

FUTURE SCENARIOS AND FORESIGHTS OF ENVIRONMENTAL MANAGEMENT FOR ASTRONOMY AND SPACE LEARNING CENTERS IN THAILAND

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Abstract

This research aims to analyze and forecast future scenarios regarding the environmental management of astronomy and space learning centers in Thailand over the next decade. As the initial phase of a broader mixed-methods study, this article adopts a qualitative approach utilizing the Ethnographic Delphi Futures Research (EDFR) technique. A panel of 24 key experts was purposively selected; notably, 75% of the informants hold doctoral degrees, while 54.2% possess more than 16 years of professional experience. Data collection was conducted through in-depth inquiries, followed by rigorous content analysis.

The Phase 1 qualitative findings, extracted from in-depth inquiries, establish three distinct future scenarios. First, the worst-case scenario underscores impending crises driven by urban expansion, physical structures obstructing astronomical visibility, environmental negligence, and a disproportionate focus on research that consequently marginalizes public service. Second, the desirable scenario portrays the successful integration of Sustainable Development Goals (SDGs), net-zero carbon policies, responsible tourism, and the advancement of citizen science. Third, the most probable scenario reflects a pragmatic adaptation characterized by the concurrent use of technology and nature conservation, the establishment of collaborative networks, and workforce development designed to accommodate the emerging space economy. Ultimately, these findings provide a strategic empirical foundation for elevating Thailand's astronomical learning facilities toward long-term sustainability.

Keywords: Foresights; Future scenarios; Environmental Management; Astronomy Learning Centers

Introduction

Environmental management in the 21st century is undergoing a major transition driven by globalization and climate change. The global community has prioritized the United Nations Sustainable Development Goals (SDGs) as the primary framework for balancing economic growth, natural resource conservation, and social equity. However, with rapid scientific and technological advancement, environmental conservation is no longer limited to terrestrial resources such as forests, water sources, or the troposphere. The concept has expanded to include the space environment and dark sky preservation, which are now recognized as human natural heritage [1] [2]. This awareness coincides with the growth of the space economy, driven by space innovation, satellite communication, and astrotourism, generating significant value for local economies worldwide.

Given these developments, astronomy and space learning centers—such as observatories, astronomical parks, and science centers—are no longer solely physical observation sites. They have shifted toward becoming science communication spaces that connect advanced knowledge with the general public. These centers inspire

youth, develop the workforce for the space industry, and promote citizen science. Additionally, they help attract tourists and distribute income to surrounding communities through responsible tourism, aligning with the Bio-Circular-Green (BCG) Economy Model [3].

Beyond providing academic services, astronomy learning centers are highly energy-intensive infrastructures. This is primarily due to climate control systems maintaining strict temperature and humidity standards for advanced scientific instruments, alongside the energy demands of large exhibition areas. Furthermore, environmental issues like light pollution and fine particulate matter (PM2.5) directly compromise observational capabilities. Consequently, integrating energy and environmental management is a critical prerequisite for the long-term survival and sustainability of these centers. Despite infrastructure development, Thailand's astronomy learning centers face mounting environmental threats. A primary crisis is light pollution from unplanned urban expansion and improper lighting installations that obstruct sky visibility. Light pollution not only reduces observational capacity and instrument efficiency, but it also negatively affects ecosystems, biological clocks, and human health. Furthermore, many centers struggle with internal resource management, including waste disposal, high carbon footprints from mass visitation, and energy management that has not yet reached net-zero carbon targets. The lack of an environmental management system suited to the local community context also creates a gap between the learning centers and the surrounding society. Currently, solutions to these problems are often reactive and fragmented. Most research focuses on industrial environmental management or purely astrophysical outcomes, leaving an academic gap in integrating international standards like ISO 14001 with dark sky reserve criteria specifically for astronomy centers. Because environmental problems are complex and highly uncertain, traditional research focusing only on past or current events is insufficient for long-term strategic planning. Although previous studies have explored the development of science learning centers, most research has primarily focused on educational management effectiveness, lacking concrete and in-depth investigations into energy and environmental management systems. This research thus presents a distinct novelty by integrating astronomical sciences with the dynamics of energy and environmental technology applications to formulate future scenarios that have never previously been assessed within the context of Thailand. The outcomes of this study will serve as a crucial milestone in preparing for the challenges of the coming decade.

