Digital technologies are deeply integrated into CC product development, virtual experiences, and smart management. A large number of SMEs cover digital CC, characteristic homestays, and intangible cultural heritage (ICH) experiences, with high digital-low-carbon integration [6][13].

Data sources: Statistical data from Suzhou Gusu District Bureau of Culture and Tourism, Suzhou Pingjiang Road Historical District Protection Plan, tourist questionnaires (700 distributed, 638 valid), surveys of 30 on-site SMEs, field visit records, and relevant literature [6][13].

Gulangyu (Island heritage)

Core characteristics: A cultural WHS in Xiamen City, Fujian Province, featuring island scenery, Western-style architecture, and music culture. Tourism transportation relies on ferries, with activities focusing on sightseeing and leisure. Digital technologies are mainly applied in reservation and crowd-limiting, virtual tours, and intelligent transportation scheduling. Relevant SMEs primarily provide ferry supporting services, homestay catering, and tourism retail [7][15].

Data sources: *Gulangyu World Cultural Heritage Protection and Management Annual Report (2018-2023)*, statistical data from Xiamen Municipal Bureau of Tourism Development, tourist questionnaires (800 distributed, 732 valid), interviews with 18 on-site SMEs, ferry operation data, and relevant literature [7][15].

Results of synergistic effect validation

Comparative analysis of carbon emission structures

Based on the quantitative assessment, carbon emission structures vary significantly across the four WHSs, with key sources closely related to WHS type, tourism mode, and digital economy development level (**Figure 2**):

- Huangshan: The highest total carbon emissions among the four. Transportation accounts for 45% (cable car operations contribute 68% of transportation emissions), energy consumption for 22%, accommodation and catering for 15% and 10% respectively, and digital facilities for 8% (mainly from intelligent monitoring and ticketing systems) [8]. Cultural protection-related emissions account

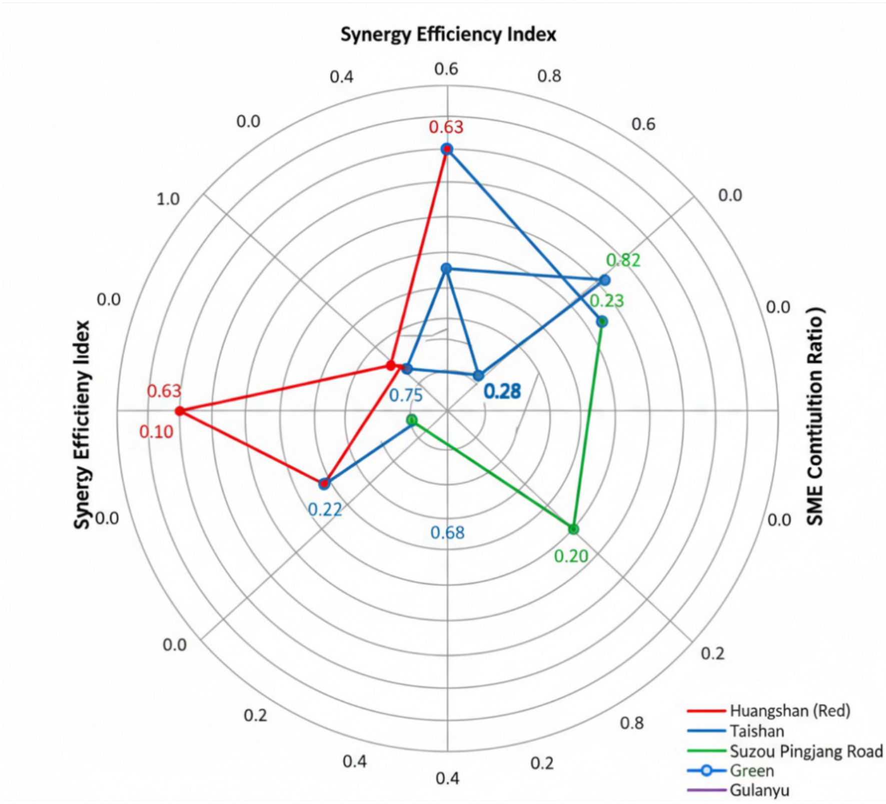

Figure 3 | Radar Chart Comparing Three Dimensions: Collaboration Efficiency, Digital Enablement, and SME Contribution

for 12%, focusing on ecological restoration and daily maintenance of ancient buildings.

