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The Interplay Between Uncontrolled Industrialization, Ecotourism, Fishery Resources in Nigerian Coastal Areas: Eco-Dynamic Modelling Approach

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Abstract

Coastal tourism is a significant economic activity in Lekki and Epe mangroves in Nigeria. However, the presence of heavy metal pollutants in these areas due to uncontrolled industrialization and ecotourism-related pollution poses a potential risk to ecosystems. This paper examined the complex interplay between uncontrolled industrialization, ecotourism development, and fishery resources in coastal areas. Utilizing an eco-dynamical modelling approach, this paper quantified the impacts of these anthropogenic activities on fishery sustainability. Modelling incorporated key parameters such as the competitive rates of industrialization and ecotourism, mitigating effects on geometric increase in ecotourism and industrialization. Simulation results obtained using matlab showed the balance required to sustain fishery resources, showing that high levels of industrialization and ecotourism significantly degrade fishery stocks, while controlled development can mitigate these impacts. Specifically, Modelling demonstrated that fishery resources flourished under conditions where the adverse effects of ecotourism and industrialization are minimized. Findings highlight the need for strict regulations and sustainable coastal management to protect fishery resources. Hence, this will offer crucial insights for policymakers on integrating economic and ecological goals in the tourism context.

Introduction

Fishery resources in coastal mangroves are vital to local communities' livelihoods, providing food security and economic stability (Garmaeepour et al., 2025; Mhatre, 2024). These resources also play a critical role in maintaining the overall health of the marine ecosystem by supporting species diversity and ensuring the provision of essential ecosystem services. Key fish species found in these mangroves, such as *Chrysichthysnigrodigitatus* and *Sarotherodonmelanotheron*, are economically significant and form the backbone of the local fishery industry (Chuku et al., 2022; Constant et al., 2024; Ellison et al., 2020). Effective and sustainable management of these resources is essential to ensuring their long-term viability in the face of rapid industrialization and burgeoning ecotourism (Xu et al., 2023), which pose significant threats to their sustainability. Understanding the ecological dynamics of these species and their habitats is crucial for developing effective conservation strategies that balance economic development with environmental protection. Proper management not only safeguards local livelihoods but also preserves the rich biodiversity and ecosystem functions provided by these mangroves (Babalola et al., 2024, Baloch et al., 2023; Xu et al., 2022).

The last decade has seen accelerated industrialization in the Lekki and Epe regions, driven by economic growth and urban development (Isukuru et al., 2024; Koko & Bello, 2023; Titilayo, 2024). This rapid expansion includes activities such as construction, manufacturing, and chemical processing, which often result in the discharge of pollutants into the environment. For example, the Dangote Refinery, located in the Lekki Free Trade Zone, poses a risk of oil spillage if its effluents are not properly monitored, reminiscent of the ongoing oil spillage issues in the Niger Delta region of Nigeria (Ekum et al., 2023a, 2023b). Heavy metals such as cadmium (Cd), copper (Cu), zinc (Zn), and lead (Pb) are concerning due to their toxicity and persistence in the environment. These pollutants can bioaccumulate in fish tissues, posing health risks to aquatic life and humans who consume contaminated fish (Abaza & Eltobgy, 2025; Adekiya et al., 2024; Adetutu et al., 2023; Hubeny et al., 2021; Zacchaeus et al., 2020).

Uncontrolled industrialization impacts fishery resources through pollution, habitat destruction, and overfishing (Mustafa et al., 2024). Industrial waste, including heavy metals and chemicals, contaminates water bodies, leading to the decline of aquatic ecosystems and fish populations (Hama Aziz et al., 2023;). Habitat destruction from industrial activities (Saravanan et al., 2024), such as dredging and land reclamation, further reduces breeding and feeding grounds for fish (Mustafa et al., 2024). Additionally, overfishing driven by industrial demand depletes fish stocks, threatening food security and biodiversity. These factors collectively disrupt the balance of aquatic ecosystems, leading to reduced fishery yields and economic losses for communities that depend on fishing (Nair & Nayak, 2023). Therefore, effective regulation and sustainable practices are essential to mitigate these adverse effects and preserve fishery resources for future generations (Adewale et al., 2024; Mor, 2023).

On the other hand, the rapid growth of ecotourism in the Lekki and Epe regions has attracted visitors to mangroves' unique natural landscapes and biodiversity (Moussa et al., 2024). Ecotourism has the potential to promote conservation and provide economic benefits to coastal communities (Andrews et al., 2021; Samal & Dash, 2023). However, if not properly managed, the influx of tourists can lead to habitat degradation, pollution, and overexploitation of natural resources, further stressing fishery resources (Onihunwa et al., 2023). Therefore, effective management strategies are essential to ensure sustainable ecotourism practices that balance economic gains with environmental preservation, benefiting existing and future generations while safeguarding mangroves' fragile ecosystems (Alhiagi & Aliraqi, 2025; Abbass et al., 2022; Anu et al., 2024; Baloch et al., 2023; Gupta et al., 2024; Metilelu et al., 2022; Mohamed et al., 2023; Samal & Dash, 2024).

In addition to the challenges posed by uncontrolled industrialization, ecotourism can also have detrimental effects on fishery resources due to pollutants generated by increased human activity (Pásková et al., 2023). Common pollutants include plastic waste, chemicals from sunscreen, and fuel emissions from boats, which can contaminate water bodies (Rashed et al., 2023). These pollutants disrupt aquatic ecosystems, harming fish populations and degrading their habitats (Thanigaivel et al., 2024). For instance, plastic debris can break down into microplastics that affect marine life's health and reproduction by introducing toxic substances into food chains. Chemical pollutants can deteriorate water quality and cause fish mortality (Ali et al., 2024). Furthermore, increased boat traffic can lead to habitat destruction and increased turbidity, impacting fish feeding and breeding grounds (Deng et al., 2022; Saeedi, 2024; Ziani et al., 2023). Therefore, effective management and pollution control measures are crucial to mitigating these impacts and protecting fishery resources (Nwafor, 2024).

Industrialization and ecotourism's dual impact on pollution and antibiotic resistance highlights the need for sustainable management and strict regulations to protect the Lekki and Epe mangroves. Balancing economic development with environmental conservation is essential for ensuring the long-term sustainability of fishery resources (Hart, 2024; Nashwan et al., 2024). To address these intertwined challenges, understanding the interactions between fishery resources, industrialization, and ecotourism is needed. An eco-dynamical modelling approach offers a valuable framework for examining these complex relationships (Lankers et al., 2023; Radosavljevic et al., 2023).

Modelling fishery resources, ecotourism development, and industrialization dynamics, scholars can predict how changes in one factor influence others. This approach helps in identifying sustainable management strategies that balance economic development with environmental conservation (Akbari et al., 2023; Nair & Nayak, 2023; Uddin et al., 2021). Understanding these interactions is crucial for mitigating the adverse impacts of rapid industrialization and ecotourism on fishery resources in coastal areas, ensuring long-term sustainability. Such modelling provides insights into current challenges and aids in forecasting future scenarios (Hariram et al., 2023), guiding policymakers toward informed decision-making and effective resource management practices (Choudhary et al., 2024). This integrated approach is essential for fostering resilient coastal ecosystems that support ecological integrity and economic development (Pásková et al., 2023).

Previous studies have highlighted individual impacts of industrial pollution and tourism on coastal ecosystems (Dilman-Gokkaya et al., 2024; Hariram et al., 2023; Lukman et al., 2022; Nair & Nayak, 2023; Pásková et al., 2023; Uddin et al., 2021). However, there is a significant gap in research regarding integrated approaches that consider the simultaneous effects of industrialization and ecotourism on fishery resources. Čábelková et al. (2023); Dunlop et al. (2024); and Hariram et al. (2023) tend to focus on either ecological or economic aspects, without fully capturing the interactive dynamics between these sectors. Several limitations prevent a comprehensive understanding of how industrial activities and ecotourism development collectively influence coastal ecosystems. Addressing these knowledge gaps are crucial for developing effective management strategies that can mitigate the combined impacts of these activities. In turn, this ensures fishery resource sustainability and overall health of coastal ecosystems.

This paper aims to fill these gaps by developing and analyzing an eco-dynamical model that describes the relationship between fishery resources, ecotourism, and industrialization in Lekki/Epe mangroves. Main objectives of this paper are 1) to quantify the impacts of industrial pollutants and ecotourism activities on fishery resources, 2) to identify key factors and interactions that influence the sustainability of fisheries, and 3) to provide recommendations for managing industrial and tourism activities to ensure the long-term health of fishery resources. By employing an eco-dynamical modelling, this paper explores the complex relationships between fishery resources, ecotourism development, and industrialization. This modelling provides keen insights into how these factors interact and affect fishery resources' sustainability in this region. Achieving these objectives will contribute to more effective and integrated coastal management practices, supporting economic development and environmental sustainability.

