Vol.7, Issue 1, pp.960-971, 2026
DOI: https://doi.org/10.62754/ais.v7i1.972

https://journals.ap2.pt/index.php/ais/index

Towards Low-Emission Coastal Tourism: Integrating Life Cycle Assessment and Nature-Based Solutions at Indrayanti Beach, Indonesia

Ninin Gusdini[1], Bernard Hasibuan[2], Lisa Ratnasari[3], Moch Sambas[4]

Abstract

The growth of coastal tourism in tropical regions has accelerated environmental pressures, particularly through elevated carbon emissions and ecosystem degradation. This study proposes an integrated framework for low-emission tourism development at Indrayanti Beach, Indonesia, by combining Life Cycle Assessment (LCA) with Coastal Ecosystem Services (CES). Key interventions—including centralized wastewater treatment with solar-biogas energy, greywater recycling, sludge composting, and electric mobility infrastructure—are analyzed for their carbon reduction potential and feasibility. Results demonstrate that integrated WWTP systems can lower emissions by up to 30%, while electrified transportation can reduce sectoral emissions by 70%. By embedding CES principles, the framework strengthens ecological resilience and community participation. Policy recommendations highlight the role of adaptive carbon standards, fiscal incentives, and digital monitoring in achieving the 2060 net-zero goal. This study presents a transferable model for climate-compatible tourism planning in vulnerable coastal regions.

Keywords: *Low-Emission Tourism, Life Cycle Assessment, Carbon Footprint, Sustainable Tourism, CES.*

Introduction

Beach tourism has become a global economic driver with average visitation growth reaching double-digit percentages post-pandemic. However, this surge carries significant environmental implications. The coastal tourism sector is now estimated to contribute more than 1.5 billion tons of CO_2-eq per year, with the most significant portion coming from tourist transportation and energy consumption in accommodations. Indrayanti Beach in Tepus Village, Gunungkidul, has experienced a 15%-18% annual increase in visitation since 2019, as the local community has enhanced its facilities and digitalized its promotional efforts. This growth has coincided with soaring carbon emissions: tourist transportation to Indrayanti, mostly by motorcycle and fossil-fueled travel, is estimated to account for 70% of the destination's total carbon footprint. On the other hand, the vulnerability of coastal ecosystems, including karst cliff abrasion and seagrass degradation, requires spatial data-driven adaptive policies to prevent environmental and social carrying capacity from collapsing in the face of extreme weather and seasonal fluctuations. Recent research confirms that the increase in carbon load is directly proportional to coral reef degradation, shoreline erosion, and declines in water quality (Smith et al., 2023).

The vulnerability of coastal areas to climate change exacerbates this condition. Sea level rise, intensification of tropical storms, and increased sea temperatures accelerate coastal erosion and fragment mangrove habitats, undermining the ecological and social carrying capacity of coastal communities. The complex impact chains, ranging from transportation emissions to vegetation degradation and increased disaster risks, have been thoroughly described (Arabadzhyan et al., 2021). Conventional reactive tourism policies often fail to address seasonal dynamics and localized climatic conditions, potentially leading to destination collapse during peak visitation or extreme weather events (Jarratt & Davies, 2020).

[1] Environmental Engineering, Sahid University, Jakarta, Indonesia, Email: ninin_gusdini@usahid.ac.id (Corresponding Author)
[2] Environmental Management, Sahid University, Jakarta, Indonesia, Email: Bernard_hasibuan@usahid.ac.id
[3] Industrial Engineering, Sahid University, Jakarta, Indonesia, Email: Lisa_ratnasari@usahid.ac.id
[4] Industrial Engineering, Sahid University, Jakarta, Indonesia, Email: Moch_sambas@usahid.ac.id

In a technical context, Integrated Life Cycle Assessment (LCA) is emerging as a quantitative tool capable of evaluating the total environmental impact of the coastal tourism sector, combining the carbon footprint of transportation, energy consumption, and waste management in a single framework. It was found that centralized wastewater treatment systems integrated with renewable energy sources can reduce carbon footprints by up to 25% compared to decentralized systems in tropical tourism areas (Pasciucco et al., 2023). Meanwhile, the importance of sludge management was demonstrated, as composting resulted in emissions six times lower than landfilling and supported the restoration of coastal vegetation (Ogbu et al., 2025).

Challenges and opportunities in Indonesia lie in decentralized sanitation practices, limited access to renewable energy sources, and the dominance of fossil fuel-based transportation. A study demonstrated that fiscal incentive schemes for solar panel installation and electrification of tourist fleets increased the adoption of green technology by 30% in similar tropical beach destinations (Ali et al., 2024). On the other hand, the Coastal Ecosystem Services (CES) approach was introduced, emphasizing the conservation of mangroves, sea cypress, and seagrass beds, as well as empowering local communities through culture-based ecotourism and ecosystem restoration programs (Sholeha & Sumarmi, 2025). The integration of LCA with this CES model represents a strategic innovation to create destinations that are not only low-emission but also socially, ecologically resilient, and inclusive.

The urgency of this research is even more pressing in light of Indonesia's commitment to the Paris Agreement and its goal of achieving net-zero emissions by 2060. It has been recommended to combine mitigation and adaptation policies, from destination emissions regulation, fiscal incentives for low-carbon technologies, to community-based offset mechanisms, as pillars of carbon neutrality in the tourism sector (Hatamifar et al., 2025). Meanwhile, the urgency of policy interventions to address coastal erosion and facilitate sustainable ecotourism in Bali has also been emphasized, serving as a model for other regions in Indonesia (Hoe & Abdullah, 2025). Multi-stakeholder collaboration and green investments in renewable energy and NBS are imperative to effectively decarbonize coastal tourism.