- Taishan: The second-highest total carbon emissions. Transportation accounts for 38% (evenly split between cable cars and sightseeing vehicles), cultural protection-related emissions for 18% (mainly from religious building restoration and cultural relic protection equipment), accommodation and catering for 16% and 11% respectively, and digital facilities for 9% (mainly from virtual research platforms and intelligent navigation devices). SMEs' digital tourism services contribute 6%, primarily from digital CC production and intelligent service operations [1][17].
- Suzhou Pingjiang Road: The lowest total carbon emissions. Accommodation accounts for 32% (characteristic homestays contribute 75% of accommodation emissions), cultural protection-related emissions for 25% (core from historical building maintenance and ICH exhibitions), catering for 18%, and digital facilities for 10% (mainly from digital CC development and virtual experience projects). Transportation accounts for only 8% due to walking-focused tourism [6].
- Gulangyu: Moderate total carbon emissions. Transportation accounts for 42% (ferry operations contribute 82% of transportation emissions), indirect emissions from material transportation for 28% (high dependence due to island geography), accommodation and catering for 15% and 10% respectively, and digital facilities for 5% (mainly from reservation and crowd-limiting systems and virtual tour platforms) [7].

Comparison of synergistic efficiency, digital empowerment, and SME participation

Three core indicators are used to compare synergistic development levels: synergistic efficiency index (cultural protection satisfaction per unit carbon emission), digital empowerment coefficient (digital technology-induced emission reduction/total emission reduction), and SME contribution (SME-induced emission reduction/total emission reduction) (Figure 3):

- Synergistic efficiency ranking: Suzhou Pingjiang Road (0.82) > Taishan (0.75) > Gulangyu (0.68) > Huangshan (0.63). Suzhou Pingjiang Road achieves the lowest carbon emission intensity with high cultural protection satisfaction through its "walking tourism + in-depth cultural experience + digital-low-carbon integration" model. Taishan benefits from profound cultural connotations and SME digital service innovation. Gulangyu is constrained by high material transportation emissions, while Huangshan faces high carbon emission intensity due to high-altitude transportation dependence and large-scale ecological restoration needs.
- Digital empowerment coefficient ranking: Suzhou Pingjiang Road (0.35) > Gulangyu (0.32) > Taishan (0.28) > Huangshan (0.22). Suzhou Pingjiang Road's digital technologies are deeply integrated into cultural dissemination

and low-carbon operations (e.g., VR ICH experiences reducing physical tourism pressure, smart energy management systems lowering building energy consumption). Gulangyu's digital reservation system effectively controls tourist peaks. Taishan's virtual research platforms expand cultural dissemination but need deeper low-carbon technology integration. Huangshan's digital technologies focus on management efficiency, with underutilized emission reduction potential [16].

- SME contribution ranking: Taishan (0.23) > Suzhou Pingjiang Road (0.20) > Gulangyu (0.15) > Huangshan (0.10). Taishan's SMEs excel in digital CC development and intelligent navigation, reducing emissions through innovative service models. Suzhou Pingjiang Road's SMEs (characteristic homestays, digital CC) enhance synergy through green renovations and low-carbon services. SMEs in Gulangyu and Huangshan focus on traditional tourism services with low participation and capacity in low-carbon digital transition [17].