Theoretical framework

Eco-dynamical systems theory

Our theoretical framework utilizes eco-dynamical systems theory to explore the complex, interdependent relationships between industrialization, ecotourism, and fishery resources within coastal ecosystems. Eco-dynamical systems theory provides a lens for understanding how human activities, such as industrial development and tourism, interact with natural processes in dynamic and evolving ways. This framework is particularly useful for analyzing the feedback loops that arise from the combined pressures of industrialization and ecotourism on coastal environments. Industrial activities may lead to pollution, habitat degradation, and resource depletion, while ecotourism can either mitigate or exacerbate these effects, depending on management practices. Applying eco-dynamical systems theory, we can model these interactions and examine how they affect the sustainability of fishery resources, which are critical to local economies and biodiversity. Ultimately, this framework allows us to assess the long-term consequences of human activities and inform strategies for balancing environmental preservation with economic development in coastal areas (Failler et al., 2022).

The gaps in the existing literature that this study seeks to bridge are multifaceted. First, while there is considerable study on the individual impacts of industrialization and ecotourism on coastal ecosystems, few studies have integrated both factors to assess their cumulative and interactive effects on fishery resources. This study aims to fill that gap by examining how industrialization and ecotourism work together to influence fishery resources in coastal areas. Additionally, much of the existing literature tends to focus on the direct environmental impacts of these human activities without accounting for the complex feedback loops within coastal ecosystems. Focusing on these feedback dynamics, this paper will offer a more comprehensive understanding of how industrial and tourism pressures lead to long-term and cascading effects on marine resources.

Fishery resources

Fishery resources are the vital biological and economic assets within coastal ecosystems, playing a critical role in supporting biodiversity, food security, and community livelihoods. These resources sustain diverse aquatic species and provide essential ecosystem services (e.g., nutrient cycling and habitat stability). For coastal communities, fishery resources are a cornerstone of economic activities, contributing to income generation through fishing, processing, and related industries. They also enhance food security by serving as a primary protein source. Effective management of fishery resources ensures biodiversity preservation, promotes sustainable practices.

Industrialization and its Impact on Coastal Ecosystems

Industrialization refers to the process of urban and economic growth driven by human activities, particularly in coastal areas, leading to substantial ecological pressures (Duarte et al., 2021). It encompasses anthropogenic activities such as pollution, habitat destruction, and the over-exploitation of natural resources, all of which adversely affect coastal ecosystems. The introduction of heavy metals and toxic chemicals from industrial processes into marine environments is a critical concern, as these substances can lead to water contamination, bioaccumulation in aquatic organisms, and the disruption of marine food chains (Hama et al., 2023).

Industrial activities such as dredging, land reclamation, and infrastructure development contribute to the degradation of natural habitats, reducing essential breeding and feeding grounds for marine species (Khan et al., 2023). These activities not only harm biodiversity but also reduce fishery sustainability by disrupting the ecological processes that support marine life. Furthermore, the unsustainable exploitation of coastal resources, such as overfishing and the destruction of mangroves for industrial purposes, intensifies environmental stress, posing long-term threats to ecological balance and local economies (Ali et al., 2024).

Addressing these challenges requires the adoption of effective environmental regulations, sustainable practices, and increased community awareness to mitigate the detrimental effects of industrialization on coastal ecosystems. Integrating eco-dynamical systems theory can help model the complex interactions between industrialization, ecosystem degradation, and the socio-economic impacts on local communities, offering insights into the pathways for sustainable coastal management (Zelenić et al., 2022).

Dynamic Systems Theory (DST)

Dynamic Systems Theory (DST) is an interdisciplinary framework used to understand and model complex systems that evolve over time through interdependent relationships among components. It provides insight into how the behaviors and patterns of these systems are affected by feedback loops, delays, and non-linear interactions. DST can be particularly useful for understanding the complex interactions between industrialization, ecotourism, and fishery resources in coastal ecosystems, where multiple factors and processes are involved.

In the context of the Nigerian coastal areas, DST can help capture the multifaceted interactions between human activities, such as industrialization and ecotourism, and the natural environment, including fishery resources. Industrialization often introduces pollution, habitat destruction, and over-exploitation of resources, which can negatively affect biodiversity, water quality, and the sustainability of fishery resources. On the other hand, ecotourism, if managed sustainably, can generate economic benefits while promoting conservation. However, uncontrolled or poorly managed ecotourism can lead to habitat degradation, pollution, and increased pressure on the environment.

Applying DST, the dynamics of these interrelated activities can be modeled, revealing how the feedback loops between human interventions (e.g., industrial activities and ecotourism practices) and the environment (e.g., fishery resource depletion and habitat loss) can exacerbate or alleviate the pressures on coastal ecosystems. The theory allows for the identification of leverage points—specific factors or practices where interventions can have the most significant impact—and informs the development of policies and management strategies that balance ecological preservation with socio-economic development. Through this eco-dynamic modelling approach, DST provides a robust framework for analyzing and addressing the challenges posed by uncontrolled industrialization and ecotourism in Nigerian coastal areas.

Ecotourism and its Impact on Ecosystem Sustainability

Ecotourism refers to responsible travel to natural areas that conserves the environment and improves the well-being of local people (Honey, 2020). It emphasizes the dual role of tourism: on one hand, promoting environmental conservation, and on the other, potentially imposing stress on natural ecosystems (Baloch et al., 2023). Ecotourism fosters environmental awareness by educating travelers about the importance of protecting biodiversity, while generating economic benefits for local communities through sustainable activities like wildlife viewing, nature hikes, and cultural exchanges (Saha et al., 2023). These benefits create economic incentives for local populations to engage in conservation efforts, which can lead to the protection of vital habitats and species, promoting long-term sustainability (Sayer et al., 2021).

However, unregulated ecotourism can have detrimental effects on the environment, particularly when it leads to habitat degradation, pollution, and resource overexploitation (Gössling et al., 2021). Excessive foot traffic, improper waste disposal, and increased demand for local resources, such as water and fuel, can disrupt delicate ecological balances (Liu et al., 2023). This overuse of natural resources can result in the degradation of ecosystems, especially in fragile environments such as mangroves and coral reefs, which are already under threat from other anthropogenic pressures (Nguyen et al., 2024).

To harness the benefits of ecotourism while mitigating its negative impacts, it is crucial to adopt sustainable practices and implement effective management strategies (Gao et al., 2022). These strategies include establishing ecotourism regulations, monitoring tourism activities, promoting low-impact tourism, and enhancing local capacity for sustainable development. Integrating sustainability into ecotourism models ensures that the economic benefits derived from tourism do not compromise the ecological integrity of the ecosystems that attract tourists in the first place (Zhao et al., 2022).

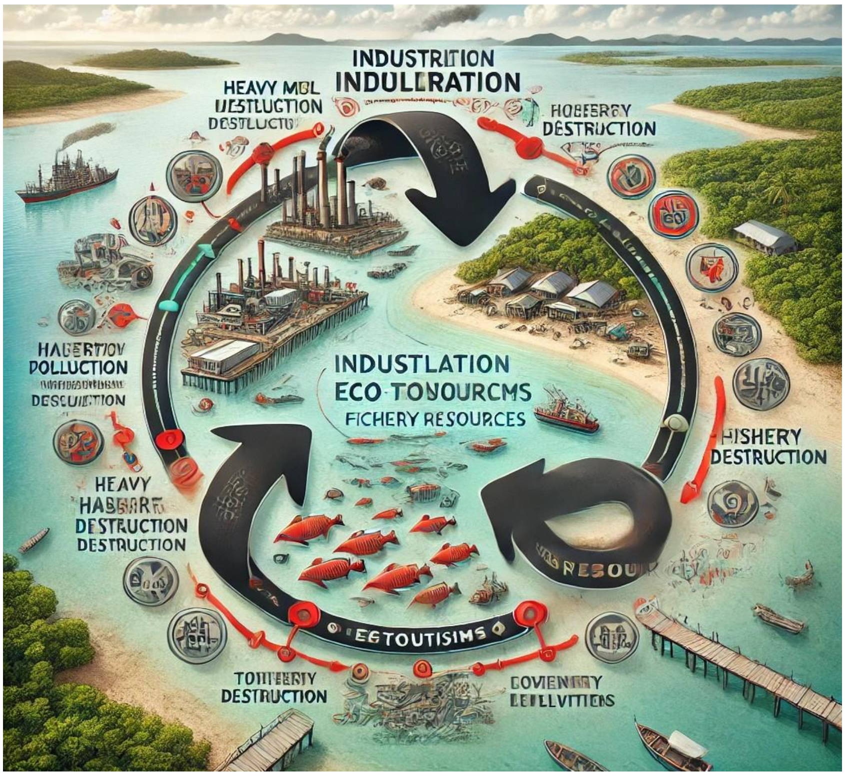

Figure 1: Conceptual diagram illustrating the interactions between industrialization, ecotourism, and fishery resources in coastal areas

***Source**: Constructed with OpenAI*

Figure 1 shows that fishery resource growth is influenced by intrinsic biological factors and is negatively impacted by industrial pollutants and unregulated tourism activities. Industrialization introduces pollutants, such as heavy metals, that degrade water quality and accumulate in aquatic species, reducing fishery sustainability. Ecotourism activities, while promoting conservation awareness, can lead to habitat degradation, pollution, and overexploitation if not managed sustainably.