As noted, the tourism industry is highly vulnerable to the impacts of climate change, which directly affects the viability and attractiveness of tourist destinations (Arabadzhyan et al., 2021). It has also been emphasized that destination management that does not consider carrying capacity limits will exacerbate environmental degradation and create social stress.

The main objective of this paper is to identify the problems and impacts of tourism activities from an environmental engineering perspective, particularly carbon footprinting and LCA, and provide evidence-based policy inputs for sustainable tourism management in Indonesia and other developing countries.

Going forward, beach destinations should be reimagined as sustainability laboratories that pilot eco-technological innovation and adaptive governance. The implementation of real-time monitoring systems based on big data and spatial modelling will enable visitation management, carrying capacity evaluation, and the dynamic identification of emission hotspots (Arabadzhyan et al., 2021; Jarratt & Davies, 2020). By combining integrated LCA, CES approach, and adaptive carbon policy, this research is expected to serve as a blueprint for governments, business actors, academics, and local communities in building sustainable, resilient, and competitive beach destinations that will endure across generations.

This study advances existing research by integrating Life Cycle Assessment (LCA) with the Coastal Ecosystem Services (CES) framework to formulate an operational model for low-emission tourism at a site-specific level. Unlike prior studies that often treat technical and ecological interventions separately, this paper presents a unified evaluation of wastewater, greywater, sludge, and transportation systems, explicitly tied to policy instruments and community-based carbon offset mechanisms. The novelty lies in combining engineering-based emission modeling with nature-based and governance-oriented interventions in a coastal tourism context—a convergence that is rarely addressed in the literature. The output serves as both a technical roadmap and a policy reference for achieving net-zero tourism targets in tropical developing nations.

Method

This study employs a descriptive qualitative approach, utilizing a structured literature review that integrates scientific and policy documents from both national and international sources. The literature search was conducted using Scopus, Web of Science, and Google Scholar databases with the keywords "low-emission tourism," "Life Cycle Assessment," "coastal ecosystem services," and "sustainable coastal tourism" within the publication range of 2014–2025. Only peer-reviewed literature in English and Indonesian directly relevant to the research topic was included. The selection process followed the PRISMA flow, comprising identification, screening, eligibility, and inclusion stages. Articles were analyzed in depth, encompassing technical studies, policy frameworks, and nature-based approaches for sustainable coastal tourism management.

The primary focus of the analysis includes: (1) domestic wastewater treatment systems (WWTP); (2) solid waste management technologies; (3) conservation and efficiency of clean water use; (4) carbon footprint policies; (5) implications for sustainable destination management; and (6) stakeholder roles in coastal tourism governance. This review is reinforced by the Life Cycle Assessment (LCA) approach, as implemented in previous studies evaluating wastewater management systems and tourism activities based on seasonal variations in emissions, energy consumption, and waste treatment efficiency (Pasciucco et al., 2023). Specifically, LCA was applied to assess and compare the environmental impacts of decentralised and centralised WWTP systems operating in coastal tourism areas, such as Indrayanti Beach. Furthermore, the carbon footprint approach was used to estimate the tourism sector's contribution to total greenhouse gas emissions, following the IPCC methodology and carbon accounting practices adopted in developed countries such as Spain (Campos et al., 2023).

Results

A study demonstrated that wastewater treatment systems in tourist areas exhibit fluctuations in energy consumption and emissions production, which are strongly influenced by the high and low tourism seasons (Pasciucco et al., 2023). In the case of Indrayanti Beach, the number of tourists during the peak season can increase by up to three times the normal number, resulting in a significant increase in the load on the WWTP infrastructure. The study compared centralized and decentralized scenarios and found that centralized systems have a 25% lower carbon footprint when combined with the use of renewable energy.

Another study in Spain's coastal tourist areas found that approximately 60–70% of the total environmental impact originated from electricity and chemical consumption in the wastewater treatment process (Gomez et al., 2025). This highlights the importance of energy efficiency and selecting appropriate technology in planning tourist area sanitation systems.

In the context of Indrayanti Beach, the lack of a centralized treatment system is a significant issue. Based on a simple LCA scenario developed from the assumption of using traditional septic tanks and anaerobic biofilter systems, it was found that: The septic tank system produces an average emission equivalent of 0.6 kg CO_2-eq/m^3 of effluent; The anaerobic-aerobic biofilter system can reduce emissions to 0.35 kg CO_2-eq/m^3, with COD removal efficiency reaching 80%.

Seasonal Aspects and Tourist Transportation

It has been highlighted that the most significant carbon emissions from coastal tourism activities originate from transportation, particularly fossil-fueled private vehicles (Chenel, 2014). In the context of Indrayanti, data shows that more than 85% of visitors use private or travel vehicles fueled by diesel or gasoline.

Data from the DIY Tourism Office showed a 3-fold surge in visitors at the peak of the holiday, resulting in a dramatic rise in vehicle fuel consumption. Annual transportation emissions are estimated at 380 tons CO_2-eq, equivalent to the electricity consumption of 90 households. At small-scale tropical destinations, an electrification strategy reduced transportation emissions by 30% through integrated EV charging stations.(Ali et al., 2024). This model can be replicated in the Indrayanti parking area, allowing for the estimation of the transportation sector's impact on the area.

Strategic recommendations that can be implemented based on the study include the use of electric vehicles with charging stations in the integrated parking area, the utilization of solar panels for kiosks and local accommodations, and the implementation of a carbon offset scheme based on the reforestation of coastal vegetation.