Therefore, this research applies futures studies, specifically Ethnographic Delphi Futures Research (EDFR), to gather expert insights. This method helps anticipate trends and forecast future scenarios—including worst-case, desirable, and most probable scenarios—over the next decade. Analyzing these scenarios provides a strategic direction for environmental management in Thailand's astronomy learning centers. The findings will offer empirical data for policymakers, local governments, and relevant agencies to develop practical management models. The ultimate goal is to upgrade Thailand's astronomy learning centers to international standards, creating spaces that sustainably balance space science advancement, environmental conservation, and local economic growth.

Research Objective

The objective of this research is to analyze and forecast future scenarios for environmental management in Thailand's astronomy and space learning centers, including the desirable, worst-case, and most probable scenarios.

Research Methodology

This research is part of a larger mixed-methods project utilizing the Ethnographic Delphi Futures Research (EDFR) technique [4]. However, to ensure a comprehensive and in-depth analysis of future scenarios and systemic contexts, this article focuses specifically on presenting the qualitative findings from Phase 1 (In-depth Inquiry). The detailed procedures are as follows:

Key Informants: The key informants consisted of a panel of 24 experts selected through purposive sampling. This sample size ensures data saturation and comprehensive stakeholder coverage, which is standard and highly appropriate for futures research prioritizing qualitative depth over statistical generalization [5] [6]. To obtain highly reliable, in-depth insights capable of comprehensively reflecting future scenarios, the researcher established strict selection criteria. These criteria thoroughly considered the individuals' qualifications, specialized expertise, empirical achievements, and long-standing professional experience. The selection encompassed five primary professional disciplines essential to driving the learning ecosystem: 1) astronomy and space, 2) environmental education, 3) architecture and urban planning, 4) educational technology, and 5) learning center management. The experts were categorized into three distinct groups: 6 policymakers, 9 practitioners, and 9 academics. Most informants were in the peak experience bracket, with 41.7% aged 40–49 and 37.5% aged 50–59. Furthermore, 75% of the panel held a doctoral degree, and 54.2% possessed more than 16 years of direct working experience in astronomy, environmental fields, and learning center management.

Research Instruments: The primary instrument for data collection was an open-ended, in-depth inquiry questionnaire. This tool was adapted from the Ethnographic Futures Research (EFR) approach to encourage experts to envision and forecast the environmental management of astronomy learning centers over the next 10 years. The experts were asked to project future scenarios in three dimensions: 1) the best-case scenario, 2) the worst-case scenario, and 3) the most probable scenario. To ensure content validity, the instrument was evaluated by three independent experts. All questions achieved an Item-Objective Congruence (IOC) index of 0.50 or higher, meeting the standard criteria.

Data Collection: In-depth data were collected individually using flexible methods suited to each expert's context. These methods included self-administered open-ended questionnaires, online video interviews, and face-to-face interviews. The process emphasized giving experts sufficient time and freedom to reflect, ensuring the most complete and insightful perspectives possible.

Data Analysis: Data were systematically analyzed using thematic and content analysis. Following the transcription of recorded interviews and the integration of written questionnaire responses, the consolidated textual data were subjected to a rigorous coding process to extract key terms, which were then categorized into coherent conceptual groups. These concepts were synthesized into distinct variables to formulate the three future scenarios serving as the foundation for presenting the research findings.