Key theoretical constructs

The existing paper uses a system of differential equations to simulate the dynamics:

d*x*/d*t*: Growth rate of fishery resources, moderated by industrialization (z) and ecotourism (y).

d*y*/d*t*: Growth of ecotourism influenced by fishery resource availability (xxx) and industrial activity (z).

dz/d*t*: Growth of industrialization and its competitive interactions with ecotourism.

Mitigation effects (f, g): Mechanisms that reduce the negative impacts of overpopulated ecotourism and uncontrolled industrialization.

Competitive rates (e,de, de,d**)**: Parameters that reflect the direct competition between industrial and tourism activities for natural resources.

Growth parameters (a,ca, ca,c**)**: Change rates in fishery resources and ecotourism driven by ecological and economic factors.

Materials and Methods

Research design

This paper adopts descriptive and simulation methodologies, conducted for twenty-four months, from January 2022 to December 2023. Data was collected across 12 strategically selected stations from Lekki to Epe mangroves. These locations were chosen to provide a comprehensive representation of conditions affecting fishery resources. This paper involved extensive seasonal sampling to capture variations in metallic concentrations in hydrological cycles. Twenty-five numbers of C. nigrodigitatus of average weight of 500g and twenty-five numbers of S. Melano Theron of average weight of 100g were collected each month from landing sites during the experimental period. Laboratory analyses were carried out to evaluate heavy metal pollutants in water samples and two economically key fish species using AAS equipment (i.e., Atomic Absorption Spectrophotometer) and data collection on patronage level of selected tourist attractions close to Lekki/Epe mangroves. This stage employed an observational method of data collection. Attractions were selected based on their proximity and popularity.

Study area

Lekki and Epe mangroves, located along Nigeria's coastline at 6.4415°N, 3.5358°E, and 6°31'N, 4°E, are renowned for their rich biodiversity and significant economic importance (Olaniyi, 2023). These regions provide essential habitats for numerous fish species and support local fishing, ecotourism, and industrial activities. However, rapid and uncontrolled industrialization and ecotourism growth are threatening the sustainability of these coastal fishery resources (Aliu et al., 2022; Ogbeibu & Oribhabor, 2023). Nigeria, the largest country in Africa and the third largest in the world, has an estimated mangrove area of 10,515 km², accounting for 5.8% of the world's mangroves (Ellisson et al., 2020). The high litter fall and microbial activity in these ecosystems contribute to their exceptional productivity and diversity (Faridah-Hanum & Salleh, 2018; Olaniyi, 2023). This ecosystem supports approximately 25% of global biological production and primary productivity, estimated at 24 tons/ha/year (Olaniyi, 2023).

Lekki and Epe are located, respectively, on geo-referenced points 6.4415°N, 3.5358°E, and 6'31oN, 4oE, in the coastal area of Lagos State, Nigeria. The study selected 12 sampling locations across these areas to capture spatial variability. Multiple sampling points were identified within each location, ensuring a comprehensive assessment of environmental conditions. This strategic approach allowed for a detailed analysis of heavy metal concentrations in water and fish of economic importance, crucial for understanding the environmental impact in the region. These attractions are Epe Resort & Spa, Jubilee Chalets, Lufasi Nature Park, Fara Park, and Eleko Beach.

The distance from Epe Resort & Spa to Jubilee Chalets is 112.14 km; from Epe Resort & Spa to Lufasi Nature Park is 35.25 km; from Epe Resort & Spa to Fara Park is 35.20 km; from Epe Resort & Spa to Eleko Beach is 19.54 km. Then from Jubilee Chalets to Lufasi Nature Park is 90.07 km, from Jubilee Chalets to Fara Park is 89.59 km, and from Jubilee Chalets to Eleko Beach is 110.09 km. Also, from Lufasi Nature Park to Fara Park is 0.60 km, from Lufasi Nature Park to Eleko Beach is 22.33 km, and from Fara Park to Eleko Beach is 22.58 km. This dual approach of field data collection and lab analysis aimed to provide a robust understanding of the environmental factors impacting fishery resources in these coastal mangroves, to offer valuable insights for managing and mitigating the adverse effects of uncontrolled industrialization and ecotourism.

Data description

Fishery resources data were on metal pollutants (mg/kg wet weight), Cd,Cu, Zn, Cr, Fe, Mn, Pb, Ni, and Vin tissues/organs, gill, liver, bone, gut, and muscle of two economically vital fish species*Chrysichthysnigrodigitatus*and*Sarotheredonmelanotheron*fromLekki-Epe Mangroves of Lagos coastal area from January 2023 to December 2023. The second data collected were values of metal pollutants in water (mg/kg) from Lekki-Epe mangroves between January 2022 to December 2023 for the heavy metals Cd,Cu, Zn, Cr, Fe, Mn, Pb, Ni, and Vin 12 sampling stations. The third set of data was collected at five tourist attractions. This data was collected on the last Saturday of every month, for twelve months, simultaneously from the five attractions by trained research assistants from 12 noon to 7 pm using the observational method of data collection. Two research assistants were stationed at each attraction for data collection using counting sheets.

Mathematical modelling

Uncontrolled industrialization and ecotourism can affect fishery resources around Lekki/Epe mangroves of Lagos Coastal area. Eco-dynamical modellings describe the relationship between fishery resources (x), ecotourism development (*y*), and industrialization (z) in the set-up.

$$\begin{aligned} \dot{x} &= cx - e_1xz + (d_1 - f)xy \\ \dot{y} &= y(ak - b_1z - d_2x) \\ \dot{z} &= \delta_1 z + e_2xz + (b_2 - g)yz \end{aligned} \tag{1}$$

were

d_1, d_2 = effects of ecotourism on fishery resources

b_1, b_2 = effects of industrialization on fishery resources.

f = mitigating effect on overpopulated ecotourism

g = mitigating effect on uncontrolled industrialization

e_1, e_2 = competitive rates of industrialization and ecotourism on exploitation of natural resources

δ_1 = Arrival of industrial development in mangrove areas as follows:

a = growth rate in fishery resources

c = growth rate in ecological tourism

These systems of equations capture the dynamic interactions between fishery resources, ecotourism development, and industrialization over time.

Modelling Description

This eco-dynamical modelling is designed to explore the complex interactions between uncontrolled industrialization, burgeoning ecotourism, and their impacts on fishery resources in coastal areas, focusing on the coastal area of Lagos. The modelling integrates ecological principles with dynamic systems theory to simulate these interconnected components. This modelling considers the growth and decline of fish populations based on their intrinsic growth rate, c, which is moderated by the negative impacts of industrialization, z and ecotourism, y. Additionally, there are synergistic effects (d_1 - f) xy) where ecotourism can enhance or mitigate pressures on fishery resources.

Ecotourism development represents the growth of ecotourism activities in the coastal areas. It is influenced by ecosystem attractiveness (a), but negatively affected by industrial activities (b_1z) and by the impact on fishery resources (d_2 x). Ecotourism can also contribute to mitigating the impacts of industrialization and enhancing this region's attractiveness for tourism development**.** Moreover**,** industrialization impacts fishery resources through pollution, habitat destruction, and competition for natural resources. The growth of industrial activities (δ_1 z) is moderated by competitive exploitations with ecotourism (e_2 y) and the direct impact on fishery resources ($e_1$xz).

Further, this modelling provides a framework to assess how changes in industrialization and ecotourism policies affect fishery resource sustainability in coastal mangrove ecosystems. By integrating these components and their interactions, this modelling helps to predict future scenarios and inform policy decisions for sustainable management practices. This modelling is applied to Lekki and Epe mangroves of Lagos's coastal area to analyze the current and potential future impacts of industrialization and ecotourism on fishery resources. By calibrating this modelling with empirical data and using scenario analysis, it can predict how different levels of industrial and tourism activities will affect fish populations and ecosystem health over time.