Greywater Reuse and Process Emission Reduction

A Life Cycle Assessment study revealed that graywater recycling systems can reduce the carbon footprint by up to 30% compared to conventional treatment methods in tropical resorts (Pasciucco et al., 2023). This technology has not yet been applied in the Indrayanti Beach area, but it has great potential given the high use of water for bathing and washing.

Greywater reuse systems, when combined with slow sand filtration and UV, can produce medium-quality water for watering and toilet flushing, with emissions of only 0.18 kg CO_2-eq/m³ compared to conventional systems that reach 0.55 kg CO_2-eq/m³ (Leong et al., 2019).

At Indrayanti Beach, domestic wastewater is estimated to comprise 60-70% graywater, the leftover water from bathing, dishwashing, and light laundry, which offers an excellent opportunity for nonpotable recycling. Research demonstrated that decentralized greywater systems, such as constructed wetlands and slow sand filtration with UV disinfection, can save 40–50% of freshwater use and reduce CO_2-eq emissions by 0.20–0.30 kg/m³ compared to systems without reuse (Khajvand et al., 2022). In terms of energy, the electricity consumption of pumps and aeration in the decentralized WWTP system in Indrayanti generates about 0.6 kg CO_2-eq/m³ of effluent. A centralized WWTP system integrated with 10 kWp solar panels and biogas digesters was shown to reduce operational emissions by 25%–28% through the substitution of fossil-based energy with renewables (Pasciucco et al., 2023). The pinch analysis approach in industrial ecology recommends utilising biogas from greywater as a minor energy source for aerators, thereby maximising energy efficiency and closing material flows in communal Wastewater Treatment Plants.

LCA of the Sludge Management System and its Utilisation

Waste sludge generated from WWTP systems often goes unnoticed, even though its contribution to the carbon footprint is significant. Sludge management in tourist-area WWTPs can contribute up to 40% of total CO_2-eq emissions in the final treatment stage (Ogbu et al., 2025). In a comparative study of landfilling, composting, and sludge incineration, the composting option was found to have the lowest environmental impact, particularly in terms of methane emissions and energy consumption.

Waste sludge from the treatment process can also be processed into high-quality compost for the revegetation of seagrass and mangroves around coastal areas. Sludge composting lowers CO_2-eq emissions by a factor of six compared to landfilling and yields approximately 300 kg of compost per ton of sludge. (Ouedraogo et al., 2024). Additionally, it produces 300 kg of compost per tonne of sludge, which is beneficial for stabilizing coastal ecosystems. The combination of greywater reuse, pump electrification with renewable energy, and sludge composting at Indrayanti could reduce the carbon load of the sewage treatment system by 30%-35%, bringing the destination closer to low-emission tourism targets.

Integrative Approach to Energy and Water Systems in Tourism Areas

Integrating wastewater systems with renewable energy sources is essential for reducing emissions in tourism destinations. Utilizing methane gas from anaerobic digesters installed in WWTPs can generate energy, with 1 m³ of sewage producing 0.25 m³ of biogas or 5.5 MJ (Pasciucco et al., 2023). In Indrayanti Beach, an integrated system scenario between an anaerobic digester WWTP and solar panels can be proposed as a nature-based solutions (NBS) approach. Integration can reduce system emissions by 32% compared to a standalone WWTP scheme without renewable energy (Arzoumanidis et al., 2021).

Integration of Coastal Ecosystem Services (CES) and Life Cycle Assessment (LCA) for Low-Emission Tourism

The integration of Coastal Ecosystem Services (CES) and Life Cycle Assessment (LCA) provides a comprehensive framework to reduce the environmental footprint of coastal tourism while simultaneously enhancing ecological resilience and community benefits. CES encompasses regulating services (carbon sequestration, shoreline stabilization, water purification), provisioning services (biomass resources), cultural services (recreational and aesthetic value), and supporting services (habitat provision and nutrient cycling).

At Indrayanti Beach, regulating services are particularly critical. Mangrove and seagrass ecosystems store significant amounts of carbon in both biomass and sediments, while coastal vegetation, such as *Casuarina equisetifolia*, mitigates wind and wave impacts, reducing erosion risk. These natural processes can be quantified in carbon dioxide equivalent (CO_2-eq) terms and incorporated into LCA as harmful emissions (carbon "footprint").

In practical terms, integrating CES into LCA involves mapping ecosystem functions to LCA impact categories. For example, mangrove restoration contributes directly to climate change mitigation by increasing long-term carbon storage. At the same time, seagrass meadows improve water quality, reducing treatment requirements for greywater and thus lowering the carbon intensity of water management systems. By aligning engineered interventions (centralized WWTP with renewable energy, greywater reuse, sludge composting, and electric mobility infrastructure) with CES enhancement (habitat restoration and vegetative buffers), the destination can achieve a net reduction in carbon footprint that exceeds the sum of the individual measures.

This combined approach supports evidence-based policy-making. By expressing both technological and ecosystem-based contributions in comparable units (e.g., t CO_2-eq/year avoided), policymakers can design carbon standards, fiscal incentives, and offset schemes that prioritize investments with the highest combined benefits in terms of mitigation and resilience.

