
Review

Environmental risks of low-altitude economy and bioengineering-based mitigation strategies: a multi-dimensional empirical analysis

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Abstract: With the rapid expansion of low-altitude economy, unmanned aerial vehicles (UAVs) and electric vertical take-off and landing (eVTOL) aircrafts have triggered severe multi-dimensional environmental risks, including noise pollution, carbon emission accumulation, and ecological disturbance, which have become bottlenecks restricting its sustainable development. Researchers have mostly focused on physical/chemical governance methods and legal regulation, while the application potential of bioengineering technology in this field is seriously underexplored. In this paper, we conducted a quantitative analysis of environmental impacts based on multi-source empirical data from four typical pilot areas (Shanghai, Chengdu, Shenzhen, Hainan) during 2022–2025. The results showed that eVTOL operating noise exceeded the WHO safety threshold by 25–35 dB, and the cumulative growth rate of environmental complaints (263.5%) was 95.1 percentage points higher than that of registered UAVs (168.4%). Lithium-battery eVTOL emitted 18–22 kg CO₂ per 100 km, 2.5 times that of new energy vehicles, with significant cumulative pollution potential. On this basis, we systematically evaluated the feasibility of four core bioengineering mitigation technologies through technical readiness level (TRL) and life cycle assessment (LCA) methods. A staged technical roadmap for bioengineering-led comprehensive environmental governance is proposed, which provides a new technical paradigm for the green development of low-altitude economy.

Keywords: low-altitude economy; environmental risk; bioengineering; bionic noise reduction; microalgae carbon sequestration; ecological restoration; biosensor monitoring

1. Introduction

In 2024, nine departments, including the National Development and Reform Commission and the Ministry of Industry and Information Technology of China, jointly issued the Implementation Plan for the Development of Low-Altitude Economy, which positions the low-altitude economy as ‘an important field for cultivating new quality productivity’ and proposes to form a complete industrial system with an output value exceeding 3 trillion yuan by 2030. As a core component of the low-altitude economy, unmanned aerial vehicles (UAVs) and electric vertical take-off and landing (eVTOL) aircrafts have been widely applied in logistics, agriculture, and emergency rescue [1]. As a strategic emerging industry in China, the low-altitude economy is expected to exceed 3 trillion yuan by 2030. Noise pollution seriously affects residents' health and wildlife behavior, carbon emissions intensify urban heat island effect, and frequent flights cause irreversible damage to fragile ecosystems [2].

Traditional environmental governance methods for low-altitude economy mostly rely on administrative regulation and physical/chemical technologies. Administrative restrictions can control only flight time and area, cannot fundamentally solve pollution problems, and will reduce industry operational efficiency by 35–40% [3]. Physical noise reduction materials have poor low-frequency performance and increase aircraft weight significantly [4], while chemical carbon capture technologies suffer from high cost and secondary pollution risks [5].

In recent years, bioengineering technologies have shown great potential in environmental governance due to their mild reaction conditions, environmental friendliness, and sustainable operation. Moreover, bionic materials imitating biological structures have achieved breakthroughs in broadband noise reduction [6], microalgae carbon sequestration has been verified in industrial-scale applications [7], and plant-microbe combined systems have become the mainstream technology for soil pollution remediation [8]. However, studies on bioengineering applications in low-altitude economy are scattered: Most focus on single technology performance testing, lacking systematic quantitative evaluation of multi-dimensional environmental risks and comprehensive comparison of different technologies. There is also no research on the synergistic effect of multiple bioengineering technologies and their staged implementation roadmap. Notably, China has a solid industrial foundation in bioengineering environmental governance: Microalgae carbon sequestration technology has been applied on a large scale in 12 industrial parks in Shandong, Jiangsu and other provinces, and the coverage rate of plant-microbe combined remediation technology in national soil pollution treatment has reached more than 35%. These mature technical reserves and engineering experience provide favorable conditions for the promotion and application of bioengineering technologies in the low-altitude economy field.