Theorem 1: *Let the function be piece-wise for all t > 0, unique and existing, then the Laplace transform of the derivatives satisfy*

$$\mathcal{L}(X'') = S''X(S) - S^{n-1}X(0), \dots, X'(0)$$

and

$$\mathcal{L}(X') = SX(S) - SX(0), \dots, X'(0)$$

Proof

Since the non-linear systems is first order, it is evaluated at $n = 1$. Evaluating the nonlinear systems $\mathscr{L}\{X'\}$ = SX(X) – SX (0), X*'* (0), which is first order, evaluated at $n = 1$, gives

$$\mathcal{L}(X') = SX(S) - X(0) = cX(S) + eX(S)Z(S) + fX(S)Y(S)$$

$(S-c) = eZ + fY$ (2)

$$\mathcal{L}(Y') = SX(S) - X(0) = \delta Z(S) - b_1 Y(S)Z(S) - d_2 X(S)Z(S)$$

$(S-a) = -bZ - dX$ (3)

$$\mathcal{L}(Z') = SZ(S) - Z(0) = \delta Z(S) - bY(S)Z(S) - d_1 X(S)Y(S)$$

$(S-\delta) = -b_1 Z - d_2 X$ (4)

Combining equations (2), (3), (4) gives

$$Y(S) = \frac{bd_2(s-c) + ed_1(S-a) - ed_1(S-\delta)}{bfd_2 - b_1 ed_1}$$

$$y = \mathcal{L}^{-1}\{Y(S)\}$$

$$y(t) = k_1 \exp[-(t-c)] + k_2 \exp[-(t-a)] + k_3 \exp[-(t-\delta)]$$

Where

$$k_1 = \frac{bd_2}{bfd_2 - b_1 ed_1}, \qquad k_2 = \frac{ed_2}{bfd_2 - b_1 ed_1}, \qquad k_3 = \frac{ed_1}{bfd_2 - b_1 ed_1}$$

$$X(S) = \frac{bb_1(S-c) + eb_1(S-a) + ed_1(S-\delta) - (s-\delta)(bfd_2 - b_1 ed_1)}{bfd_2 - b_1 ed_1}$$

$$x(t) = \rho_1 \exp[-(t-c)] + \rho_2 \exp[-(t-a)] + \rho_3 \exp[-(t-\delta)]$$

Where

$$\rho_1 = \frac{bb_1}{bfd_2 - b_1 ed_1}, \qquad \rho_2 = \frac{eb_1}{b_1 fd_2 - b_1 ed_1}, \qquad \rho_3 = \frac{b_1 ed_1}{bfd_2 - b_1 ed_1}$$

$$Z(S) = \frac{-bfd_1(S-c) + efd_2(S-a) + ed_1 f(S-\delta) + (S-c)(bfd_2 - b_1 ed_1)}{ebfd_2 - b_1 ed_1}$$

$$z(t) = \mathcal{L}^{-1}\{Z(S)\} = \xi_1 \exp[-(t-c)] + \xi_2 \exp[-(t-a)] + \xi_3 \exp[-(t-\delta)]$$

Where

$$\xi_1 = \frac{bb_1}{bfd_2 - b_1 ed_1}, \qquad \xi_2 = \frac{eb_1}{b_1 fd_2 - b_1 ed_1}, \qquad \xi_3 = \frac{b_1 ed_1}{bfd_2 - b_1 ed_1}$$

Taking inverse Laplace transforms of X, Y, Z, gives solutions that are inexistence, piece wise continuous for all values of t.

Results

Datasets were analyzed using descriptive statistics and one-way analysis of variance (ANOVA) with Ducan multiple comparison post-hoc test. Tables 1 and 2 show heavy metal pollutants in two economically key fish species, while Tables 3 and 4 show heavy metal concentration in water from contiguous Lekki and Epe mangroves, which serve as tourist attraction center.

Table1: Mean(±SD) of metal pollutants(mgkg$_{-1}$wetweight) in Chrysichthysnigrodigitatus from contiguous Lekki and Epe mangroves

Period	Tissue/Organ	Cd	Cu	Zn	Cr	Fe	Mn	Pb	Ni	V
January-June	Gill	1.33	0.4	47.27	54.76	78.38	10.90	26.80	10.80	0.028
	Liver	1.23	17.30	44.70	61.36	140.16	2.23	42.97	8.24	0.025
	Bone	1.04	0.15	90.41	48.7	39.28	22.12	35.47	10.00	0.023
	Gut	0.96	0.11	38.65	21.62	110.83	12.30	17.70	5.89	0.017
	Muscle	0.97	0.50	5.97	46.74	38.52	5.82	75.61	12.57	0.019
	Total	5.53	18.46	227	233.18	407.17	53.37	198.55	47.5	0.112
	Mean	1.106	3.69	46.64	46.64	81.43	10.67	39.71	9.50	0.02
	SD	0.16^c	7.6^c	15.1^b	15.1^b	44.6^a	7.6^c	22.2^b	2.5	0.004^c
July -December	Gill	0.001	1.21	7.88	0.26	13.68	5.925	0.086	0.185	0.005
	Liver	0.204	2.88	7.45	10.23	23.36	0.372	0.372	1.373	0.004
	Bone	0.002	0.13	15.07	0.86	39.46	2.487	0.054	17.579	0.004
	Gut	0.001	0.52	6.44	0.326	9.797	2.328	0.037	0.528	0.003
	Muscle	0.001	0.19	1.00	2.006	164.42	8.275	0.067	69.282	0.003
	Total	0.209	4.93	37.84	13.682	250.717	19.387	0.616	88.947	0.019
	Mean	0.042	0.986	2.736	2.736	50.143	3.877	0.123	17.789	0.004
	SD	0.09^b	1.14^b	4.25^b	4.25^b	64.9^a	3.17^b	0.14^b	29.7^b	0.001^b
	W.H.O THRESHOLD									
Standard		**0.1**	**3.0**	**60.0**	**50**	**43.0**	**9.0**	**0.2**	**2.5**	**0.5**

*W.H. O = World Health Organization

Table 1 presents mean (± SD) concentrations (mg/kg wet weight) of heavy metal pollutants in various tissues/organs of Chrysichthysnigrodigitatus from Lekki-Epe Mangroves for January-June and July-December 2023. Metals included Cd, Cu, Zn, Cr, Fe, Mn, Pb, Ni, and V. The Duncan multiple comparison test reveals that Iron (Fe) has significantly higher mean concentrations than other metals. From January to June, the highest levels were observed in livers for Fe at 140.16 mg/kg and in muscles for Pb at 75.61 mg/kg. Significant levels of Zn, Cr, and Fe were noted. For July to December 2023, concentrations were lower overall, with Fe reaching 164.42 mg/kg in muscles. Mean concentrations were lower, indicating seasonal variation. All sampled heavy metals exceeded standard regulatory limits, suggesting potential toxic pollution from anthropogenic sources (e.g., tourism, industrial discharge, domestic sewage, mining, and agricultural runoff). Metals pose risks even within allowable limits, underscoring the need for continuous biomonitoring by regulatory authorities to ensure food safety.

Table2: Mean(±SD) of metal pollutants(mgkg^{-1}wetweight) in Sarotheredonmel another on from contiguous Lekki and Epe mangroves

Period	Tissue/ Organ	Cd	Cu	Zn	Cr	Fe	Mn	Pb	Ni	V
Jan-June	Gill	1.21	0.807	54.627	21.665	258.77	1.099	15.245	4.242	0.018
	Liver	1.127	14.06	37.16	38.125	148.29	0.378	27.25	4.253	0.017
	Bone	0.987	0.644	27.492	32.302	23.797	0.152	32.583	12.43	0.012
	Gut	0.843	6.66	26.693	27.997	180.26	0.127	19.318	10.7	0.008
	Muscle	0.925	0.757	16.567	16.417	26.64	0.155	30.257	12.77	0.012
	Total	5.092	22.927	162.54	136.505	637.76	1.910	124.65	44.40	0.066

	Mean(± SD)	1.018 ±0.149[b]	4.585 ±5.885[b]	32.508 ±14.352[b]	27.301 ±8.557[b]	127.55 ±101.705[a]	0.382 :0.414[b]	24.931 ±7.376[b]	8.880 ±4.301[b]	0.013 ±0.004[b]
July –**Dec**	Gill	0.0025	1.109	2.08	1.733	102.77	49.207	0.1067	1.079	0.006
	Liver	0.0011	1.699	2.16	1.002	1906.25	18.538	1.01	1.063	0.006
	Bone	0.0036	0.234	1.63	0.2461	16.275	9.058	0.076	0.079	0.004
	Gut	0.0046	1.648	1.67	982.25	196.48	1.709	ND	63.286	0.003
	Muscle	0.0122	0.302	1.89	5205	914.42	6.251	0.018	5.563	0.004
	Total	0.024	4.992	9.43	6190.23	3136.20	84.763	1.211	71.07	0.023
	Mean(± SD)	0.005 ±0.004[b]	0.998 ±0.71[b]	1.886 ± 0.237[b]	1238 ±2257.9[a]	627.239 ±798.79[a]	16.953 ±19.05[b]	0.242 ±0.43[b]	14.214 ±27.51[b]	0.005 ±0.001[b]
	W.H.O THRESHOLD LIMIT									
Standard		**0.1**	**3.0**	**60.0**	**50**	**43.0**	**9.0**	**0.2**	**2.5**	**0.5**

*W.H. O = World Health Organization

Table 2 presents mean (± SD) bioaccumulation (mg/kg wet weight) of heavy metals in *Sarotherodonmelanotheron* tissues/organs from Lekki and Epemangroves. From January to June, high levels of Fe and Cu were found, with Fe at 258.77 mg/kg in gills and Cu at 14.06 mg/kg in livers, alongside elevated Zn and Pb. From July to December, Fe levels surged to 1906.25 mg/kg in livers and 914.42 mg/kg in muscles, indicating increased metal concentrations. This Duncan's test revealed that Fe levels were significantly higher than other metals. The seasonal distribution reflects hydrological cycle's impact on metal bioaccumulation, linked to human and industrial activities as noted by Abdullahi et al. (2023) and ina-Nicoleta (2024).