Results and Discussion

Research Findings: Based on the content analysis of qualitative data from in-depth inquiries with 24 experts during the first round of the Ethnographic Delphi Futures Research (EDFR) process, the researcher synthesized future scenarios for the environmental management of Thailand's astronomy and space learning centers over the next decade. These scenarios are categorized into three main types as follows:

1. The Worst-Case Scenario: Degradation and Social Disconnection

This scenario reflects the experts' concerns about a situation where learning center management lacks vision, fails to perform maintenance, and neglects the social and environmental contexts. This would lead to a decline across all areas, specifically:

1.1 Outdated Technology and Personnel Shortages: Experts indicated that without long-term budget planning and strategic management, advanced equipment—which required massive initial investment—would quickly deteriorate and become outdated. A severe concurrent issue is the shortage of specialized personnel and brain drain. When technical problems occur, there would be a lack of capable staff to repair or upgrade the systems. Consequently, the learning centers would fail to meet their functional objectives and completely lose their capacity to provide academic services.

1.2 Pollution, Climate Threats, and Urban Planning: The learning centers will face severe environmental crises, particularly high levels of PM2.5 and light pollution. Combined with unplanned urban expansion and a lack of strict zoning regulations, this will lead to the construction of high-rise buildings that obstruct the horizon and visibility for astronomical observation. Furthermore, climate change impacts, such as extreme weather and unseasonal dense cloud cover, will pose serious operational limitations. Additionally, inefficient management and the neglect of occupational health and safety standards will inevitably result in municipal waste problems and the destruction of surrounding ecosystems.

1.3 Infrastructure Degradation from Policy Discontinuity: Facilities lacking continuous maintenance will gradually deteriorate into deserted areas or abandoned monuments. This reflects a structural vulnerability caused by the discontinuity of executive policies that fluctuate with administrative terms. Such instability causes large-scale projects to be suspended or face mid-project budget cuts. Consequently, these infrastructures will not only lose their visual appeal, but the lack of risk management or emergency response plans will also turn them into significant safety hazards for users and the surrounding communities.

1.4 Inequality, Conflict, and Ultimate Abandonment: Focusing solely on physical buildings or advanced research while neglecting local residents will create conflicts with the surrounding communities. The learning centers will become closed spaces inaccessible to the general public. Coupled with high admission or service fees that create access inequalities, these astronomical facilities will become ivory towers or exclusive spaces serving only elites or specific academic groups. Ultimately, lacking social acceptance and a shared sense of public ownership, these learning centers will face severe budget shortages and be completely abandoned.

2. The Desirable Scenario: A Green Learning Ecosystem and International Standards

This scenario represents an ideal future where learning centers transform into key drivers for national development while sustainably maintaining ecological balance. It comprises the following aspects:

2.1 Advanced Technology and the Metaverse: The learning centers will overcome physical limitations by integrating advanced technologies. Specifically, applying the Metaverse alongside Artificial Intelligence (AI) will connect the physical and virtual worlds without borders, allowing users to experience highly realistic space learning simulations. Furthermore, developing online observatory networks and utilizing Big Data will enable the public and researchers worldwide to access astronomical data 24/7. This effectively removes traditional barriers to learning.

2.2 Carbon Neutrality and Dark Sky Reserves: Environmental management will be upgraded to the highest international standards. The learning centers will transition to 100% clean energy, such as solar power, to achieve carbon neutrality. Crucially, they will push for the establishment of Dark Sky Reserves—areas completely free from light pollution, optimized for astronomical research. Additionally, Circular Economy principles will be systematically applied to resource management, aiming for zero-waste goals and highly efficient wastewater recycling.

2.3 Universal Design and Green Infrastructure: Spatial design will be based on Universal Design principles, ensuring that everyone, regardless of gender or age, including vulnerable groups like the elderly and persons with disabilities, can access the space safely. This reflects a commitment to equity in science education. Concurrently, building infrastructure will follow green architecture standards. This involves using eco-friendly materials, designing structures to blend with the surrounding natural landscape, and relying on natural lighting and ventilation to minimize building energy consumption.