Table 1. Relationship between CES and LCA Parameters

CES Category	**Example at Indrayanti**	**LCA Parameter**	**Unit**	**Impact Category**
Regulating	Mangrove carbon sequestration	Sequestration rate in biomass & sediments	t CO_2-eq/ha/year	Climate change mitigation
Regulating	Seagrass sediment stabilization	Avoided erosion repair (infrastructure)	m³ sediment/year	Resource depletion
Regulating	Coastal vegetation buffers	Reduced storm damage repair needs	USD/year	Resource & energy savings
Cultural	Ecotourism value	Visitor willingness-to-pay for conservation	USD/visitor	Socio-economic benefit
Supporting	Habitat provision	Biodiversity index improvement	Index points/year	Ecosystem health

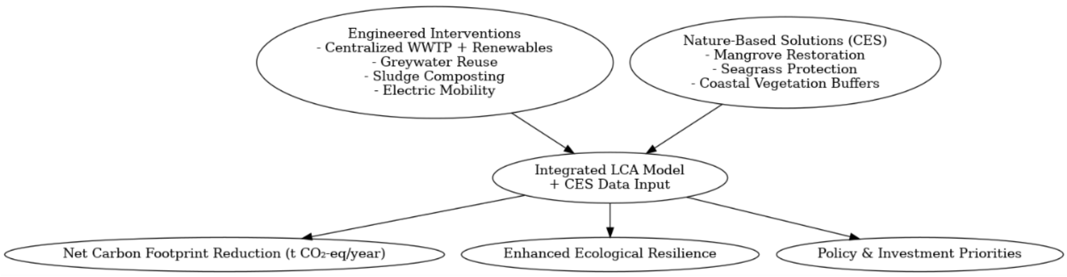

Figure 1. CES–LCA integration framework for Indrayanti Beach

Carbon Footprint Policies in the Tourism Industry: Opportunities and Challenges

The application of carbon footprint policies in tourism areas is still limited, both in terms of regulation and incentives. In Spanish, it demonstrates that an approach based on carbon footprint calculation can motivate industry players to offset their emissions through donations to green projects, thereby improving operational efficiency (Campos et al., 2023). A similar scheme can be adopted in Indonesia with the following steps:

1. Establishment of carbon standards for tourist destinations by local governments.
2. Online application-based emission reporting by tourism business managers;
3. Development of a local marketplace for carbon offsets, such as beach vegetation planting or support to communal landfills;
4. Green labelling for tourism businesses that can measurably reduce emissions.

In the effort to create a sustainable beach tourism destination, a carbon footprint policy plays a strategic role as a controlling instrument and driver of the tourism industry's transformation towards low-emission practices. Beach tourism, which relies heavily on the attractiveness of coastal ecosystems, is one of the most vulnerable sectors to climate change impacts and a significant contributor to carbon emissions, especially from the transportation and accommodation infrastructure sectors (Hatamifar et al., 2025).

Achieving carbon neutrality in tourism requires comprehensive policies including emissions regulation, green technology incentives, and community-based offset mechanisms (Hatamifar et al., 2025). In the context of coastal tourism, these policies can be implemented through the establishment of destination carbon standards, digital-based emissions reporting, and the development of local carbon markets that support coastal vegetation reforestation or LCA-based waste management.

Carbon policy effectiveness can be enhanced by integrating spatial approaches and long-term climate modelling, particularly in coastal areas (Arabadzhyan et al., 2021). In their study, policies that do not consider the seasonal dynamics and ecological vulnerability of coastal areas are likely to fail in significantly reducing emissions. Therefore, adaptive policies based on spatial data and local climate change predictions are needed.

Current tourism policies often remain reactive and lack systematic integration of sustainability principles into planning frameworks (Jarratt & Davies, 2020). They recommend a "blue space governance" approach that places human-environment relations at the core of destination planning, including in the formulation of carbon policies.

Effective implementation of carbon footprint policies in coastal tourism areas requires an approach that is not only regulation-based but also adaptive to local characteristics and involves all stakeholders. Strategies towards achieving carbon neutrality in the tourism sector should encompass three main pathways: individual behaviour change, industry initiatives, and integrated destination policies (Hatamifar et al., 2025). In the context of coastal tourism, this means encouraging the use of low-emission transportation, promoting energy efficiency in accommodations, and implementing waste management practices based on Life Cycle Assessment (LCA).

Furthermore, successful carbon policies in coastal areas must consider complex impact chains, including the linkages between tourism activities, ecological vulnerability, and climate stress (Arabadzhyan et al., 2021). They emphasized the importance of spatial modelling and long-term impact prediction as a basis for formulating policies that are responsive to seasonal dynamics and anthropogenic pressures.

An example of effective policy practice can be found in the *Integrated Coastal Zone Management* (ICZM) approach, which has been implemented in several tropical tourist destinations. This approach combines zoning regulations, fiscal incentives for green technologies, and engagement of local communities in coastal vegetation-based carbon offset schemes. Case studies in Bali, for example, show that policy interventions combining scientific monitoring, tourist education, and ecosystem-based adaptation can significantly reduce environmental pressures while maintaining tourist appeal.

Thus, an effective carbon footprint policy in coastal tourism should be:

a. Be based on scientific and spatial data to identify key emission sources;

b. Encourage multi-stakeholder collaboration, including businesses, local governments, and communities;

c. Integrate economic incentives and tourist education to encourage behaviour change.

d. Adopt an adaptive and contextual approach, considering the ecological and social characteristics of the region.

Such policies not only reduce carbon emissions but also strengthen the social-ecological resilience of coastal tourism destinations in the face of long-term climate change. Thus, carbon footprint policies are not only a control tool, but also a catalyst for innovation and multi-stakeholder collaboration in building coastal tourism destinations that are resilient to climate change and ecologically competitive.

Implications for Sustainable Beach Tourism Management

The findings of this study demonstrate that Life Cycle Assessment (LCA)-based approaches and carbon footprints have strategic implications for the management of coastal tourism destinations, particularly in the context of sustainability (Pasciucco et al., 2023); (Ouedraogo et al., 2024). The implementation of the results of this study can help formulate more comprehensive policies and technical strategies for tourist areas such as Indrayanti Beach.