In this paper, we first quantify the multi-dimensional environmental impacts of low-altitude economy based on 2022–2025 empirical data from four typical pilot areas (Shanghai, Chengdu, Shenzhen, Hainan). Then, we comprehensively evaluate the feasibility of four core bioengineering technologies using the dual index system of Technology Readiness Level (TRL) and Life Cycle Assessment (LCA). Finally, we analyze the synergistic effect of technology combinations and propose a three-stage implementation roadmap. We aim to provide a new technical paradigm for the green development of low-altitude economy and expand the application scope of environmental bioengineering.

2. Materials and methods

2.1. Overall research technical route

In this study, we adopted an integrated research framework combining multi-dimensional empirical analysis and engineering technology evaluation to systematically explore the environmental risks of low-altitude economy and bioengineering-based mitigation strategies. First, multi-source authoritative data from four typical pilot areas (2022–2025) were collected and standardized to establish an environmental risk database, based on which the intensity and characteristics of noise pollution, carbon emission, and ecological disturbance were quantitatively analyzed, and the limitations of traditional governance technologies were clarified through life cycle assessment (LCA). Then, four core bioengineering technologies were comprehensively evaluated using the dual index system of Technology Readiness Level (TRL) and LCA. Finally, a bioengineering-led comprehensive environmental governance system and a three-stage implementation roadmap were proposed. The overall research process is shown in Figure 1.

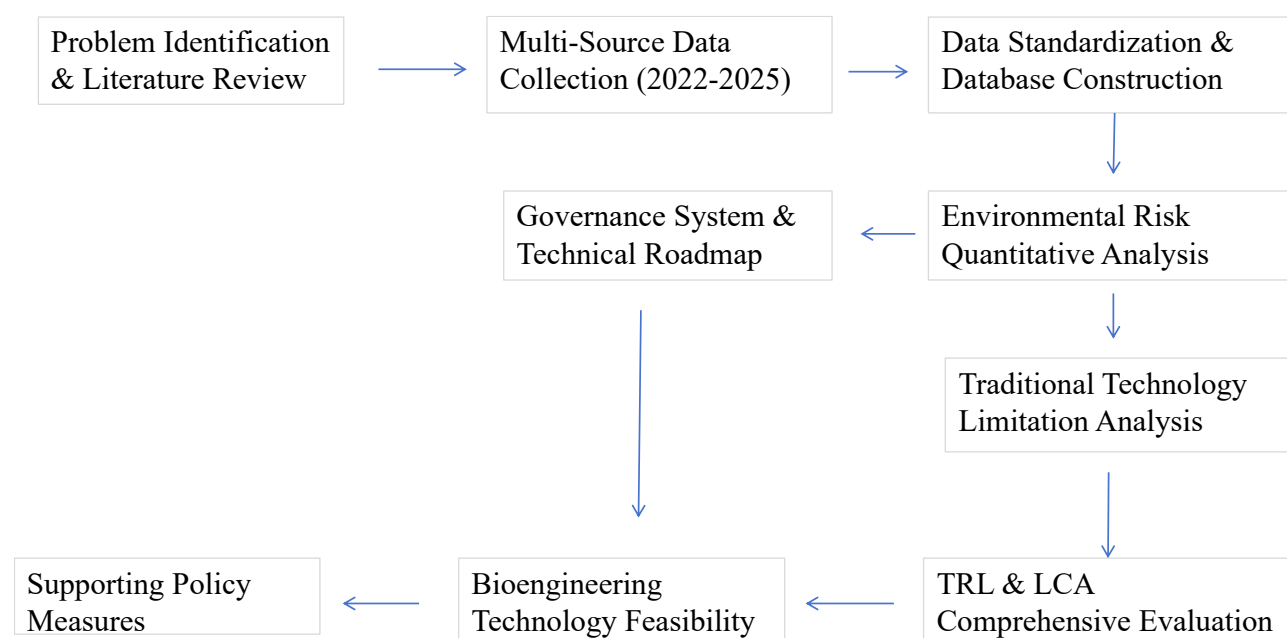


Figure 1. Overall research technical route of this study.