Analysis of key driving factors

Comparative analysis identifies four key drivers of synergistic effects:

- Cultural connotations and tourism modes: WHSs with profound cultural connotations and lightweight tourism modes (e.g., walking, in-depth experiences) achieve better synergy—such as Suzhou Pingjiang Road's "slow life" culture and Taishan's religious culture with in-depth research [9].
- Depth of digital technology integration: Higher integration of digital technologies with heritage protection and low-carbon operations—especially virtual experiences, smart energy management, and precise tourist flow control—significantly reduces emissions and enhances cultural dissemination [15][16].
- Quality of SME participation: Higher SME participation and skill adaptability in digital tourism services and low-carbon technology application strongly promote synergistic effects—e.g., Taishan's SMEs driving innovation in digital CC and intelligent services [17].
- Management and policy support: Sound low-carbon management systems and policy support (e.g., subsidies for green homestays in Suzhou Pingjiang Road, ferry energy-saving renovation in Gulangyu) facilitate emission reduction [4].

Empirical conclusions

Carbon emission structures vary significantly across WHS types: mountain WHSs focus on transportation and energy consumption emissions; historical district WHSs on accommodation and cultural protection-related emissions; island WHSs on transportation and material transportation emissions.

Synergistic effects between heritage protection and low-carbon development are feasible but influenced by cultural connotations, tourism modes, digital technology integration, and SME participation. WHSs with profound culture, lightweight tourism, deep digital integration, and high-quality SME participation achieve higher synergistic efficiency.

The digital economy and SMEs have become key emerging drivers: digital technologies reduce emissions and enhance cultural dissemination through virtual experiences and smart management; SMEs promote the application of digital and low-carbon technologies in niche scenarios through flexibility and innovation.

Synergistic development pathways are heterogeneous—WHSs must develop targeted strategies based on key carbon sources, resource endowments, and development stages.

Synergistic Mechanisms for WHS Protection and Low-Carbon Development

Based on empirical results and theoretical support, a four-dimensional synergistic mechanism—"cultural concept guidance-technical support-SME implementation-institutional guarantee"—is constructed, clarifying the core functions, action pathways, and circular reinforcement logic of each dimension, providing a systematic theoretical framework for synergistic development (**Figure 4**).

Cultural concept guidance mechanism: Value foundation of synergistic development

The rich ecological wisdom and cultural connotations of WHSs serve as the core value guidance for synergistic development, providing fundamental principles for technology application, agent participation, and institutional design:

Concept transformation pathway: Integrating traditional ecological concepts (e.g., "harmony between humans and nature," "moderation in resource use") with modern low-carbon and digital dissemination concepts to form contemporary low-carbon values and cultural communication perspectives [9]. For example, Taishan's religious culture of "reverence for nature" is transformed into low-carbon tourist behavior and green operational guidelines for enterprises; Suzhou Pingjiang Road's "slow life" culture shapes tourism values of "in-depth experience, simple consumption, and low-carbon travel."

Behavioral constraint and incentive: Strengthening the sense of responsibility for heritage protection among the public, enterprises, and managers through cultural dissemination and scenario immersion, and internalizing low-carbon behavior [11]. Cultural norms restrain destructive and high-carbon behaviors (e.g., Taishan's religious culture lectures reducing damage to ancient buildings); "culture + low-carbon" values incentivize enterprises to develop green products (e.g., Suzhou Pingjiang Road's homestays implementing energy-saving renovations).

Brand value shaping: Building a "culture + low-carbon + digital" heritage tourism brand to enhance cultural, ecological, and economic value. For example, Gulangyu combines "island culture + low-carbon ferries + virtual tours" to attract tourists, reduce emissions, and expand cultural influence.