Table 3: Mean values of metal pollutants in the water (mg/kg) from contiguous Lekki and Epe mangroves between January and June

Station	Cd	Cu	Zn	Cr	Fe	Mn	Pb	Ni	V
1	1.84	12.8	129.6	5.86	610.8	594.4	1.41	2.25	0.05
2	1.76	46.7	280.4	8.23	133,727	690	5	3	0
3	2.48	35.1	326.5	15	4,785.60	174.00	4.60	2.73	0.07
4	2.01	22.5	188.7	8.08	87,414.25	760.33	3.89	3.18	0.05
5	2.77	29.9	257.1	14.7	16,397.19	167.80	1.52	2.59	0.00
6	2.32	10.9	144.4	7.88	48,441.50	768.61	1.39	2.84	0.01
7	1.93	49.6	476.5	16.5	24,182.32	252.58	4.68	2.57	0.01
8	1.84	78.2	218.6	8.5	69,442.75	641.19	4.60	3.60	0.01
9	1.94	33.1	222.9	12.1	23,531.50	210.00	3.18	2.91	0.01
10	1.05	4.98	112.5	10.9	57,045	356	6	4	0
11	1.13	33.8	273.7	16.8	3,284.86	192.02	6.37	1.66	0.01
12	1.00	39.9	166.1	8.72	86,698.00	436.20	2.82	11.67	0.00
Mean (± SD)	1.84 ± 0.6	33.12 ± 19.91	233.0 ± 101.05	11.11 ± 3.80	46296.67 ± 41761.68	436.92 ± 241.02	3.78 ± 1.75	3.60 ± 2.62	0.02 ± 0.02
USEPTHRESHOLD LIMIT									
Standard	0.01	1.0	1.0	1.0	1.0	0.05	0.05	15.0	0.04

*USEP= United States Environmental Protection

Table 3 shows the mean values of heavy metal pollutants (mg/kg) in water samples collected from twelve stations in the Lekki-Epe mangroves between January to June for the analysis of the following heavy metals: Cd, Cu, Zn, Cr, Fe, Mn, Pb, Ni, and V. Heavy metal concentrations in water from January to June had the high concentrations of Fe across various stations, with the highest at 87,414.25 mg/kg at Station 4. Zn and Cu also show significant level of concentrations, with averages of 233.08 mg/kg and 33.12 mg/kg, respectively. Notably, there was an increase in Cd and Cr levels: Cd at 16.4 mg/kg and Cr at 97.4 mg/kg at Station 5. Fe levels remain high, with a significant increase in some stations.

Table 4: Mean values of metal pollutants in water (mg/kg) from contiguous Lekki and Epe mangroves between July and December

Station	Cd	Cu	Zn	Cr	Fe	Mn	Pd	Ni	V
1	10.9	9.1	80.7	34.7	688.60	903.8	8.36	13.3	0.28
2	10.4	19.1	169.9	48.7	15,126	2,135	28	20	0
3	14.7	24.9	203.3	88.8	4,299.30	541.3	27	16.2	0.39
4	11.9	20.3	141.4	47.8	12,991.80	24,858.30	23.5	18.8	0.32
5	16.4	21.2	160.1	87.1	14,731.10	519.7	9	15.3	0.01
6	13.7	18.6	86.9	46.6	10,589.60	119,616.68	8.2	16.8	0.05
7	11.4	35.2	296.7	97.4	21,725.20	782	27.7	15.2	0.03
8	10.9	25	104.7	50.3	27,926.50	186,099	27.2	20.3	0.03
9	11.5	23.5	138.8	71.8	21,140.50	650.17	18.8	17.2	0.03
10	6.2	20.9	90.3	64.3	17,866.00	157,062	37	25	0
11	6.7	24	170.4	99.7	2,899.00	594.5	37.7	9.8	0.03
12	5.9	11.8	103.4	51.6	27,183.00	30,306.00	16.7	13.8	0.01
Mean (± SD)	10.88 ± 3.29	21.13 ± 6.63	145.55 ± 61.65	65.73 ± 22.49	14763.88 ± 9021.83	43672.38 ± 68930.76	22.40 ± 10.30	16.73 ± 3.79	0.12 ± 0.14
USEPTHRESHOLD LIMIT									
Standard	0.01	1.0	1.0	1.0	1.0	0.05	0.05	15.0	0.04

*USEP= United States Environmental Protection

Table 4 shows mean values of heavy metal pollutants (mg/kg) in water samples collected from various stations in the Lekki-Epe mangroves between July and December for Cd, Cu, Zn, Cr, Fe, Mn, Pb, Ni, V in Stations 1 to 12. The major findings showed that Mn is highest in the station 8 (186,099). These heavy metals could find their ways via environmental and non-environmental-oriented development (Miftahul*et al.*, 2022)

Accordingly, comprehensive data on the concentrations of heavy metal pollutants in two fish species of economic importance and water samples collected from adjoining Lekki and Epe mangroves. The data allows for analysis of seasonal variations and spatial distributions of pollutants impacted by uncontrolled industrialization and ecotourism. It also examines their effects on fishery resources in these coastal areas, along with the attendant health implications such as cancer and vital organ failures in fish consumers from these regions. (David & Isangedighi, 2019).

Table 5: Level of patronage of selected tourist resources close to Lekki/Epe mangroves

Months	**Epe Resort & Spa, Epe**	**Jubilee Chalets, Epe**	**Lufasi Nature Park, Lekki**	**Fara Park, Lekki**	**Eleko beach, Lekki**	**Total**
January	1160	3040	2805	3124	5309	15438
February	1060	2995	2900	3110	4599	14664
March	1028	3020	2741	3090	4845	14724
April	1131	3100	2781	3120	5401	15533
May	1123	3149	2752	3004	4056	14084
June	996	3097	2914	3088	4877	14972
July	1149	3124	2945	3140	4994	15352

August	1172	3239	2961	3202	5451	16025
September	1158	3235	2955	3165	5123	15636
October	974	3085	2541	3113	4657	14370
November	889	3022	2326	3101	4983	14321
December	1159	3240	2988	3247	5324	15958
Mean	1083.25	3112.17	2800.75	3125.33	4968.25	15089.75
Std dev.	92.5155	88.2608	197.0769	60.9341	401.8996	658.0214
CoV	8.5405	2.8360	7.0366	1.9497	8.0894	4.3607
Skewness	-0.9671	0.3980	-1.4977	0.2000	-0.9418	-0.0725
Kurtosis	-0.11639	-1.1516	2.0796	1.4171	1.0418	-1.3671
Latitude (ºN)	6.5887	6.9492	6.4644	6.4696	6.4387	
Longitude (ºE)	3.9481	3.0000	3.6546	3.6530	3.8548	

Table 5 provides monthly data on visitors to five tourist attractions near Lekki/Epe mangroves over a year. The total number of visitors each month is given, along with statistical measures such as mean, standard deviation, coefficient of variation (CoV), skewness, and kurtosis. In support of Metilelu's (2022) observations, Table 5 suggested that increased coastal tourism can bring economic benefits to local communities, potentially funding better fishery management and conservation practices. Tourism can raise awareness about the importance of preserving mangrove ecosystems and promote sustainable fishing practices (Add REF). Enhanced infrastructure (e.g., waste management systems) can benefit fishery resources. However, the construction of tourist facilities can lead to the destruction of critical habitats, essential for fish breeding and nursery grounds. As noted by Akhtar et al. (2021); Bashir et al. (2020); and Mishra et al. (2023) increased human activity can result in higher levels of litter, sewage, and chemical runoff, degrading water quality and harming fish populations.