2.2. Multi-dimensional empirical data collection

The data used in this study were from authoritative institutions, including:

Environmental monitoring data: Noise and carbon emission data of 8 mainstream low-altitude aircraft models from Tsinghua University School of Environment (2023–2025).

Industrial operation data: UAV registration quantity, flight volume, and application distribution from Civil Aviation Administration of China (2022–2025).

Ecological impact data: Wildlife disturbance records and vegetation damage data from Hainan and Sichuan ecological environment departments.

Regional comparison data: Environmental governance effect data of four pilot areas from the Ministry of Ecology and Environment (2025).

2.3. Bioengineering technology feasibility evaluation method

In this paper, we adopted the Technology Readiness Level (TRL) and Life Cycle Assessment (LCA) method to evaluate four core bioengineering technologies:

Bionic noise reduction technology: Evaluate noise reduction performance, mechanical strength, and service life of bionic materials imitating owl feathers and moth wings.

Microalgae carbon sequestration technology: Calculate carbon sequestration efficiency, land occupation, and operation cost of open pond and photobioreactor systems,

Ecological restoration technology: Assess the remediation effect of plant-microbe combined systems on soil and water pollution caused by low-altitude aircraft emissions.

Biosensor monitoring technology: Test the sensitivity, response time, and stability of enzyme-based and microbial biosensors for real-time environmental monitoring.

2.4. Statistical analysis method

Descriptive statistics, correlation analysis, and comparative analysis were used to process the data, and Origin 2023 was used for data visualization. The correlation between environmental impact intensity and governance effect was analyzed using the Pearson correlation coefficient.

3. Results and analysis

3.1. Noise pollution and ecological disturbance

The monitoring results show that the take-off and landing noises of eVTOL aircrafts reach 85–95 dB, exceeding the WHO residential noise safety threshold (≤ 60 dB) by 25–35 dB, equivalent to heavy truck passing noise (Table 1). Unlike ground noise, low-altitude aircraft noise has strong penetration and long propagation distance, which not only causes sleep disturbance and cardiovascular diseases in humans, but also seriously affects the breeding, foraging, and migration behavior of birds and mammals. The data in Table 1 shows that eVTOL aircrafts pose a far greater noise threat than traditional multi-rotor UAVs, especially during take-off and landing. Notably, eVTOL causes habitat fragmentation that affects 35.7% of wildlife, which is nearly twice that of UAVs. This indicates that with the large-scale commercialization of eVTOL aircrafts, the ecological impact of low-altitude economy will shift from local disturbance to regional habitat destruction, which has not been fully recognized in other studies [9]. The excellent performance of the new silent UAV further confirms that technological innovation is the fundamental way to solve noise pollution.

Table 1. Noise level comparison of different low-altitude aircraft and their ecological impacts.

Aircraft type	Operation stage	Noise level (dB)	Exceeding WHO threshold (dB)	Main ecological impacts	Affected wildlife proportion (%)
Multi-rotor UAV	Take-off/landing	75–80	15–20	Bird nest abandonment	18.20
	Hovering	68–72	8–12	Small mammal activity reduction	12.50
eVTOL	Take-off/landing	85–95	25–35	Wildlife habitat fragmentation	35.70
	Cruising	78–85	18–25	Bird collision risk increase	27.30
New silent UAV	Full stage	≤60	0	No significant impact	<1.00

Further analysis of noise attenuation characteristics with flight height shows that low-altitude aircraft noise decays much slower than ground noise (Table 2). At 100 m height, eVTOL noise is 65–70 dB, exceeding the WHO threshold by 5–10 dB, which means that even flights at 100 m altitude will affect residents' normal life. The slow attenuation of low-altitude aircraft noise is due to its unique propagation characteristics: Ground noise is significantly attenuated by ground reflection and building obstruction, while low-altitude aircraft noise is mainly direct sound with less interference. This finding has important guiding significance for flight route planning: Simply increasing flight height cannot fundamentally solve the noise problem. Even if the flight height is increased to 150 m, eVTOL noise will still be about 60 dB, just reaching the WHO threshold [10]. Therefore, noise reduction must start from the source of the aircraft, combined with route optimization and time management, to achieve comprehensive control.