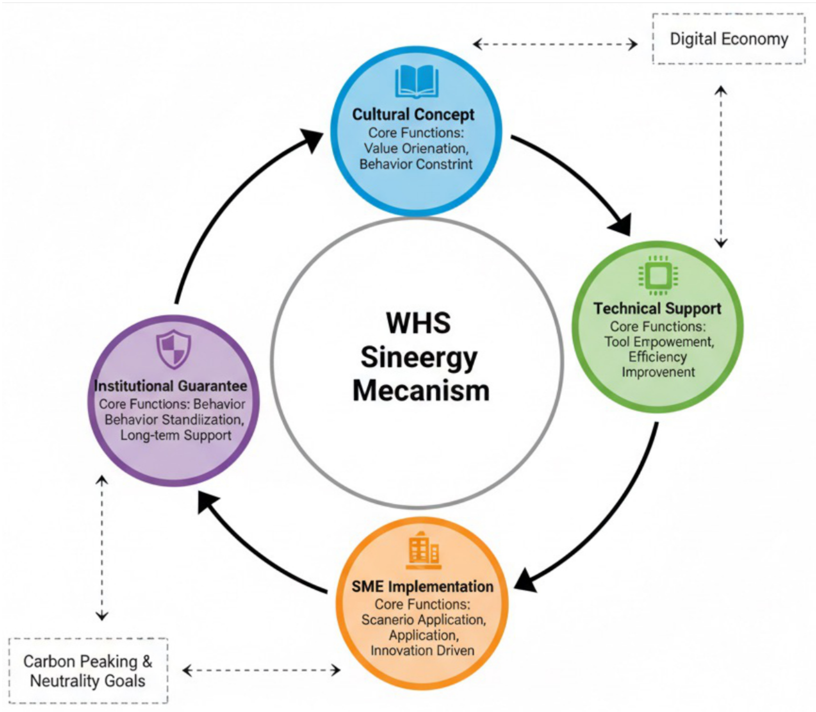

Figure 4 | Four-Dimensional Collaborative Mechanism Cycle Diagram

Technical support mechanism: Implementation pathway of synergistic development

The integrated application of digital and low-carbon technologies provides key technical support, bridging cultural concepts and practical implementation—with application effects closely linked to SME participation:

- Low-carbon renovation technologies: Energy-saving and low-carbon renovations of heritage buildings and tourism facilities to reduce energy consumption and emissions [6][13]. Examples include using thermal insulation materials and solar panels for historical buildings, electrifying cable cars and sightseeing vehicles, and promoting rainwater collection and waste classification.
- Digital dissemination and experience technologies: Innovating cultural heritage dissemination and experience through VR/AR, big data, and AI [15][16]. Virtual heritage experiences (e.g., Taishan's virtual research platforms, Suzhou Pingjiang Road's digital ICH exhibition halls) reduce physical tourism emissions; digital media platforms expand cultural influence. SMEs excel in digital content creation and virtual experience development, quickly responding to market demands [17].
- Precision management and monitoring technologies: Achieving precise management of carbon emissions and cultural protection through IoT, big data, and cloud computing [8][16]. Sensors monitor carbon emissions, air quality, and cultural relic status in real time; big data analyzes tourist flow and consumption habits to optimize transportation and energy allocation; blockchain establishes credible traceability systems for heritage protection and low-carbon transition.

SME implementation mechanism: Micro-carriers of synergistic development

As key micro-agents integrating the digital economy and heritage tourism, SMEs are critical for the implementation of the synergistic mechanism, with core roles in skill matching, service innovation, and scenario-based application [17]:

- Skill mismatch bridging: The application of digital and low-carbon technologies in WHSs requires interdisciplinary talents proficient in technology, heritage culture, and tourism operations. SMEs—with flexible employment and training systems—quickly cultivate or introduce qualified talents, promoting technology application in specific scenarios (e.g., Taishan's SMEs collaborating with universities to train talents in digital technology and cultural communication).
- Service and product innovation: SMEs' innovation vitality and market responsiveness enable them to develop diversified products and services around "culture + low-carbon + digital" (e.g., Suzhou Pingjiang Road's digital ICH products, low-carbon homestay packages; Gulangyu's "low-carbon travel + virtual experience" combined services).
- Industrial chain synergy and integration: SMEs play roles in niche segments of the WHS tourism industrial chain, forming collaborative relationships with large enterprises and governments to build a complete "cultural protection-low-carbon development-digital empowerment" industrial chain. For example, in Taishan, large enterprises con-

struct digital infrastructure, while SMEs focus on digital CC and intelligent navigation, creating a complementary industrial ecosystem.