2.4 International Standards and the Community Economic Ecosystem: The learning centers will be elevated to gain global recognition. Beyond serving as knowledge hubs, they will act as key mechanisms in driving the Space Economy by promoting responsible astrotourism. This will generate income for surrounding communities, allowing the local economy to grow sustainably alongside the institutions. Most importantly, their primary role will be fostering a citizen science society, where local residents are aware of and actively participate in protecting natural resources in collaboration with the centers.

3. The Most Probable Scenario: Dynamic Adaptation through Multilateral Cooperation

Given the realistic budget and resource constraints in Thailand, the experts evaluated the most likely direction, which emphasizes flexible management as follows:

3.1 Practical and Hybrid Technologies: The most probable future will not involve heavy investments in expensive, cutting-edge technologies. Instead, it will focus on cost-effectiveness by using hybrid technologies to provide both online and offline services. Concurrently, the lifespan of existing astronomical equipment will be extended through system upgrades and the promotion of open-source databases. This approach meets diverse user needs in practical situations and helps reduce the digital divide under a limited budget.

3.2 Contextual Green Management and Efficiency Enhancement: Environmental management will not leap directly to advanced green technologies. Instead, it will implement basic standards and progress gradually, prioritizing the specific context of each area. The focus will be on resource management through the 3Rs (Reduce, Reuse, Recycle) principles and basic energy-efficiency measures. The goal is to minimize environmental disturbance given limited resources, while also promoting Community-based Monitoring systems to oversee environmental impacts.

3.3 Renovating Existing Structures and Flexible Spaces: Instead of constructing large new buildings, the learning centers will focus on routine maintenance and upgrading existing structures to extend their lifespan. This includes managing areas as flexible spaces (or adaptive reuse) that can be easily adjusted to support various activities. The highest priority will be given to core safety standards for both the public and staff.

3.4 4P Collaborative Networks and Resource Sharing: The survival of these learning centers will not depend on working alone or relying solely on government funding. Instead, it will rely on strong collaborative networks through Public-Private-People Partnership (4P) mechanisms. This involves integrated management

among government agencies, the educational sector, and local communities to jointly drive initiatives and share resources—such as equipment, personnel, and knowledge. This collaboration is the most crucial strategy for overcoming resource shortages.

To provide an overview of the directions and specific characteristics of each dimension, the researcher has synthesized all findings into a comparative summary, as shown in Table 1.

Table 1. Comparative summary of the three future scenarios for environmental management in Thailand's astronomy and space learning centers.

Dimensions	The Desirable Scenario	The Worst-Case Scenario	The Most Probable Scenario
Technology	Advanced Technology and the Metaverse: Integrating the Metaverse, AI, and Big Data to overcome limitations, alongside creating a Virtual Observatory network.	Outdated Technology and Personnel Crisis: Damaged equipment, lack of specialized experts for maintenance and development, and severe brain drain.	Hybrid Systems and Cost-Effectiveness: Utilizing hybrid systems, extending the lifespan of existing equipment, and supporting Open Educational Resources (OER).
Environment	Carbon Neutrality and Dark Sky Reserves: Utilizing 100% clean energy, driven by the Circular Economy and zero-waste goals.	Pollution, Climate Threats, and Urban Planning: Facing PM2.5 and light pollution, urban expansion obstructing visibility, and adverse climate change impacts.	Contextual Green Management and the 3Rs: Efficient resource utilization based on 3Rs principles, focusing on energy efficiency and community-based monitoring.
Infrastructure	Universal Design and Green Architecture: Applying Universal Design integrated with Green Architecture, using eco-friendly materials to ensure safety for all.	Degradation from Policy Discontinuity: Degenerating into abandoned monuments, lacking emergency plans, and turning into hazard zones.	Structural Upgrades and Flexible Spaces: Focusing on building performance improvements and maximizing the utilization of adaptable, flexible spaces.
Management	International Standards and Community Economic Ecosystems: Promoting astrotourism, driving the Space Economy, and fostering a citizen science society.	Exclusive Spaces and Conflicts: Creating access inequality (exclusive spaces), conflicting with communities, and facing budget suspensions due to lack of acceptance.	4P Collaborative Networks and Resource Sharing: Managing through Public-Private-People Partnerships (4P) and emphasizing shared resource utilization.