First, from the aspect of infrastructure planning, wastewater and solid waste management should refer to the principles of energy efficiency and low emissions. A communal wastewater treatment plant (WWTP) system integrated with renewable energy sources, such as solar panels or biogas utilization from sludge treatment, is a rational choice that can reduce the area's carbon footprint (Gomez et al., 2025). Second, from a governance perspective, there needs to be synchronization among local governments, businesses, and communities in implementing green tourism standards. Local regulations can be optimized to require emission reporting and the preparation of LCA-based environmental management documents. Local regulations will encourage businesses to be more accountable in their operational activities (Simpson, Julia, 2023).

Third, in the management of visitors and tourism activities, the application of digital-based monitoring systems to control the carrying capacity and carbon footprint of visitors can be used as an educational and social control tool (Zhong et al., 2025). Visitors can be provided with information regarding the estimated carbon footprint of their trip and offered compensation options such as planting coastal vegetation or contributing to the construction of a local TPST (Integrated Waste Management Site) (Hasibuan et al., 2024).

Fourth, ecologically, the results of this study reinforce the urgency of conserving coastal ecosystems, such as mangroves, sea cypress, and seagrass beds, which have a high capacity to sequester carbon (Chenel, 2014). Coastal vegetation management is not only important for conservation, but also serves as a nature-based solution (NBS) to support regional sustainability.

Fifth, in terms of long-term sustainable tourism development, LCA-based data and indicators can be used as the basis for green investment planning, both from the public and private sectors. This aligns with the global trend in destination management, which is not only economically attractive but also ecologically resilient (Xu & Li, 2025).

Sustainable management of coastal tourism has multidimensional implications, encompassing ecological, social, and economic aspects. In the context of climate change and increasing anthropogenic pressures, the sustainability approach is no longer an option, but a strategic necessity to maintain the environmental carrying capacity and long-term resilience of tourist destinations.

A Coastal Ecosystem Services (CES)-based approach can strengthen the sustainability of coastal tourism by integrating ecosystem protection, local community empowerment, and equitable economic growth (Sholeha & Sumarmi, 2025). This approach places ecological values, such as coastal vegetation, water quality, and biodiversity, at the primary foundation of destination planning.

Furthermore, an effective coastal tourism management strategy should combine SWOT analysis with spatial planning policies, environmentally friendly infrastructure improvements, and collaboration among the government, businesses, and local communities (Ali et al., 2024).   not only become more resilient to environmental pressures but are also able to improve community welfare inclusively.

Another important implication is the need for integration between scientific data and public policy. Many tourists are aware of the importance of environmental conservation, but still lack an understanding of ecotourism practices (Hidajat et al., 2020). Therefore, environmental education and involving tourists in conservation activities are key in building collective awareness and shared responsibility.

Sustainable management of coastal tourism has multidimensional implications, encompassing ecological, social, and economic aspects. In the context of climate change and increasing anthropogenic pressures, the sustainability approach is no longer an option, but a strategic necessity to maintain the environmental carrying capacity and long-term resilience of tourist destinations.

Overall, sustainable coastal tourism management has strategic impacts that extend beyond economic aspects, with tangible contributions to environmental conservation, social empowerment, and long-term destination resilience.

a. Conservation of coastal ecosystems is the primary foundation, considering that coastal areas play important ecological functions, such as serving as abrasion barriers, carbon sinks, and habitats for marine biodiversity. The *Coastal Ecosystem Services (CES)* approach can enhance conservation effectiveness by protecting coastal vegetation and promoting community-based waste management.

b. Increasing the capacity of local communities as the leading actors in ecotourism is proven to strengthen social sustainability. Community involvement in destination planning and management not only increases the sense of ownership but also expands cultural and nature-based economic opportunities.

c. Diversification of the local economy through the development of cultural, culinary, and handicraft-based tourism products is an adaptive strategy to fluctuations in the tourism market. This also strengthens the economic resilience of coastal communities, especially outside the peak visitation season.

d. Strengthening collaborative governance between government, academia, businesses, and local communities is key to long-term success. This multi-stakeholder approach enables the integration of scientific data, public policy, and context-specific local practices, as demonstrated in a study on the integrated management of tourism areas in Indonesia.

e. The resilience of destinations to climate change and global market dynamics is also increased through the application of sustainability principles. By adopting green technologies, implementing carrying capacity monitoring systems, and providing tourist education, coastal destinations can become more resilient to environmental risks and changes in global tourist preferences.

Thus, the success of coastal tourism management is no longer measured by the quantity of visits, but by its contribution to ecosystem sustainability, community welfare, and social-ecological resilience of the destination. This approach aligns with the Sustainable Development Agenda and serves as a strategic model for tourism development in the coastal areas of developing countries.

Thus, the management of Indrayanti Beach tourism requires not only a separate sectoral approach but also cross-sectoral integration, supported by scientific data, environmentally friendly technology, and collective awareness of the importance of minimizing the carbon footprint for the preservation of the coastal environment.

Role of Stakeholders in Environmental Impact Control of Tourism Areas

The success of environmental impact control in coastal tourism areas, such as Indrayanti Beach, is highly dependent on the synergy between *stakeholders*, including the government, tourism businesses, local communities, academics, and non-governmental organizations. This collaborative role has been identified as one of the important indicators in the success of sustainable tourism development (www.world-tourism.org, 2005). Local governments play a crucial role as regulators and facilitators in establishing environmental policies and regulations, including determining carrying capacity limits, offering environmental incentives, and implementing training and education programs for businesses. In addition, the government can encourage cross-sector collaboration through the preparation of integrated management plan documents and multi-stakeholder forums (Khajvand et al., 2022).