Institutional policy guarantee mechanism: Long-term support for synergistic development

A sound institutional policy system provides stable guarantees for the effective operation of the synergistic mechanism, regulating behaviors, stimulating participation, resolving conflicts, and ensuring sustainability:

- Planning constraint mechanism: Integrating cultural protection, low-carbon development, digital empowerment, and SME cultivation into WHS protection and development plans, clarifying goals, key tasks, and assessment indicators [12]. Examples include formulating "climate-resilient heritage management plans" and digital economy special plans, and incorporating SME participation into planning.
- Incentive mechanism: Establishing a diversified incentive system to stimulate participation from enterprises, tourists, and residents. Measures include financial subsidies, tax breaks, and credit support for low-carbon and digital transformation enterprises (especially SMEs); ticket discounts for low-carbon tourists; and innovation funds for SME digital-low-carbon R&D [17].
- Collaborative governance mechanism: Building a multi-stakeholder governance system—"government-scenic management institutions-enterprises (including SMEs)-community residents-tourists"—clarifying rights and responsibilities. Governments formulate policies and supervise; scenic management institutions coordinate planning and implementation; enterprises provide products and services; residents participate in protection; tourists practice low-carbon consumption. Regular communication mechanisms resolve conflicts, forming a co-construction and shared governance model [11].
- Supervision and assessment mechanism: Establishing a scientific supervision and assessment system incorporating synergistic efficiency, emission reduction effects, cultural protection quality, digital empowerment, and SME participation. Third-party evaluation ensures objectivity; assessment results are linked to government performance, scenic operation rights, and enterprise support policies; information disclosure accepts public supervision [5].

Operational logic of the mechanism

The four-dimensional synergistic mechanism operates through a circular reinforcement logic: "concept guidance-technical support-enterprise implementation-institutional guarantee-concept deepening":

Cultural concepts guide technology application, enterprise participation, and institutional design, ensuring synergistic development aligns with "cultural protection priority and low-carbon transition empowerment."

Technical means provide tools for concept transformation, enterprise implementation, and institutional landing, converting abstract concepts into practical actions, and providing data support for assessment.

SMEs integrate cultural concepts and technical tools into products and services, promoting scenario-based implementation and providing feedback for concept innovation, technology optimization, and institutional improvement.

Institutional policies regulate behaviors, stimulate motivation, and resolve conflicts, providing a stable environment for cultural inheritance, technology promotion, and SME development.

Practical feedback deepens cultural concepts, promotes technological upgrading, optimizes enterprise participation models, and improves institutional design, forming a positive cycle of continuous synergistic development.

Optimization Pathways for WHS Protection and Low-Carbon Development

Based on the four-dimensional synergistic mechanism and empirical results, targeted and operable optimization pathways are proposed from four aspects—cultural communication, technological innovation, agent cultivation, and institutional improvement—addressing the core characteristics and practical dilemmas of different WHS types.

Cultural communication optimization: Strengthening concept guidance and consolidating synergistic foundations

Targeted communication strategies

Developing differentiated communication content and methods for different groups:

- Tourists: Focus on "cultural experience + low-carbon guidelines" through scenic navigation, brochures, and digital platform pushes—e.g., setting up religious ecological culture exhibition boards in Taishan, and providing low-carbon living guides in Suzhou Pingjiang Road's homestays.
- Community residents: Focus on "cultural inheritance + benefit linkage" through community lectures and cultural activities, emphasizing employment and income growth from synergistic development to stimulate participation.
- Enterprises (including SMEs): Focus on "cultural value + business opportunities" through industry forums and case sharing, guiding enterprises to develop products with profound cultural connotations and low-carbon attributes (e.g., digital CC, green homestays) [17].
- Managers: Focus on "synergistic concepts + governance capacity" through training and exchange visits, enhancing understanding of synergistic logic and policy formulation capabilities.