In-depth Insights and Synthetic Conclusions

Synthesizing the three future scenarios—Optimistic, Pessimistic, and Most Probable—reveals key insights that reflect the actual direction for developing astronomy and space learning centers in the Thai context:

1. A Paradigm Shift from Physical Infrastructure to Dynamic Management: Expert consensus indicates that the future success of these centers depends less on building size or equipment modernity than on effective dynamic management. As demonstrated in the negative scenario, buildings risk becoming abandoned monuments

due to policy discontinuity and brain drain. Therefore, the key factor is the efficiency of dynamic management, particularly upgrading existing structures and designing multi-purpose spaces for maximum cost-effectiveness. Ensuring long-term equipment maintenance and resource sharing are decisive factors for organizational sustainability under budget and personnel constraints.

2. Environmental Sustainability as a Condition for Survival, Not an Option: Environmental issues are more than just a social trend; they are a direct requirement for the survival of astronomy learning centers. These institutions face multiple threats, including light pollution, urban expansion, PM 2.5, and climate variability. Failure to manage these challenges will lead to the loss of their primary function: celestial observation. Consequently, implementing circular economy principles, pursuing zero-waste goals, and adopting basic energy-saving measures are not merely social contributions but essential strategies to reduce operational costs and achieve long-term self-reliance, as projected in the most probable scenario.

3. Technology as a Tool for Expanding Learning Opportunities and Reducing Inequality: Although the optimistic scenario mentions advanced technologies like the Metaverse, AI, and Big Data, the analysis shows that technology is not meant to replace genuine on-site experiences. Instead, it acts as a bridge to overcome accessibility limits, preventing the learning centers from becoming exclusive spaces. Developing online observatory networks and Open Educational Resources (OER) allows people from remote areas or vulnerable groups to access astronomical knowledge equally with urban residents. Therefore, experts highly agree that a hybrid learning model is the most effective solution for addressing educational inequality.

4. Multilateral Networks and Community Engagement as the Foundation of Stability: Lessons from the pessimistic scenario demonstrate that learning centers cannot survive in isolation without community involvement. The desirable model must move beyond being merely an educational facility to become a Social Space that supports surrounding communities. This is driven by 4P (Public-Private-People Partnership) networks, the promotion of astrotourism to generate local income, and the cultivation of a citizen science network. When the community feels a sense of ownership and receives benefits, they naturally shift from being mere observers to active protectors, automatically helping to safeguard the facility and monitor environmental issues.

Discussion

This research aimed to analyze and forecast future scenarios for the environmental management of Thailand's astronomy and space learning centers, covering three distinct models: the desirable, worst-case, and most probable scenarios. The findings align with the theoretical foundations of futures studies established Wendell Bell [7] who suggested that this discipline requires exploring multiple futures to broaden perspectives and prepare strategically. The experts' collective reflection on the worst-case scenario serves as an early warning, which is consistent with the perspective of Ketudat [8]. Meanwhile, the desirable and most probable scenarios reinforce Ziauddin Sardar's [9] view that the future is dynamic and can be shaped by current management practices. Based on the synthesis of these three scenarios, the researcher discusses the in-depth findings across four core dimensions as follows:

1. Transitioning to Dynamic Management: A comparative analysis of the scenarios reveals a notable concern among the experts: learning centers could be abandoned and turned into mere monuments. This contrasts sharply with the optimistic scenario, which envisions astronomical facilities as fully integrated green architecture. This contrast leads to a practical synthesis: the most viable and likely solution is to focus on upgrading the

performance of existing structures while designing flexible spaces. This approach allows facilities to adapt to technological changes and budget constraints. Such circumstances highlight that structural failure, often caused by policy discontinuity at the executive level, is a major vulnerability. This aligns with Tekhanmag [10] who noted that futures research must account for the sensitivity of socio-political contexts, as these factors directly impact the sustainability of large-scale government projects. Therefore, management over the next decade should not fixate on new construction. Instead, it should transition to flexible environmental management based on international standards to extend the lifespan of existing infrastructure and maximize cost-effectiveness amid budget fluctuations. This concept is supported by Thamwapi and Thongkamsamut [11] who studied building renovation guidelines based on green building criteria at the College of Local Administration, Khon Kaen University. Their study showed that retrofitting existing public buildings using green criteria is a cost-effective and sustainable strategy, particularly for Thai educational institutions. They found that upgrading existing structures with simple yet effective techniques—such as optimizing lighting systems and building envelopes—can transform older facilities into smart learning spaces without requiring massive budgets for new construction. This also corroborates the findings of Khetkrathok and Suluksna [12] who indicated that renovating the library building at Suranaree University of Technology under green building standards significantly reduced environmental impacts and generated value throughout the building's life cycle. Regarding spatial management, Klinchoey and Boonyaputthipong [13] suggested that retrofitting existing buildings with flexible designs to support diverse activities (multi-functional spaces) is key. This approach enables government agencies to increase space utilization rates under severe budget constraints. This is consistent with Bullen and Love [14] who studied the adaptive reuse of heritage buildings in Australia. They confirmed that reusing existing structures is a more efficient alternative to demolition and reconstruction for achieving both economic and environmental sustainability goals. However, the findings of this study expand on previous research by demonstrating that, within the context of Thailand's astronomy and space learning centers, dynamic management is no longer merely an architectural choice. Rather, it has become a survival strategy that acts as a shield against the uncertainties of public policy. This strategic resilience ensures that these scientific learning institutions can continue to serve society continuously without being left behind in the future.

2. Systemic Environmental Management for Sustainability: The findings reflect a concerning future scenario: without an effective environmental management system, astronomy learning centers will inevitably face pollution crises and environmental threats. Specifically, the worsening PM2.5 pollution and light pollution will obscure celestial visibility. This situation confirms that environmental sustainability is no longer a secondary management issue, but a fundamental prerequisite for the centers to survive and fulfill their core functions. This aligns with the study by Youyuenyong [15] on the impact of light pollution on public astronomical research services. His research examined how urban expansion and unregulated artificial lighting affect observatory operations in Thailand. That study clearly indicated that light pollution not only degrades the quality of scientific research data but also deprives the public of their right to access astronomical learning services. On the other hand, the optimistic scenario focuses on establishing Dark Sky Reserves and achieving carbon neutrality. This elevates environmental management standards beyond conventional carbon footprint reduction. This approach is consistent with the practices of global organizations like the European Southern Observatory (ESO), which proactively uses 100% renewable energy to tangibly reduce greenhouse gas emissions. When comparing these localized future scenarios with international astronomical facilities, similar environmental management trajectories become highly evident.