Tourism can increase demand for local seafood, potentially leading to overfishing and depletion of fish stocks (Add REF). Increased boat traffic and recreational activities can disturb aquatic life, affecting fish feeding, breeding, and migration patterns. Uncontrolled Industry and tourism-related pollution can increase nutrient levels, causing algal blooms and hypoxia (low oxygen levels), which are detrimental to fish health and survival. While controlled industrialization and tourism development in Lekki/Epe mangrove areas can boost local economies and raise environmental awareness, it must be managed to avoid detrimental effects on fishery resources. Sustainable tourism practices are essential to balance economic benefits with the conservation of critical fish habitats and water quality.

Mathematical simulation of eco-dynamical modelling

This paper models the impact of uncontrolled industrialization and ecotourism on fishery resources in Lekki/Epe mangroves of Lagos coastal area using an eco-dynamical modelling approach. Lekki/Epe mangroves face challenges due to uncontrolled industrialization and the rise of ecotourism. This paper employs an eco-dynamical model to explore the complex relationships between fishery resources (x), ecotourism development (y), and industrialization (z).

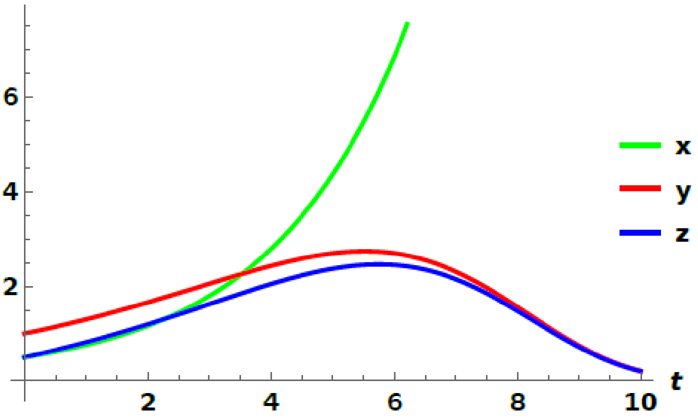

Figure 2: Simulation of the equation show the behaviour of fishery resources, ecotourism, and industrialization at Epe Mangrove area.

Source: Researchers' output

Figure 2presents a mathematical simulation depicting the dynamics between fishery resources (x), ecotourism development (y), and industrialization (z) over a period of time (t). At initial phase (t = 0 to t ≈ 3), all variables start at the similar level. Fishery resources (x) and industrialization (z) show a gradual increase. Ecotourism development (y) also increases but at a slower rate compared to x and z. At the intermediate phase (t ≈ 3 to t ≈ 6), fishery resources (x) begin to increase at faster rates, indicating significant growth. Ecotourism development (y) continues to grow and reaches a peak around t ≈ 6. Industrialization (z) also increases and peaks slightly after y, around t ≈ 7. At the later phase (t ≈ 6 to t = 10), fishery resources (x) experience exponential growth, diverging significantly from y to z. Ecotourism development (y) starts to decline after reaching its peak. Industrialization (z) also starts to decline but at slower rates compared to y.

Fishery resources (x) initially grow steadily and then exhibit exponential growth after t ≈ 6. Hence, this suggests that under certain conditions, fishery resources can thrive and expand rapidly, due to effective management or favorable environmental factors. Ecotourism development (y) increases initially and reaches a peak at t ≈ 6. Afterwards, it declines, which could indicate the saturation point of ecotourism activities or negative impacts from over-exploitation. Industrialization (z) shows a similar trend to ecotourism, with a steady increase followed by a decline after peaking. Hence, this suggests that industrial activities initially boost economic aspects but lead to unsustainable practices that hinder long-term growth.

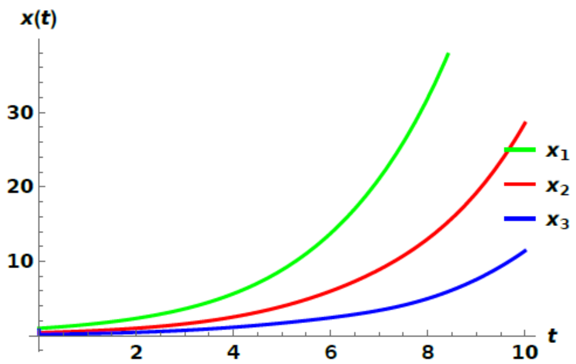

Figure 3: Uniquely values of fishery resources at e = 0:1; 0:3; 0:05; f = 0:1; 0:25; 0:5

Source: Researchers' output

Figure 3 illustrates the simulation results showing the unique values of fishery resources (x) at different levels of e and f. Parameters (i.e., e and f) are the competitive rate of industrialization on the exploitation of natural resources and mitigating effect on overpopulated ecotourism respectively. The general trend shows that fishery resources (x) exhibit different behaviours based on varying levels of e and f. This trend suggests that competitive rates of industrialization and the mitigating effect on ecotourism significantly influence fishery resources. The impact of e (competitive rate of industrialization) at a high value of e = 0.3 significantly reduces fishery resources, a highly competitive rate of industrialization leads to more intense exploitation of natural resources, thus negatively impacting fishery resources. At moderate values of e = 0.1, fishery resources show less decline compared to e = 0.3. Hence, this indicates that a moderate competitive rate of industrialization is less harmful to fishery resources, allowing for some sustainability. At low value of e = 0.05, fishery resources exhibit minimal decline or potentially stable levels. A low competitive rate of industrialization suggests that industrial activities are less intrusive, allowing fishery resources to sustain better.

The impact of f (mitigating effect on ecotourism) for high value of f = 0.5, fishery resources show the highest levels of sustainability. A strong mitigating effect on ecotourism helps control overpopulation and excessive tourist activities, protecting fishery resources. For moderate value of f = 0.25, fishery resources are moderately sustained. Some mitigating measures are in place, but the impact is not as strong as with f = 0.5. For a low value of f = 0.1, fishery resources show a significant decline. Weak mitigating measures allow overpopulated ecotourism to harm fishery resources, leading to unsustainable levels.

The competitive rate of industrialization, has a direct impact on the sustainability of fishery resources. Lower values of e are associated with less exploitation and more sustainable fishery levels. The mitigating effect, f plays a crucial role in protecting fishery resources from the adverse effects of overpopulated ecotourism. Higher values of$f$ correlate with better sustainability of fishery resources. Management strategies include reducing industrial impact by implementing regulations to lower the competitive rate of industrialization can help sustain fishery resources. Hence, this includes controlling industrial activities and their impact on natural resources. Enhancing ecotourism management by strengthening mitigation measures to control overpopulated ecotourism can protect fishery resources. Thus, this involves managing tourist numbers, promoting eco-friendly practices, and ensuring minimal environmental disruption.

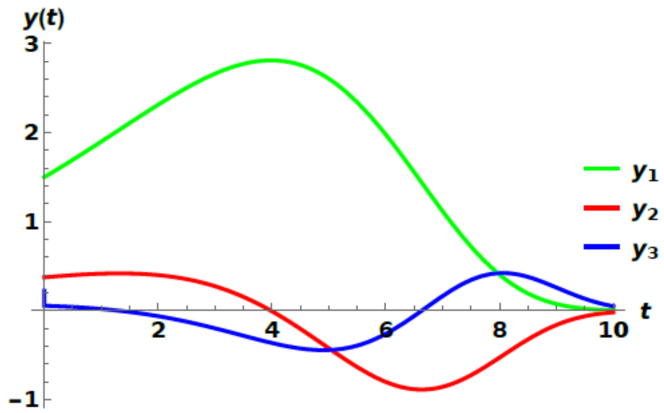

Figure 4: Simulation shows excessive ecotourism development is brought under control at values of a = 0:1; 0:13; 0:5; b = 0:1; 0:25; 0:35

Source: Researchers' output

Figure 4 illustrates the simulation results showing how excessive ecotourism development can be brought under control at different values of the parameters *a* and *b*. Parameter *a* represents the growth rate in fishery resources, and *b* represents the effects of industrialization on fishery resources. The graph shows how ecotourism development (*y*) can be regulated at different values of *a* and *b*. As the values of *a* and *b* increase, the control over excessive ecotourism development improves, leading to more stable trends. At low growth rate, ecotourism development shows upward trends, indicating insufficient control over excessive growth. At *a* = 0.13, moderate control is achieved, with ecotourism development showing a stabilization effect compared to *a* = 0.1. At *a* = 0.5, high growth rate in fishery resources significantly curtails excessive ecotourism development, leading to more controlled and stable trends.