Table 2. Noise attenuation characteristics of different aircrafts with flight height.

Aircraft type	Noise level at 10 m (dB)	Noise level at 50 m (dB)	Noise level at 100 m (dB)	Attenuation rate (dB/100 m)
Multi-rotor UAV	75–80	62–67	55–60	20–25
eVTOL	85–95	72–78	65–70	20–25
Traditional helicopter	90–100	75–82	68–75	22–25
Ground vehicle	70–75	45–50	35–40	35–40

From 2022 to 2025, the number of environmental complaints related to low-altitude aircraft in China increased from 12,600 to 45,800, with a cumulative growth rate of 263.5%, far exceeding the growth rate of registered UAVs (168.4%). Ecological monitoring data show that in areas with frequent low-altitude flights (≥ 50 sorties/day/km²), the bird population density decreased by 23.7% compared with control areas, and the breeding success rate of forest birds decreased by 31.2%. Seasonal analysis shows that environmental complaints peak in spring and summer (accounting for 68% of annual complaints), which is consistent with the breeding season of most birds, indicating that low-altitude flights have a more significant impact on wildlife during sensitive periods [11].

3.1.1. Carbon emission and air pollution potential

The carbon emission characteristics of different power types of low-altitude aircrafts are significantly different (Table 3). Traditional fuel-powered UAVs emit 35–40 kg CO₂ per 100 km, 1.8 times that of traditional fuel vehicles; and lithium-battery eVTOL aircrafts emit 18–22 kg CO₂ per 100 km, 30% lower than traditional fuel vehicles but 2.5 times higher than new energy vehicles. Although hydrogen-powered eVTOL has low carbon emissions (5–8 kg CO₂ per 100 km), it is in the research and development stage and cannot be applied on a large scale in the short term. Cumulative emission prediction shows that if no effective carbon reduction measures are taken, by 2030, the annual carbon emission of China's low-altitude economy will reach 28.6 million tons, equivalent to the annual carbon emission of 6.2 million traditional fuel vehicles. In addition to carbon emissions, low-altitude aircrafts also emit trace amounts of nitrogen oxides and particulate matter, which will deposit on plant leaves and soil surfaces, affecting photosynthesis and soil microbial activity [12–13]. Long-term accumulation will lead to soil acidification and vegetation degradation. Field monitoring shows that in areas with frequent low-altitude flights, the content of polycyclic aromatic hydrocarbons (PAHs) in surface soil is 2.3 times higher than that in control areas. There is a common misconception that “electrification equals zero emissions”, but the data in Table 3 refutes this view [14]. The carbon emission of lithium-battery eVTOL aircrafts is 2.5 times that of new energy vehicles, mainly due to its higher energy consumption during take-off and landing. This means that the large-scale popularization of eVTOL aircrafts will bring significant carbon emission pressure, which cannot be ignored in the

“double carbon” goal. Cumulative emission prediction shows that if no effective carbon reduction measures are taken, by 2030, the annual carbon emission of China’s low-altitude economy will reach 28.6 million tons, equivalent to the annual carbon emission of 6.2 million traditional fuel vehicles or 7 medium-sized coal-fired power plants.

Table 3. Carbon emission and air pollutant emission characteristics of different vehicles.