Tourism businesses, such as homestay managers, restaurants, and tourist attractions, play a crucial role in the direct implementation of environmentally friendly technologies and LCA-based waste management. Their commitment to implementing environmentally friendly operational standards will significantly contribute to reducing regional emissions (Hatamifar et al., 2025).

Local communities serve as both custodians of the environment and primary beneficiaries of tourism. The Community-Based Tourism (CBT) model promotes community involvement in environmental monitoring, enforcement of rules, and the development of local programs, such as waste banks or culture-based ecotourism initiatives (Hasibuan et al., 2024). The role of academics and research institutions, including higher education institutions such as universities, is vital in providing scientific data and appropriate technology. Research based on LCA, carbon footprints, and environmental audits of tourist areas can be used as the basis for evidence-based policy making (Pasciucco et al., 2023); (Gomez et al., 2025).

Non-governmental organizations and environmental communities also play roles as watchdogs, capacity-building facilitators, and advocates for environmental policy. Their collaboration with governments and communities can strengthen social monitoring mechanisms and encourage the adoption of sustainable technologies.

This synergy between stakeholders is key in controlling long-term environmental impacts and preserving the quality of coastal ecosystems. With a participatory and collaborative approach, Indrayanti Beach tourism management can develop into a resilient and inclusive sustainable destination model.

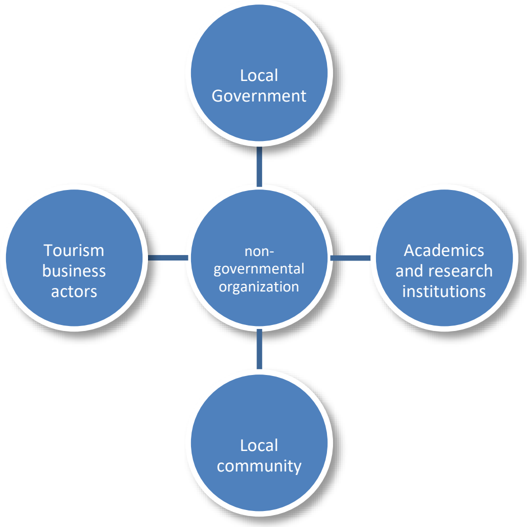

Figure 2. Stakeholder collaboration scheme

1. Local Government: As the leading actor in regulation, local governments are responsible for formulating environmental policies and zoning tourism areas. They play a strategic role in determining the carrying capacity of the environment, regulating the development standards for tourism infrastructure, and applying sanctions for environmental violations. The Ministry of Tourism and Creative Economy of the Republic of Indonesia emphasizes the need for a sustainable governance framework at the local level to prevent tourism practices from damaging local ecosystems (Hidajat et al., 2020).

2. Tourism Business Actors: Businesses, including hotel managers, restaurants, and recreation service providers, play a crucial role in mitigating environmental impacts. They are responsible for waste management, energy saving, and educating tourists about environmental ethics. Operational efficiency in the tourism industry is significantly influenced by the level of awareness and investment in environmentally friendly practices by businesses (Waaje et al., 2025). Acts as policy steward and regulator of sustainable governance. Defines environmental carrying capacity, sets destination emission standards, and facilitates green technology incentives. Expected to demonstrate proactive adoption of eco-technologies and emission reporting via LCA frameworks. Their operational commitment shapes regional emission profiles.

3. Local Communities: Local communities serve as custodians of the cultural and ecological values of tourism areas. They support conservation through social supervision and implementation of programs such as waste banks, conservation gardens, and community-based water management. The Community-Based Tourism (CBT) approach positions the community as the subject of development rather than merely the object of tourism's impact (Hasibuan et al., 2024). They act as custodians of ecological and cultural values. Participates in conservation through CBT models, tourist education, and community-based waste management practices.

4. Academics and Research Institutions: Educational institutions and researchers play a crucial role in generating scientific knowledge, conducting LCA studies, and providing the basis for evidence-based policy formulation. Academic studies are crucial for evaluating the life cycle of tourism infrastructure and pinpointing critical points that contribute to emissions or environmental pollution (Gomez et al., 2025). Assume an analytical and contributive role, providing scientific data, LCA modeling, and evidence-based policy input. Their involvement ensures transparency and validity in the decision-making process.

5. NGOs/Environmental Communities: Non-governmental organizations play a crucial role in overseeing the implementation of environmental policies, advocating for regulatory changes, and providing technical training to communities and businesses. The role of NGOs is becoming increasingly important amid the growing vulnerability of tourist areas due to climate change and overexploitation (Jarratt & Davies, 2020). Act as advocates and facilitators. Promote

progressive regulation, monitor environmental impacts, and strengthen community and business capacities through targeted training.

The success of the transformation to *low-emission tourism* in Indrayanti depends on the cooperation of the Gunungkidul Regency Government, Tepus Village, businesses, environmental NGOs, and academics. Multi-level governance and digital spatial monitoring are emphasized as key to adapting carbon policy (Arabadzhyan et al., 2021). This scenario needs to be tested through a local emission monitor application in Indrayanti.

Although *carbon footprint* analysis and *Life Cycle Assessment* (LCA) approaches have been the primary foundation in assessing the environmental impacts of coastal tourism, recent studies emphasize the need for cross-sectoral and *multi-level governance* approaches in sustainable destination management strategies. *Coastal tourism* not only generates emissions from transportation and infrastructure, but is also highly vulnerable to the impacts of climate change, such as rising sea levels, coastal erosion, and an increased frequency of tropical storms (Smith et al., 2023).