At *b* = 0.1, similar to low *a*, low *b* values lead to less control over ecotourism development, resulting in a more pronounced upward trend. At *b*= 0.25, moderate effects of industrialization provide a balancing effect, contributing to better control over ecotourism development. At *b*= 0.35, higher *b* values show a significant reduction in the upward trend of ecotourism development, indicating strong control measures. Growth rates in fishery resources, *a* and the effects of industrialization *b* play crucial roles in managing ecotourism development. Higher values in these parameters help in stabilizing ecotourism growth. The combined effect of increasing *a* and *b* values indicates that improving the growth rate in fishery resources while managing industrial impacts can control ecotourism development. Adopting sustainable fishing practices and regulating industrial impacts are essential to controlling ecotourism development.

Enhancing fishery resources growth in promoting sustainable fishing practices that increase the growth rate *a*, ecotourism development can be controlled more effectively. Implementing measures to mitigate industrial effects *b* on fishery resources will contribute to stabilizing ecotourism development. Combining efforts to improve fishery resources growth rates and manage industrial impacts will provide a balanced approach to controlling ecotourism development. For low *a* and *b* regions, focus on enhancing fishing practices and introducing industrial regulations to achieve better control over ecotourism development. For moderate *a* and *b* regions, continue improving sustainable practices in sectors to maintain control over ecotourism. For high *a* and *b* regions, maintain current practices while monitoring for any potential excesses in ecotourism development.

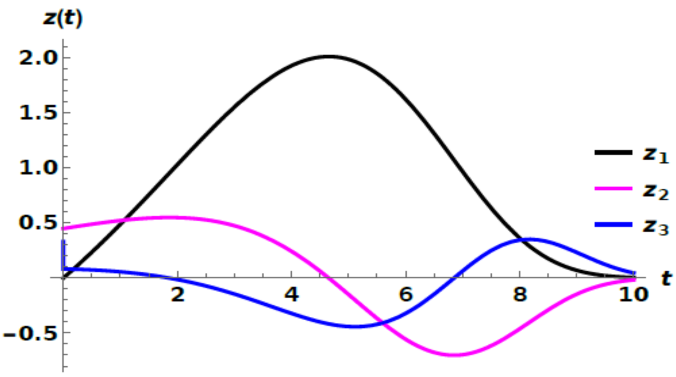

Figure 5: Simulation shows that industrialization is brought under control at values of b_1 = 0:1; 0:13; 0:5; d_1 = 0:1; 0:25; 0:35

Source: Researchers' output

Figure 5 illustrates how industrialization (z) can be controlled at various levels of parameters b_1 and d_1. The parameter b_1 measures the impact of industrialization on fishery resources, while d_1 measures the impact of ecotourism. The graph shows that as b_1 and d_1 increase, the control over industrialization improves, resulting in a more stable trend. For $b_1 = 0.1$, industrialization shows an upward trend, indicating insufficient control. At $b_1 = 0.13$, control improves moderately, and at $b_1 = 0.5$, the upward trend is significantly curbed, indicating high control. Similarly, for $d_1 = 0.1$, low ecotourism impact results in less control over industrialization, while $d_1 = 0.25$ provides moderate control, and $d_1 = 0.35$ offers strong control. Hence, this reduces the upward trend. Higher values of b_1 and d_1 enhance the control over industrialization, indicating that effective management of parameters is crucial. Sustainable practices in industrialization and ecotourism regulation are essential for better control. Enhancing fishing practices and regulating ecotourism can stabilize industrial growth. Integrating efforts to manage industrialization and ecotourism impacts provides balanced approaches to controlling industrialization. For low values, improve practices; sustain improvements; and for high, monitor and adjust as needed.

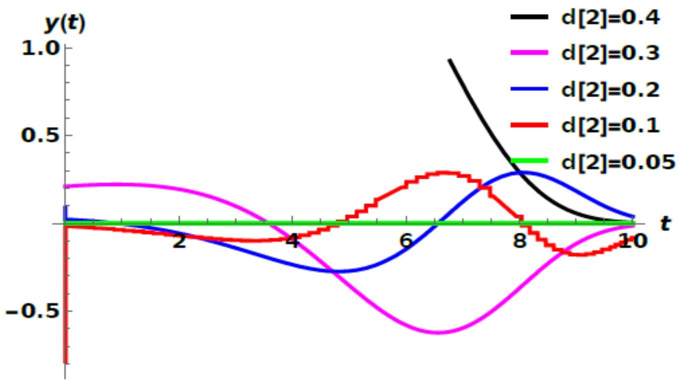

Figure 6: Simulation shows effect of excessive industrialization on fishery resources at d_2 = 0:4; 0:3; 0:2; 0:1; 0:05

Source: Researchers' output

Figure 6 shows how excessive industrialization impacts fishery resources (x) at different values of parameter d_2, which measures ecotourism's effect. As d_2 increases, the negative impact of industrialization on fishery resources intensifies, indicating a strong correlation between industrial activities and resource depletion. At $d_2 = 0.4$, the decline is steep, demonstrating that high ecotourism levels, combined with industrialization, lead to significant depletion. For moderate values of d_2 (0.3 and 0.2), fishery resources experience a moderate decline. Low values of d_2 (0.1 and 0.05) show relatively stable or slower decline, suggesting minimal impact from ecotourism. Effective management of industrialization and ecotourism is essential to sustain fishery resources. Implementing sustainable practices in these sectors can help mitigate their adverse effects and preserve fishery resources.

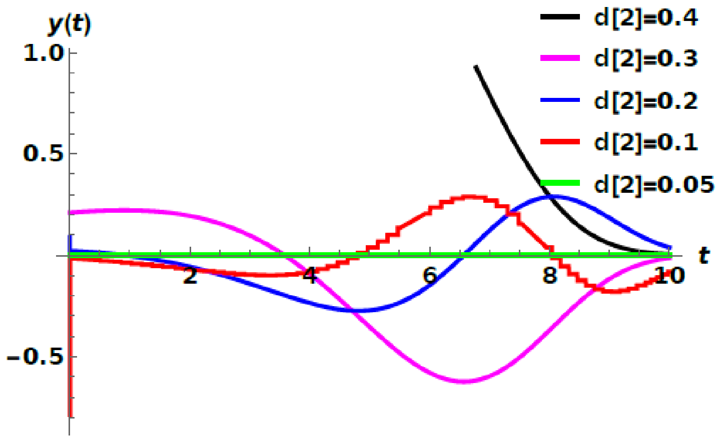

Figure 7: Simulation shows effect of ecotourism development on fishery resources at d_2 = 0:4; 0:3; 0:2; 0:1; 0:05

Source: Researchers' output

Figure 7 shows the impact of ecotourism development on fishery resources (x) at different values of parameter d_2, which measures the effect of ecotourism. As d_2 decreases, fishery resources improve, indicating better sustainability. At $d_2 = 0.4$, high ecotourism levels severely decline fishery resources. At $d_2 = 0.3$, the decline is slightly less, but still negative. At $d_2 = 0.2$, the impact starts to stabilize with less decline. At $d_2 = 0.1$, the adverse effects are minimal, allowing for recovery and stability. At $d_2 = 0.05$, the impact is negligible, and resources flourish. Sustainability improves with lower d_2 values, highlighting the need for effective management of ecotourism. Targeting lower d_2 values through regulations and sustainable practices is essential. Hence, this includes limiting visitor numbers and promoting eco-friendly tourism. Continuous monitoring and adaptive management can help maintain low d2 values. Therefore, this ensures the long-term health of fishery resources.

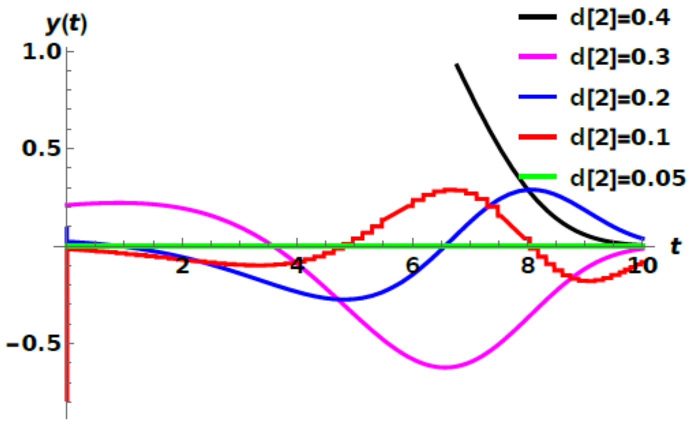

Figure 8: Simulation shows the joint effect of ecotourism development and industrialization on fishery resources at d_2 = 0:4; 0:3; 0:2; 0:1; 0:05

Source: Researchers' output

Figure 8 depicts the impact of ecotourism and industrialization on fishery resources (x) with varying values of d_2, which represents the effect of ecotourism. As d_2 decreases from 0.4 to 0.05, the negative impact on fishery resources diminishes. Higher values (0.4 and 0.3) show significant declines in fishery resources, indicating severe ecosystem stress. Moderate values

(0.2 and 0.1) exhibit reduced but still negative effects, while the lowest value (0.05) shows minimal decline. Sustainable practices and management are crucial to mitigate these impacts, stabilize fish populations, and ensure long-term ecological balance.