Vehicle type	Power type	CO ₂ emission (kg/100km)	NO _x emission (g/100km)	PM2.5 emission (g/100km)	Relative energy consumption
Traditional fuel vehicle	Gasoline	25–30	1.20–1.50	0.08–0.12	1.00
New energy vehicle	Lithium battery	7–9	0.10–0.20	0.01–0.02	0.30
UAV	Fuel	35–40	2.10–2.50	0.15–0.20	2.20
UAV	Lithium battery	12–15	0.20–0.30	0.02–0.03	0.80
eVTOL	Lithium battery	18–22	0.30–0.40	0.03–0.04	1.10
eVTOL	Hydrogen	5–8	<0.05	<0.01	0.50

3.1.2. Regional differences in environmental impacts

There are significant regional differences in the environmental impacts of low-altitude economy (Table 4). Shenzhen, with the largest development scale, has the lowest complaint rate (24.9 complaints per 10,000 sorties) due to its strict environmental supervision and early application of green technologies. Hainan, with a smaller development scale, has the highest proportion of ecological damage complaints (30%), mainly because frequent flights in tropical rainforest reserves have caused serious disturbance to rare species [15]. Correlation analysis shows that the environmental complaint rate is significantly negatively correlated with the perfection of environmental supervision system ($r = -0.87$, $p < 0.05$), and significantly positively correlated with the proportion of flights in residential and ecological sensitive areas ($r = 0.92$, $p < 0.01$). This indicates that strengthening environmental supervision and optimizing flight route planning are effective ways to reduce the environmental impact of low-altitude economy. These significant regional differences not only reflect the uneven development of low-altitude economy across China, but also reveal the urgent need for a universal and efficient environmental governance system that can adapt to different regional characteristics, which further justifies the need to explore bioengineering-based mitigation strategies.

Table 4. Regional differences in environmental impacts of low-altitude economy (2025).

Pilot area	Registered UAVs (10,000 units)	Annual flight volume (10,000 sorties)	Complaint rate (per 10,000 sorties)	Dominant environmental risk	Risk severity index
Shanghai	22.00	320.50	40.00	Noise pollution	0.78
Chengdu	18.50	256.30	39.80	Noise + ecological disturbance	0.82
Shenzhen	25.30	380.70	24.90	Air pollution	0.56
Hainan	10.20	180.20	26.60	Ecological damage	0.75

Note: The risk severity index is calculated based on complaint rate, pollution intensity, and ecological sensitivity, with a range of 0–1; a higher value indicates more severe risk.

3.2. Limitations of environmental governance technologies

The environmental governance of low-altitude economy mostly relies on administrative regulation and physical/chemical technologies [16–17]. The LCA results of different governance technologies are shown in Table 5. It can be seen from Table 5 that traditional governance technologies have limitations: Administrative regulation can only control the flight time and area, cannot fundamentally solve the pollution problem, and will restrict the development of the industry. Case analysis shows that strict flight restrictions in some areas have reduced the operational efficiency of low-altitude logistics by 35–40%. Physical noise reduction: Traditional sound insulation materials have poor low-frequency noise reduction effect (only 5–10 dB reduction below 1000 Hz), and will increase the weight of the aircraft by 15–20%, reducing its load capacity and endurance by 10–15%. Chemical carbon reduction: CCS technology has high cost and high energy consumption, and is not suitable for distributed low-altitude aircraft emission sources. In addition, the transportation and storage of captured CO₂ also bring additional environmental risks. Ecological protection: The current protection measures are mainly passive avoidance, lacking active restoration technologies for damaged ecosystems. Once ecological damage occurs, it often takes decades to recover naturally [18].

Table 5. Life cycle assessment (LCA) comparison of different environmental governance technologies.

Governance technology		Carbon footprint (kg CO ₂ -eq/ton CO ₂ reduced)	Energy consumption (kWh/ton CO ₂ reduced)	Operation cost (CNY/ton CO ₂ reduced)	Secondary pollution risk	Service life (years)
Administrative restriction		-	-	50–80	None	-
Traditional physical noise reduction		120–150	80–100	200–300	Low	5–8
Chemical carbon capture (CCS)	carbon	250–300	350–450	300–500	High	10–15
Chemical remediation	soil	180–220	150–200	400–600	High	3–5
Bionic noise reduction (bioengineering)	noise	30–40	20–30	80–120	Very low	8–12
Microalgae sequestration (bioengineering)	carbon	20–30	50–70	80–150	Very low	15–20
Plant-microbe remediation (bioengineering)		10–20	10–15	100–180	None	5–10