One aspect that needs to be strengthened is the role of carbon policies and economic incentives in driving the tourism industry's transformation towards carbon neutrality. Achieving carbon neutrality in the tourism sector requires a combination of mitigation and adaptation strategies, including changes in tourist behaviour, fiscal incentives for businesses, and the integration of low-carbon technologies in destination operations (Hatamifar et al., 2025).

Additionally, community-based approaches and climate justice are emphasized. Economic benefits from coastal tourism are often unevenly distributed, while local communities disproportionately bear the environmental burden (Smith et al., 2023). Therefore, management strategies should consider the social-ecological dimension and ensure active participation of communities in planning and decision-making.

From a technical perspective, the use of spatial indicators and predictive modelling based on big data enables the real-time mapping of carbon emissions and the identification of emission hotspots in tourist areas (Arabadzhyan et al., 2021). This opens up opportunities to develop app-based monitoring systems that can be used directly by destination managers and tourists.

Finally, the coastal tourism sector contributes more than 1.5 billion tons of CO_2eq per year, with the most significant contribution coming from transportation and energy consumption in accommodations (Simpson, Julia, 2023). Therefore, investments in renewable energy, transport electrification, and nature-based solutions are global priorities in the tourism decarbonization roadmap.

Conclusion

This literature-based study demonstrates that achieving low-emission coastal tourism at Indrayanti Beach requires integrated interventions across the tourism value chain, grounded in the combined application of Life Cycle Assessment (LCA) and Coastal Ecosystem Services (CES) approaches. The adoption of centralized wastewater treatment systems (WWTPs) powered by renewable energy sources, such as solar panels and biogas, can reduce the carbon footprint by approximately 25% compared to conventional decentralized systems. Composting-based sludge management yields six times lower emissions compared to landfill disposal, while producing organic amendments that support coastal vegetation restoration. Integrating greywater reuse into the water management system reduces emissions by up to 30% and conserves clean water resources for sanitation, while the electrification of the tourist transport fleet and carbon offset schemes based on coastal reforestation substantially mitigate transportation-related emissions, which account for 60–70% of the destination's total carbon footprint.

Furthermore, the incorporation of Nature-Based Solutions, particularly mangrove and seagrass conservation, within the LCA framework enhances social–ecological resilience, creates opportunities for community-based ecotourism, and increases the potential for natural carbon sequestration. Adaptive governance, including the implementation of destination-specific carbon standards, digital emissions reporting, fiscal incentives for green technologies, and locally managed offset mechanisms, is essential to ensure the long-term sustainability of low-emission initiatives in alignment with Indonesia's 2060 net-zero target.

The integration of CES into LCA for Indrayanti Beach highlights that nature-based solutions and engineered infrastructure can jointly deliver significant emission reductions and resilience gains. By quantifying CES in carbon-equivalent terms and incorporating them into life cycle models, policymakers and stakeholders can identify strategies that simultaneously address climate change mitigation, support socio-economic development, and preserve the ecological integrity that underpins the long-term attractiveness of coastal tourism destinations.

Based on the results of the literature review, the direction of Indrayanti beach's development is to become a low-emission, sustainable tourism destination that is resilient, inclusive, and aligned with the 2060 net-zero emission target. Steps that can be pursued include the following:

1. Build a centralized WWTP integrated with renewable energy,
2. Prioritise WWTP systems equipped with solar panels and biogas digesters to reduce emissions by 25%-30 %,
3. Implement graywater reuse and sludge composting,
4. Implement slow sand filtration + UV for greywater (emissions up to 0.18 kg CO_2-eq/m³) and sludge composting for beach restoration (±65 kg CO_2-eq per ton),
5. Electrification of tourist transportation and carbon offsets
6. Provide EV charging stations at destinations and develop coastal reforestation-based offset mechanisms to reduce transportation emissions by 60%-70%.
7. Integration of Nature-Based Solutions and local empowerment
8. Protect mangroves, sea cypress, and seagrass beds as carbon sinks, as well as the basis for community-based ecotourism (CES model).
9. Adaptive policy and digital monitoring
10. Set destination carbon standards, require online emissions reporting, and utilize real-time spatial modelling to adapt policies to seasonal dynamics and local climate conditions.
11. Fiscal incentives and multi-stakeholder collaboration
12. Provide tax rebates for green energy investments, subsidize low-carbon technologies, and facilitate forums among government, businesses, academia, and local communities to ensure the sustainable implementation of these initiatives.

By following these recommendations, coastal destinations in the tropics can move towards low-emission tourism that is resilient, inclusive, and aligned with the 2060 net-zero emission target.

References

[1] Ali, M., Ekawati, S. A., Taskirawati, I., Nur, D. S. A., Irfan, M., Nasaruddin, Inayah, A. N., Zaira, M. R., & Hasnah, D. H. (2024). Sustainable Coastal Tourism: A Comprehensive Development Strategies (Tanjung Bira and Lemo-lemo Tourism Area as a Case Study). International Journal of Sustainable Development and Planning, 19(7), 2489–2499. https://doi.org/10.18280/ijsdp.190706

[2] Arabadzhyan, A., Figini, P., García, C., González, M. M., Lam-González, Y. E., & León, C. J. (2021). Climate change, coastal tourism, and impact chains–a literature review. Current Issues in Tourism, 24(16), 2233–2268. https://doi.org/10.1080/13683500.2020.1825351

[3] Arzoumanidis, I., Walker, A. M., Petti, L., & Raggi, A. (2021). Life cycle-based sustainability and circularity indicators for the tourism industry: A literature review. Sustainability (Switzerland), 13(21). https://doi.org/10.3390/su132111853

[4] Campos, C., Gallego, M., Villanueva, P., Laso, J., Dias, A. C., Quinteiro, P., Oliveira, S., Albertí, J., Fullana-i-Palmer, P., Mélon, L., Sazdovski, I., Roca, M., Xifré, R., Margallo, M., & Aldaco, R. (2023). Life cycle assessment to address the environmental impacts of tourism in a Spanish tourist destination: The case of Rias Baixas (Galicia) holidays. Science of the Total Environment, 896(June). https://doi.org/10.1016/j.scitotenv.2023.166242

[5] Chenel, S. (2014). ScienceDirect Eco-efficiency analysis of Spanish WWTPs using the LCA þ DEA method. 8.