Discussion

This paper underscored the critical need for effective management of industrialization and ecotourism to sustain fishery resources. This paper also demonstrated that achieving sustainable fishery levels requires lower competitive rates of industrialization and higher mitigating effects on ecotourism. Simulation results reveal the importance of balancing growth rates in fishery resources with industrial and ecotourism impacts, as supported by recent studies (Perkumienė et al., 2023; Sapriani et al., 2024; Xu et al., 2023). Effective management and policy interventions are crucial to controlling these activities and ensuring long-term sustainability (Alieva et al., 2023).

This paper also highlighted that high industrial and ecotourism impacts lead to significant depletion of fishery resources, emphasizing the need for stringent management strategies. Areas with high industrial impacts require immediate measures to reduce exploitation. In moderate impact areas, balancing industrial activities with sustainable practices is pivotal. However, low impact areas benefit from continuous monitoring and maintaining low competitive rates. For ecotourism, strong mitigating measures are essential in high-impact areas, and enhancing measures in moderate areas can further protect resources. Findings aligned with Agius and Briguglio (2021), who emphasize the importance of marine protected areas and sustainable peak-season tourism. This paper advocated for regular monitoring of heavy metal levels, public awareness on pollution risks, and encouraging sustainable practices among industries and tourism operators.

This paper revealed the complex interplay between fishery resources, ecotourism, and industrialization. This paper confirmed that while these activities can initially coexist and grow, unsustainable practices eventually lead to decline. Aligning with Palacio et al. (2023), the existing paper suggested that balancing industrialization and tourism with sustainable practices can enhance the resilience and growth of fishery resources (Troell et al., 2023). Our insights benefited local communities, fisheries and aquaculture industries, environmental organizations, and tourism policymakers. This paper provides a basis for developing regulations and policies that balance economic growth with environmental conservation. By implementing our recommendations, stakeholders can enhance coastal ecosystems' sustainability, benefiting existing and future generations.

Addressing heavy metal pollution in the Lekki and Epe mangroves is essential for protecting public health, preserving the environment, and sustaining coastal tourism. Collaborative efforts among local authorities, environmental agencies, and the tourism industry are crucial for the long-term viability and safety of these regions. The study offers valuable analysis and recommendations for managing the adverse effects of industrialization and ecotourism on coastal ecosystems, highlighting the need for balanced and sustainable development strategies to preserve biodiversity and economic value.

Theoretical and practical implications

This paper significantly contributes to tourism management research by applying the eco-dynamical modelling approach to explore the intricate relationships between sporadic industrialization, ecotourism development, and the sustainability of fishery resources in coastal areas. From a theoretical perspective, it advances the understanding of how these environmental pressures interact within coastal ecosystems, highlighting the potential long-term consequences of unregulated industrialization and unsustainable tourism practices. Incorporating eco-dynamical modelling, the study offers a comprehensive framework for assessing the dynamic feedback loops between environmental degradation and economic activities, which is critical for predicting future outcomes and informing policy decisions.

Practically, the findings can guide the development of sustainable tourism management strategies that balance ecological conservation with economic growth, providing actionable insights for policymakers, environmental managers, and local communities. Ultimately, this research helps bridge the gap between environmental science and tourism management, offering novel approaches to protect fragile coastal ecosystems while promoting responsible tourism. The study also contributes to the sustainable and ecotourism literature supporting studies by Baloch et al. (2023); Metilelu et al. (2022); Onihunwa et al. (2023); Samal and Dash (2024); Sarkar et al. (2023). This contributes to the theory of ecotourism and its impact on ecosystem sustainability.

Practically, this paper emphasizes the pressing health and environmental risks associated with elevated heavy metal levels (e.g., Fe, Pb, Zn) in coastal ecosystems. Contaminated fish pose direct threats to human health, while the broader environmental degradation can harm aquatic biodiversity, jeopardize fisheries, and reduce the appeal of coastal destinations, thus diminishing tourism revenues. To address these challenges, policymakers must enforce robust and stringent regulations governing both industrialization and ecotourism. Setting clear limits on industrial activities, as well as implementing tourism regulations to minimize adverse impacts, are vital steps in mitigating environmental degradation.

Innovative and forward-thinking strategies should be employed, such as the promotion of eco-friendly technologies, continuous environmental monitoring, and the development of real-time pollution tracking systems. Encouraging sustainable tourism practices through eco-tourism models and certification programs can guide the sector toward more responsible development. Furthermore, local communities should be actively engaged in conservation efforts, educated about pollution risks, and incentivized to adopt sustainable practices. Integrating research-driven solutions to develop technologies that mitigate the impact of industrialization and tourism will ensure that coastal ecosystems are preserved for future generations. Additionally, investments in green infrastructure and community-based monitoring systems will create resilient, sustainable solutions that foster both ecological and economic well-being in coastal areas.

Limitations and further research

This paper presents several limitations that should be considered when interpreting its findings. Firstly, the study's cross-sectional design provides only a snapshot of the complex dynamics between industrialization, ecotourism, and fishery resources, limiting the depth of temporal insights. Secondly, the data used may not be fully representative of the broader coastal ecosystems, which could impact the robustness of the findings. Thirdly, the eco-dynamical model employed relies on certain assumptions, which, while useful for simplification, may oversimplify the real-world complexities involved in the interactions between industrialization, ecotourism, and environmental factors. While sensitivity analyses have been conducted to address this, it remains a limitation. Finally, the study's focus on specific time frames and regions reduces the generalizability of the results, though simulations offer a broader perspective. Moreover, capturing the full complexity of the interactions between these factors remains a challenge, as does practical policy implementation due to the differing interests of various stakeholders.

Future studies should explore the long-term effects of industrialization and ecotourism through longitudinal research, which can provide more comprehensive insights into the dynamics over time. It would be beneficial to investigate the combined impacts of climate change and human activities on coastal ecosystems to better understand the compounded effects. Additionally, research should focus on the socio-economic implications of environmental degradation and tourism development, as well as evaluate the effectiveness of existing policies in managing these challenges. Finally, studies should consider the development of adaptive policy frameworks that can accommodate evolving environmental and socio-economic conditions.

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التفاعل بين التصنيع غير المنضبط، والسياحة البيئية، وموارد مصايد الأسماك في المناطق الساحلية النيجيرية: نهج النمذجة الديناميكية البيئية

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معلومات المقالة

الكلمات المفتاحية

إدارة المناطق الساحلية؛ النمذجة الديناميكية البيئية؛ السياحة البيئية؛ موارد مصايد الأسماك؛ التصنيع.

(JAAUTH)
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الملخص

السياحة الساحلية هي نشاط اقتصادي مهم في غابات المانغروف في ليكي وإيبي في نيجيريا. ومع ذلك، فإن وجود ملوثات المعادن الثقيلة في هذه المناطق بسبب التصنيع غير المنضبط والتلوث المرتبط بالسياحة البيئية يشكل خطرًا محتملاً على النظم البيئية. بحثت هذه الورقة التفاعل المعقد بين التصنيع غير المنضبط وتنمية السياحة البيئية وموارد مصايد الأسماك في المناطق الساحلية. باستخدام نهج النمذجة الديناميكية البيئية، قامت هذه الورقة بقياس تأثيرات هذه الأنشطة البشرية على استدامة مصايد الأسماك. تضمنت النمذجة معايير رئيسية مثل المعدلات التنافسية للتصنيع والسياحة البيئية، والتخفيف من الآثار على الزيادة الهندسية في السياحة البيئية والتصنيع. أظهرت نتائج المحاكاة التي تم الحصول عليها باستخدام ماتلاب التوازن المطلوب للحفاظ على موارد مصايد الأسماك، مما يدل على أن المستويات العالية من التصنيع والسياحة البيئية تؤدي إلى تدهور مخزونات مصايد الأسماك بشكل كبير، في حين أن التنمية الخاضعة للرقابة يمكن أن تخفف من هذه التأثيرات. على وجه التحديد، أظهرت النمذجة أن موارد مصايد الأسماك ازدهرت في ظل ظروف حيث يتم تقليل الآثار السلبية للسياحة البيئية والتصنيع. وتسلط النتائج الضوء على الحاجة إلى فرض لوائح صارمة وإدارة مستدامة للسواحل لحماية موارد الصيد. ومن ثم، فإن هذا من شأنه أن يوفر رؤى حاسمة لصناع السياسات بشأن دمج الأهداف الاقتصادية والبيئية في سياق السياحة.