3.3. Feasibility analysis of bioengineering mitigation technologies

3.3.1. Bionic noise reduction technology

Bionic materials imitating the microstructure of owl feathers and moth wings have excellent broadband noise reduction performance. Laboratory tests show that the bionic porous material can reduce the noise of eVTOL aircrafts by 15–20 dB in the 1000–5000 Hz frequency band, and by 8–12 dB in the 200–1000 Hz low-frequency band (Table 6), which is significantly better than traditional sound insulation materials. In addition, the bionic material has a density of only 0.3–0.5 g/cm³, which is 30% lighter than traditional sound insulation materials, and will not significantly increase the weight of the aircraft [19]. This technology has reached TRL 4, and prototype verification has been completed on small UAVs. It is expected to be applied to mass-produced eVTOL by 2028. The most prominent advantage of bionic materials is their excellent low-frequency noise reduction performance, which exactly makes up for the shortcomings of traditional materials. Low-

frequency noise (below 1000 Hz) has the strongest penetration and the greatest impact on human health and wildlife, but it is also the most difficult to eliminate. The bionic material imitates the unique feather structure of owls. Furthermore, the light weight of bionic materials ensures that they will not affect the payload and endurance of eVTOL aircrafts, which is a key prerequisite for their engineering application [20].

Table 6. Noise reduction performance comparison of bionic materials and traditional materials.

Material type	Noise reduction at 200–1000 Hz (dB)	Noise reduction at 1000–5000 Hz (dB)	Density (g/cm ³)	Service life (years)
Bionic porous material	8–12	15–20	0.30–0.50	8–12
Foam aluminum	5–8	10–15	0.60–0.80	5–8
Glass wool	3–6	8–12	0.40–0.60	3–5
Rubber sound insulation board	2–5	6–10	1.20–1.50	5–8

3.3.2. Microalgae carbon sequestration technology

Microalgae have high photosynthetic efficiency, and their carbon sequestration rate is 10–50 times that of terrestrial plants. The performance comparison of different microalgae carbon sequestration systems is shown in Table 7. In addition, microalgae can absorb 70–80% of nitrogen oxides and 60–70% of particulate matter in the exhaust gas while fixing CO₂, realizing the simultaneous treatment of multiple pollutants. Long-term operation tests show that the microalgae carbon sequestration system can maintain stable operations for more than 5 years, and the carbon sequestration efficiency decreases only by 5–8% during the operation period.

Table 7. Performance comparison of different microalgae carbon sequestration systems.

System type	Carbon sequestration efficiency (t CO ₂ /ha·year)	Land occupation (ha/1000 t CO ₂ /year)	Operation cost (CNY/ton CO ₂)	Resource utilization potential	TRL level
Open raceway pond	15–25	40–67	80–120	High (biofuel, feed)	6
Tubular photobioreactor	80–120	8–12	120–180	Medium	5
Flat-panel photobioreactor	100–150	7–10	150–200	Medium	4
Hybrid system (pond+reactor)	50–80	12–20	100–150	High	5

3.3.3. Plant-microbe combined ecological restoration technology

The plant-microbe combined system can effectively degrade the organic pollutants and heavy metals deposited by low-altitude aircraft emissions. Field experiments were carried out in the Hainan low-altitude flight test area, and the remediation effects of different plant-microbe combinations were compared (Table 8). The results show that the ryegrass-*Pseudomonas putida* combination has the best remediation effect, with the PAHs degradation rate reaching 85.2% within 6 months, and the remediation cost is only 1/3 of chemical remediation technology. In addition, the plant-microbe system can also improve soil structure and restore soil ecological function, which is impossible for chemical remediation technology [21]. *Pseudomonas putida* can secrete a variety of degrading enzymes, which can efficiently decompose PAHs and other organic pollutants into harmless carbon dioxide and water. Moreover, ryegrass has a developed root system, which not only absorbs heavy metals, but also provides a good habitat and nutrients for microorganisms, promoting their growth and reproduction [22].