[6] Gomez, S. R., Castillo, N. A. M., Orozco, I. H., Galarza, A. Á., Larragoitia, S. A. C., Flores, M. M. A., & Vázquez, V. Á. (2025). Life Cycle Assessment of a wastewater treatment plant in an urban area using the environmental footprint method. Environment, Development and Sustainability, 27(4), 9145–9163. https://doi.org/10.1007/s10668-023-04273-y

[7] Hasibuan, B., Hanaseta, E., Gusdini, N., & Ratnasari, L. (2024). Economic Valuation of Recreational Services at Tanjung Kelayang Beach for Sustainable Tourism Development in Belitung, Indonesia. Journal of Logistics, Informatics and Service Science, 11(10), 343–351. https://doi.org/10.33168/JLISS.2024.1019

[8] Hatamifar, P., Esfandiar, K., & Ghaderi, Z. (2025). Towards carbon neutrality in tourism: pathways and future research directions. Asia Pacific Journal of Tourism Research, 1665. https://doi.org/10.1080/10941665.2025.2514016

[9] Hidajat, W. K., Anggoro, S., & Najib. (2020). Management of Coastal Areas with Sustainable Marine Ecotourism Development in Purworejo Regency, Central Java, Indonesia. Advance Sustainable Science, Engineering and Technology, 2(1), 1–8. https://doi.org/10.26877/asset.v2i1.6020

[10] Hoe, Y. F., & Abdullah, A. R. (2025). Impacts of Coastal Land Reclamation and Sand Mining Activities: Perspectives from Coastal Fishing Communities and Ecotourism Providers. Malaysian Journal of Qualitative Research, 11(1), 128–140. https://doi.org/10.61211/mjqr110110

[11] Jarratt, D., & Davies, N. J. (2020). Planning for Climate Change Impacts: Coastal Tourism Destination Resilience Policies. Tourism Planning and Development, 17(4), 423–440. https://doi.org/10.1080/21568316.2019.1667861

[12] Khajvand, M., Mostafazadeh, A. K., Drogui, P., & Tyagi, R. D. (2022). Management of greywater: environmental impact, treatment, resource recovery, water recycling, and decentralization. Water Science and Technology, 86(5), 909–937. https://doi.org/10.2166/wst.2022.226

[13] Ogbu, C. A., Alexiou Ivanova, T., Ewemoje, T. A., Alabi, H. A., & Roubík, H. (2025). Towards environmentally sustainable water management in Africa: a comprehensive review of life cycle assessment studies in water and wastewater treatment. International Journal of Life Cycle Assessment, 30(5), 956–979. https://doi.org/10.1007/s11367-025-02434-x

[14] Ouedraogo, A. S., Kumar, A., Frazier, R., & Sallam, K. A. (2024). Comparative Life Cycle Assessment of Landfilling with Sustainable Waste Management Methods for Municipal Solid Wastes. Environments - MDPI, 11(11). https://doi.org/10.3390/environments11110248

[15] Pasciucco, F., Pecorini, I., & Iannelli, R. (2023). A comparative LCA of three WWTPs in a tourist area: Effects of seasonal loading rate variations. Science of the Total Environment, 863(November 2022), 160841. https://doi.org/10.1016/j.scitotenv.2022.160841

[16] Sholeha, A. W., & Sumarmi, S. (2025). Managing Sustainable Tourism of Perawan Beach, East Java, Indonesia Based on the Coastal Ecosystem Service (Ces) Approach. Geojournal of Tourism and Geosites, 58(1), 78–88. https://doi.org/10.30892/gtg.58107-1392

[17] Simpson, Julia, G. F. T. (2023). Coastal & Marine Tourism Quantifying Its Footprint And Funding Requirements For Mitigation And Adaptation. World Travel & Tourism Council.

[18] Smith, T. F., Elrick-Barr, C. E., Thomsen, D. C., Celliers, L., & Le Tissier, M. (2023). Impacts of tourism on coastal areas. Cambridge Prisms: Coastal Futures, 1, 1–5. https://doi.org/10.1017/cft.2022.5

[19] Waaje, A., Roshid, M. M., Islam, S., Chandra Bhowmik, R., Rahaman, M. A., & Hassan, M. M. (2025). Tourism, trade, energy, and economic development: Drivers of ecological footprint in the World’s top tourist destinations. Innovation and Green Development, 4(3). https://doi.org/10.1016/j.igd.2025.100249

[20] www.world-tourism.org. (2005). Tourism Highlights 2005: Overview International Tourism.

[21] Xu, N., & Li, H. (2025). Towards management of sustainable tourism development in coastal destinations of the Bohai Rim: insights from a tourism carrying capacity analysis. Discover Sustainability, 6(1). https://doi.org/10.1007/s43621-025-00951-1

[22] Zhong, C. Y., Liu, L. J., Liang, Q. M., & Yu, Y. Y. (2025). Tackling the carbon footprint of tourism: Strategies for China’s inbound and domestic travel. Resources, Conservation and Recycling, 218(November 2024). https://doi.org/10.1016/j.resconrec.2025.108238.