Scenario-based integrated communication

Integrating heritage culture and low-carbon concepts into the entire tourism experience:

- Sightseeing scenarios: Designing "culture + low-carbon" experience projects—e.g., Suzhou Pingjiang Road's "ICH + low-carbon" routes combining traditional crafts with waste classification; Taishan's "reverence for nature" themed experience areas.
- Accommodation scenarios: Promoting homestays and hotels as cultural communication and low-carbon practice carriers—e.g., decorating homestays with traditional ecological culture themes, providing low-carbon daily necessities, and implementing "energy-saving points exchange" activities.
- Digital scenarios: Creating immersive cultural communication through VR/AR and short videos—e.g., developing "heritage culture + low-carbon science" short video series; virtual experience projects combining heritage appreciation with low-carbon knowledge learning [15][16].

Educational penetration communication

Incorporating heritage culture and low-carbon knowledge into national education to cultivate long-term synergistic development forces:

- School education: Collaborating with primary and secondary schools and universities to develop school-based courses and research programs—e.g., organizing university students to participate in WHS carbon emission monitoring and cultural surveys.
- Social education: Conducting public lectures and training through museums and community schools to popularize knowledge.
- Scenic education: Establishing science education bases in WHSs with professional interpreters, designing interactive educational activities for young tourists.

Technological innovation and application: Improving dynergistic efficiency and expanding implementation pathways

Type-specific technology adaptation strategies

Promoting targeted technologies based on the core characteristics and key carbon sources of different WHS types:

- Mountain WHSs (Huangshan, Taishan): Focusing on transportation energy-saving and digital monitoring technologies—e.g., electrifying cable cars and sightseeing vehicles, deploying IoT monitoring systems, and developing virtual research services to reduce physical tourist flow [8][16].
- Historical district WHSs (Suzhou Pingjiang Road): Focusing on building energy-saving and digital CC technologies—e.g., non-invasive energy-saving renovations of historical buildings, promoting renewable energy, and developing digital ICH products [6][15].
- Island WHSs (Gulangyu): Strengthening material recycling and digital scheduling technologies—e.g., promoting seawater desalination and rainwater collection, establishing material recycling systems, and optimizing digital reservation and ferry scheduling algorithms [7].

SME technological empowerment

Enhancing SME capacity for digital-low-carbon transition through technical support:

- R&D support: Establishing special funds for SME technological innovation, supporting collaboration with universities and research institutions; building technology sharing platforms to provide low-cost technology access and consulting services.
- Skill training support: Conducting interdisciplinary training—"digital technology + low-carbon technology + cultural knowledge"—for SME employees, improving skills in VR/AR content creation, intelligent device operation, and low-carbon management [17].
- Demonstration and promotion support: Selecting exemplary SME digital-low-carbon innovation cases for promotion; providing financial subsidies for advanced technology adoption to reduce application costs.

Construction of technology integration platforms

Building an integrated digital-low-carbon management platform for WHSs to achieve synergistic technology application and data sharing:

- Functional modules: Integrating carbon emission monitoring, tourist management, energy management, cultural communication, and SME services to realize full-process digital management from "monitoring-analysis-decision-making-implementation."
- Data sharing mechanism: Breaking data silos between governments, scenic areas, enterprises, and research institutions to share carbon emission, tourist, cultural protection, and R&D data, improving decision-making scientificity.
- Service support: Providing SMEs with technology matching, product display, and market promotion services, facilitating collaboration with large enterprises and governments to form an innovation ecosystem.

Agent cultivation enhancement: Activating micro-carriers and consolidating implementation bases

Precise SME cultivation

Developing targeted policies for SME roles and development dilemmas:

- Access and incubation support: Establishing SME incubation bases for digital-low-carbon startups, providing office space and entrepreneurial guidance; simplifying market access for SMEs in digital CC, intelligent services, and low-carbon renovations [17].