Table 8. Remediation effects of different plant-microbe combined systems on polycyclic aromatic hydrocarbons (PAHs) and heavy metal pollution in soil.

Plant-microbe combination	PAHs degradation rate (6 months, %)	Heavy metal removal rate (6 months, %)	Soil microbial activity recovery rate (%)
Ryegrass + <i>Pseudomonas putida</i>	85.20 ± 3.10	62.30 ± 2.80	78.50 ± 4.20
Tall fescue + <i>Bacillus subtilis</i>	76.80 ± 2.90	58.70 ± 3.20	72.10 ± 3.80
Clover + <i>Rhizobium</i>	72.50 ± 3.30	55.20 ± 2.50	69.40 ± 3.50
Chemical remediation (control)	68.30 ± 4.10	75.60 ± 3.50	32.70 ± 5.10

3.3.4. Biosensor real-time monitoring technology

Enzyme-based biosensors can realize real-time online monitoring of nitrogen oxides and volatile organic compounds (VOCs) in the air, with a detection limit as low as ppb level. Microbial biosensors can monitor the toxicity of pollutants to ecosystems, providing early warning of ecological risks. The performance comparison of different biosensors and traditional chemical sensors is shown in Table 9. Compared with traditional chemical sensors, biosensors have the advantages of low cost, high specificity, and no secondary pollution, and are very suitable for large-scale deployment in low-altitude flight areas [23–24]. Biosensor monitoring networks have been piloted in Shenzhen and Shanghai, and the monitoring data accuracy reaches 92–95%. The comprehensive performance evaluation of four core bioengineering technologies is shown in Table 10. The comprehensive evaluation results show that the four bioengineering technologies have their own strengths and complement each other. Microalgae carbon sequestration has the highest comprehensive score, mainly due to its high efficiency, low cost, and multi-pollutant treatment capacity, and should be used as the core technology of the governance system. Bionic noise reduction is the most direct and effective means to solve the most prominent noise problem and should be given priority in the short term [25]. Moreover, plant-microbe remediation and biosensor monitoring are important supporting technologies, which are responsible for solving soil pollution and providing data support, respectively.

Table 9. Performance comparison of biosensors and traditional chemical sensors.

Sensor type	Detection limit (ppb)	Response time (s)	Service life (months)	Cost (CNY/unit)	Secondary pollution risk
Enzyme-based biosensor	1–5	5–10	6–12	500–1000	Very low
Microbial biosensor	5–10	10–30	12–24	300–800	None
Electrochemical sensor	10–20	30–60	24–36	1000–2000	Low
Optical sensor	5–15	10–20	36–48	2000–5000	Low

Table 10. Comprehensive performance evaluation of core bioengineering mitigation technologies.

Technology type	Noise reduction effect	Carbon sequestration efficiency	Ecological restoration effect	Monitoring accuracy	TRL level	Comprehensive score
Bionic noise reduction	★★★★★	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆	4	82
Microalgae carbon sequestration	★☆☆☆☆	★★★★★	★★★★☆	★☆☆☆☆	5	88
Plant-microbe remediation	★☆☆☆☆	★★★☆☆	★★★★★	★☆☆☆☆	6	85
Biosensor monitoring	★☆☆☆☆	★☆☆☆☆	★★★☆☆	★★★★★	5	80

Note: The comprehensive score is calculated based on technical performance, cost, maturity, and environmental friendliness, with a full score of 100.

3.4. Synergistic effect analysis of bioengineering technology combinations

Single bioengineering technology can solve only one type of environmental problem, while the combination of multiple technologies can achieve comprehensive governance of multiple environmental risks. We evaluated the synergistic effect of three typical technology combinations (Table 11). The results show that the full combination of four bioengineering technologies has the best

comprehensive governance effect, with a comprehensive benefit index of 1.52, which means that the comprehensive benefit is 52% higher than the sum of the benefits of single technologies. The main reasons for the synergistic effect are: Resource sharing: The biosensor monitoring network can provide real-time data support for the operation of other technologies, improving the operation efficiency of the system [26–27]. Pollution cascade treatment: A microalgae carbon sequestration system can treat gaseous pollutants, and a plant-microbe remediation system can treat deposited pollutants, forming a complete pollution treatment chain. Cost sharing: The infrastructure (such as power supply and communication system) can be shared among technologies, reducing the overall construction cost [28].