Major global observatories, such as those in Mauna Kea, Hawaii, which emphasize community-based ecological management [16] or the Atacama Desert in Chile, where international observatories have formed the Dark Skies Council to combat light pollution [17] actively integrate rigorous environmental impact assessments into their operations. The 'desirable scenario' identified in this Thai context aligns seamlessly with the global astronomical community's broader shift towards the Sustainable Development Goals (SDGs) and mitigating observatory carbon footprints to achieve net-zero carbon operations [18] [19]. This alignment implies that for Thailand's space learning centers to remain scientifically competitive and socially responsible, they must adopt an environmental management framework that is globally aligned yet practically adapted to local constraints. Furthermore, it aligns with Martínez-Ramos et al. [3] who suggested that learning spaces in the next century must function as a Social-Ecological Model, helping people realize the deep connection between human lifestyles and ecosystems. However, comparing the findings from these future scenarios with previous literature reveals significant insights and differences. While Youyuenyong [15] focused on reactive mechanisms, such as advocating for local ordinances to control light pollution, this study presents a more strategic perspective. It suggests that future learning centers must shift their role from being victims of environmental threats to becoming economic drivers through the Space Economy and astrotourism. This transforms the pollution crisis into a strategic opportunity, utilizing the darkness of the sky as a primary resource for value creation. Additionally, whereas Martínez-Ramos et al. [3] focused on the general design of educational spaces, this research focuses specifically on the Thai context. It indicates that the sustainability of Thai astronomy learning centers must be concretely linked to the national BCG (Bio-Circular-Green) Economy model and Thailand's goal of achieving net-zero greenhouse gas emissions by 2065. Therefore, contextual environmental management in this research is not limited to facility maintenance. Instead, it integrates institutional stability with global Sustainable Development Goals (SDGs). This integration is a key strength and a novel finding that this study contributes to the current academic field of astronomy and environmental management.

While a limitation of this study lies in the absence of measured environmental baseline data from actual sites, the synthesized expert insights clearly demonstrate the feasibility of implementing practical environmental solutions. Specifically, zero-waste initiatives and circular economy concepts can be operationalized through eco-friendly exhibition designs utilizing renewable materials, as well as systematic electronic waste (e-waste) management for specialized astronomical equipment. However, effectively driving these environmental innovations in practice will still require further research to evaluate their detailed economic cost-effectiveness in the next phase.

3. Integrating Technology to Reduce Inequality and Expand Learning Opportunities: A key issue highlighted by the findings is the risk that high-cost advanced technologies could widen the inequality gap if learning centers focus solely on modernity for commercial purposes. The researcher found that although virtual reality (the Metaverse) and digital astronomy represent the optimistic scenario, in the most probable context, technology must serve as a tool to reduce inequality. This can be achieved through hybrid learning and access to Open Educational Resources (OER), creating a ubiquitous learning environment where astronomy education is accessible anywhere and anytime [20]. This approach aligns with the futurist philosophy described by Poolpatarachewin [21] who noted the necessity of considering fair alternatives to distribute scientific knowledge, ensuring equal access for all groups, particularly those in remote areas. The concept of using technology to bridge the learning gap is consistent with the study by Bamrungsetthapong et al. [22] on hybrid learning and the quality improvement of Thailand's education

in the 21st century. Their research indicated that transitioning to a hybrid teaching model is a crucial mechanism for improving the education system and overcoming domestic inequality. The flexibility of this learning model reduces physical limitations, enabling students who lack financial resources or live in remote areas to access high-quality educational materials equally with urban learners. Regarding modern technology, these findings also support the work of Mystakidis [23] who reviewed literature on the use of the Metaverse in educational institutions. His research pointed out that the true value of virtual technology is not merely in attracting attention, but in its ability to provide immersive experiences, such as space exploration. This allows learners who cannot physically travel to learning centers to experience them realistically. However, Mystakidis emphasized that the success of such technology depends on readiness and access to equipment—a concern that aligns with the views of the expert panel in this study. Comparing these findings demonstrates that this research aligns with Bamrungsetthapong et al. [22] and Mystakidis [23] in asserting that technology is a key enabler in expanding learning boundaries beyond physical constraints. However, this study expands the analytical scope to include technological sustainability. In the context of Thai astronomy learning centers, integrating technology must be accompanied by environmentally friendly information technology management (Green ICT). This prevents the issue of e-waste from becoming a long-term burden for the learning centers. Furthermore, future technological development should reduce overly complex academic barriers by integrating ethno-astronomy through digital platforms. This serves as a bridge connecting modern science with local wisdom. Ultimately, this approach will allow technology to act as a medium that fosters a sense of ownership among all groups of Thai people, enabling them to utilize it in a concrete manner.