- Financial and policy support: Establishing a diversified financing system with low-interest loans, guarantees, and subsidies; offering preferential policies on taxes, land, and energy for SMEs participating in synergistic development.
- Collaboration support: Building collaboration platforms between SMEs, large enterprises, and governments to integrate SMEs into the WHS tourism industrial chain; organizing participation in domestic and international exhibitions to expand market channels.

Multi-agent collaborative cultivation

Strengthening the participation capacity and willingness of other stakeholders:

- Enterprise stakeholders: Guiding large tourism enterprises to lead low-carbon R&D and digital infrastructure construction, and collaborate with SMEs; promoting corporate social responsibility by integrating cultural protection and low-carbon development into strategies.
- Community resident stakeholders: Cultivating community self-governance organizations to enhance organized participation; establishing incentive mechanisms for residents participating in low-carbon practices and heritage protection.
- Tourist stakeholders: Cultivating low-carbon consumption habits through publicity and incentives; establishing feedback mechanisms for tourists to contribute suggestions.

Institutional policy Improvement: Building long-term mechanisms and strengthening guarantee support

Improvement of planning and assessment systems

- Synergistic planning formulation: Developing WHS synergistic development plans integrating cultural protection, low-carbon transition, digital economy, and SME cultivation, forming a "four-in-one" planning system [12][16].
- Indicator optimization: Improving the assessment indicator system to include synergistic efficiency, emission reduction effects, cultural protection quality, digital empowerment, and SME participation, with regular evaluations.
- Dynamic adjustment mechanism: Establishing dynamic monitoring and adjustment of plan implementation, optimizing content and strategies based on assessment results, technological development, and policy changes.

Precise policy supply

Providing targeted policy support for different WHS types and development stages:

- Differentiated policies: Offering transportation energy-saving subsidies for mountain WHSs, building energy-saving subsidies for historical districts, and material recycling support for island WHSs.
- SME-specific policies: Introducing special policies for SME participation, including skill training subsidies, innovation rewards, and market access facilitation [17].
- Incentive policies: Establishing WHS carbon trading pilots; publicly recognizing low-carbon outstanding performers.
- Restrictive policies: Setting low-carbon access standards for high-energy-consuming enterprises; establishing environmental credit evaluation systems linked to policy support and market access.

Construction of cross-regional synergistic mechanisms

Establishing exchange and cooperation mechanisms between different WHS types to promote resource sharing and experience learning:

- Experience sharing platforms: Organizing seminars and field visits to share successful experiences in cultural communication, technology application, and institutional construction.
- Resource integration mechanisms: Integrating cross-regional heritage tourism routes to create "culture + low-carbon" themed routes; promoting cross-regional technology and SME collaboration.
- Policy coordination mechanisms: Strengthening inter-regional policy coordination to avoid conflicts and duplicate construction; establishing a national WHS synergistic development policy framework.

Conclusions

Based on multi-disciplinary core literature, this study constructs a comprehensive research framework of "methodological integration-empirical validation-mechanism construction-path optimization," systematically exploring the synergistic logic and implementation pathways of cultural heritage protection and low-carbon development in WHSs. Key conclusions are as follows (**Figure 5**):

Significant inherent synergy exists between cultural heritage protection and low-carbon development in WHSs, rooted in ecological wisdom in heritage cultures, enabled by digital and low-carbon technologies, implemented by SMEs, and guaranteed by institutional policies—achieving the triple enhancement of cultural, ecological, and economic value.

Carbon emission structures and synergistic efficiency vary significantly across WHS types: mountain WHSs are dominated by transportation and energy consumption emissions, with synergistic efficiency constrained by high-altitude transportation and ecological restoration; historical district WHSs focus on accommodation and cultural protection-related emissions, achieving the highest synergistic efficiency through lightweight tourism and digital-low-carbon integration; island WHSs are dominated by transportation and material transportation emissions, limited by geographical conditions. Key influencing factors include cultural connotations, tourism modes, digital technology integration, and SME participation.