Table 11. Synergistic effect evaluation of different bioengineering technology combinations.

Technology combination	Comprehensive governance effect	Cost saving rate (%)	Energy saving rate (%)	Comprehensive benefit index
Bionic noise reduction + Biosensor monitoring	Noise pollution real-time monitoring and control	15–20	10–15	1.25
Microalgae carbon sequestration + Plant-microbe remediation	Air pollution + soil pollution comprehensive treatment	20–25	15–20	1.38
Full combination (four technologies)	Noise + air + soil + ecological comprehensive governance	25–30	20–25	1.52

3.5. Sensitivity analysis and uncertainty assessment

To evaluate the robustness of the research results, we conducted sensitivity analysis on key parameters that affect the feasibility of bioengineering technologies (Table 12). Sensitivity analysis shows that microalgae carbon sequestration efficiency is the most sensitive parameter, which indicates that improving the carbon sequestration efficiency of microalgae is the key to enhancing the comprehensive benefits of the governance system. Therefore, future research and development should focus on breeding high-efficiency microalgae strains through genetic engineering and synthetic biology technologies. Bionic material noise reduction performance and energy price are medium-sensitive parameters. With the continuous progress of bionic technology and the increasing proportion of renewable energy, the economic benefits of bioengineering technologies will be further improved [29].

Uncertainty assessment shows that even under the worst-case scenario (all key parameters change in the unfavorable direction), the comprehensive benefit index of bioengineering technology combination is 1.12, which is higher than that of traditional governance technologies (0.85–0.95). This indicates that the research results have strong robustness, and bioengineering technologies have comparative advantages over traditional technologies under various possible conditions.

Table 12. Sensitivity analysis results of key parameters.

Key parameter	Parameter change range	Impact on comprehensive benefit index	Sensitivity level
Microalgae carbon sequestration efficiency	±20%	±12.50%	High
Bionic material noise reduction performance	±15%	±8.20%	Medium
Energy price	±30%	±7.60%	Medium
Plant-microbe remediation efficiency	±25%	±6.80%	Medium
Biosensor service life	±50%	±3.20%	Low

4. Conclusion

In this paper, we quantitatively analyze the multi-dimensional environmental risks of low-altitude economy based on multi-source empirical data, and systematically evaluate the feasibility of bioengineering mitigation technologies through TRL and LCA methods. The main conclusions are as follows: Low-altitude economy has caused serious noise pollution, carbon emission accumulation, and ecological disturbance, and the environmental impact growth rate has exceeded the industry development speed. If no effective measures are taken, the annual carbon emission of China's low-altitude economy will reach 28.6 million tons by 2030. Traditional governance methods have limitations in cost, energy consumption, and secondary pollution, while bioengineering technologies have unique advantages in noise reduction, carbon sequestration, pollution degradation, and ecological monitoring. The combination of bioengineering technologies has a significant synergistic effect, with a comprehensive benefit index of 1.52, which is 52% higher than the sum of the benefits of single technologies. The three-stage technical roadmap proposed in this paper provides a feasible and prioritized technical path for the comprehensive governance of multi-dimensional environmental risks in the low-altitude economy under current technical conditions, and promotes the green and sustainable development of the industry. In future research, we will focus on the development of high-performance bionic materials, efficient microalgae strains, and intelligent biosensors and carry out large-scale engineering application verification. Furthermore, the long-term ecological impact of bioengineering technologies needs to be further evaluated to ensure their safety and sustainability.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflict of interest.

Author contributions

Weitao Meng and Yi Zhang contributed equally to this work. Both authors designed the research, analyzed data, drafted and revised the manuscript, and approved the final version for publication, in line with ICMJE definitions of authorship.

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