4. Institutional Stability Through Multilateral Networks and Social Participation: The findings across all scenarios confirm that astronomy learning centers cannot survive sustainably if they operate without collaborative networks. Transitioning the space from a conventional scientific institution or academic service center to a Social Space via Public-Private-People Partnership (4P) mechanisms is a key variable in achieving the desirable scenario. This emphasis on networking aligns with systems thinking and participatory theories presented by Jamkrajang [24] who noted that the power of sustainable change comes from cultivating a sense of local ownership. This is achieved by allowing citizens to influence the decision-making process from the beginning to the end of a project. Such a process helps build trust and solidarity, leading to strong, collective environmental management. Furthermore, engaging the community as citizen scientists to monitor light pollution and protect the environment surrounding the learning centers aligns with the research of Kokamai and Weerapalangoon [25]. Their study indicated that opening spaces for community participation in operations yields concrete, shared benefits, including a cleaner environment, better health, and an effective reduction in local resource degradation. This finding also supports Kyba et al. [26] in their article, *Citizen Scientists Report Global Rapid Reductions in the Visibility of Stars from 2011 to 2022*, which used observational data from global volunteers through the *Globe at Night* project. Their findings confirm that citizen power is the most crucial mechanism for collecting massive scientific data (Big Data) that agencies cannot gather alone. It is also a primary tool for raising broad public awareness about the loss of dark sky resources. However, a comparative analysis reveals that while this study aligns with Kokamai and Weerapalangoon [25] and Kyba et al. [26] in viewing civic networks as vital mechanisms for environmental monitoring, it presents a broader strategic conclusion. Specifically, while Kokamai and Weerapalangoon focused on operational-level participation and Kyba prioritized scientific data collection, this study finds that in the Thai context, participation must be elevated to create a Community Economic Ecosystem. This can be achieved by linking the 4P network with innovative environmental

management that generates local income. Examples include encouraging surrounding communities to operate eco-lodges within Dark Sky Reserves or jointly developing local curricula with nearby schools.

This approach represents a shift from volunteer-based participation to engagement tied to local livelihoods and economic sustainability. This socioeconomic integration is a concrete driving force that can steer Thai astronomy learning centers away from the risks of undesirable scenarios, guiding them toward long-term stability and sustainability.

Conclusion

This study reports the qualitative findings obtained from Phase 1 (In-depth Inquiry) of an ongoing Ethnographic Delphi Futures Research (EDFR) project investigating future environmental management scenarios for astronomy and space learning centers in Thailand. Based on the perspectives and professional judgments of 24 experts, three future scenarios were identified: the worst-case scenario, the desirable scenario, and the most probable scenario.

The findings suggest four strategic directions for future development: 1) shifting from infrastructure-centered development toward dynamic management systems; 2) recognizing environmental sustainability as a prerequisite for long-term organizational survival; 3) utilizing technology to reduce educational inequality and expand learning opportunities; and 4) strengthening multi-sector collaboration and community participation as foundations for institutional resilience. These findings highlight the importance of integrating scientific, environmental, and social dimensions to support the sustainable development of astronomy and space learning centers in Thailand.

It should be noted that the scenarios presented in this study reflect the perceptions, experiences, and expert judgments of the participating panel members rather than measured environmental baseline data. Therefore, the findings should be interpreted as preliminary future scenarios developed during the first phase of the EDFR process. These qualitative results provide the conceptual basis for developing research instruments and conducting the subsequent Delphi rounds and quantitative assessment. The findings from Phase 2 are currently under development and will contribute to a more comprehensive evidence base for future policy and management recommendations.

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