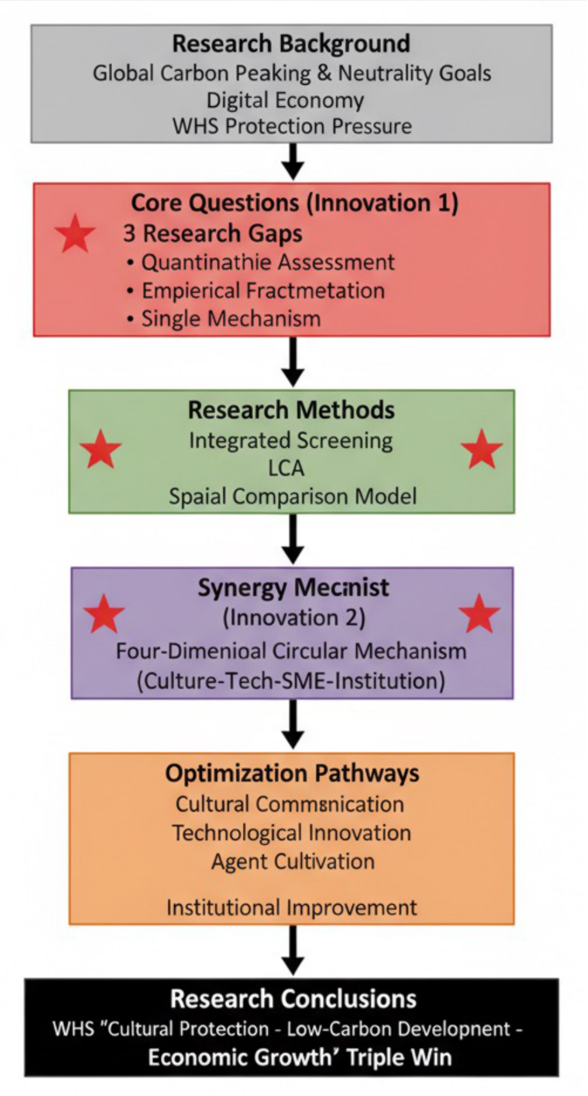

Figure 5 | Research Framework Integration Diagram

The integrated quantitative assessment system—combining screening, LCA, and spatial comparison models—comprehensively accounts for WHS ecological/carbon footprints, covering direct, indirect, and cultural protection-related emissions, and incorporating emerging indicators such as digital facility emissions and SME participation, adapting to the triple goals of "culture-low-carbon-digital."

The four-dimensional synergistic mechanism—"cultural concept guidance-technical support-SME implementation-institutional guarantee"—is the core logic for synergy, with mutual interaction and circular reinforcement: concepts guide direction, technologies improve efficiency, SMEs implement actions, and institutions ensure long-term effectiveness.

Optimization pathways balance universality and heterogeneity, proposing targeted strategies for different WHS types from cultural communication, technological innovation, agent cultivation, and institutional improvement, while emphasizing the empowering role of the digital economy and SMEs.

Future research can be deepened and expanded in three directions:

- Expanding research scope and case quantity: Including more international WHSs for cross-country comparison to verify the universality and particularity of the synergistic mechanism, and extracting differentiated rules across countries and cultural backgrounds.
- Refining quantitative models and data support: Optimizing emission factor calculation and synergistic efficiency evaluation with field monitoring, SME operational, and long-term tracking data; introducing machine learning and big data to build dynamic prediction models for precise decision support.
- Tracking technological and policy changes: Continuously monitoring the development of digital and low-carbon technologies and the deepening of "double carbon" policies, dynamically optimizing the synergistic mechanism and practical pathways. Special attention should be paid to the application prospects of emerging technologies such as AI and metaverse in WHSs, and the evolving role of SMEs in the technological revolution, providing forward-looking theoretical and practical support for WHS sustainable development.

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