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Ecosystem Based Environmental Control for Sustainable Coastal Zone Climate Mitigation

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ABSTRACT

The development of sustainable coastal tourism is essential for promoting regional growth while preserving marine ecosystems. Emissions of Greenhouse Gases (GHG) are a primary cause of global warming, which disturbs the balance of marine ecosystems and threatens biodiversity. This **research proposes** a model to reduce GHG levels through Mangrove Planting and Nutrient Waste Management in coastal zones, which serve as the main control strategies for addressing the environmental challenges. The proposed model develops previous marine ecosystem models by incorporating an additional oxygen variable, so that the system can represent marine environmental conditions more comprehensively. As a result, the model includes five main components, atmospheric GHG concentration, rising temperatures, plankton and fish populations, and oxygen levels in seawater. Its goal is to maintain a healthy marine environment with moderate temperatures, low acidity, sufficient oxygen, and adequate food sources. Simulation results show that implementing control measures over 20 years can reduce GHG growth and help stabilize marine temperatures. The **results** also indicate that the inclusion of oxygen dynamics provides a broader ecological perspective in evaluating the effectiveness of the control strategies. This ecosystem-based management model provides a practical approach to climate change mitigation and supports environmental sustainability efforts. Furthermore, the research offers a scientific foundation for coastal tourism policies that prioritize ecosystem protection and sustainable destination development. The **findings** align with the Sustainable Development Goals (SDGs), especially climate action (SDG 13) and life below water (SDG 14), and contribute to evidence-based strategies for managing coastal tourism and environmental resilience.

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1. INTRODUCTION

The coastal tourism sector plays a crucial role in supporting regional economic development, particularly in areas rich in marine biodiversity and unique natural attractions. However, the sustainability of this sector depends heavily on the maintenance of a well-preserved environment. When coastal environmental quality declines, tourism appeal and sustainability are threatened. A primary driver of this decline is GHG (GHG) emissions, which increase global temperatures and trigger climate change [1–3].

Experts in climate science recognize that the accumulation of carbon dioxide and other GHG from activities such as burning fossil fuels and forest clearing is a leading cause of global warming [4, 5]. These gases trap heat in the atmosphere, raising the global average temperature [6–8]. This warming alters sea surface temperature and contributes to ocean warming and acidification, which can disrupt food chains, reduce plankton populations, damage coral reefs, and affect fish populations that rely on stable ocean conditions [9, 10]. If not promptly addressed through appropriate mitigation and adaptation policies, climate change may reduce tourism revenue and exacerbate the socio-economic vulnerability of coastal communities [11–13].

In addition to harming biodiversity, global warming degrades coastal ecosystem quality that is essential for tourism [14–16]. The loss of coral reefs, declining fish populations, and reduced ecosystem health can weaken tourism appeal and threaten local livelihoods that depend on coastal tourism [17–20]. These environmental and socio-economic risks also make the issue highly relevant from a policy perspective, particularly in Indonesia, where post-Paris Agreement regulations increasingly emphasize climate mitigation [21], environmental protection [22], and mangrove ecosystem management [23, 24]. Therefore, ecosystem-based interventions such as mangrove restoration and environmentally compliant waste and wastewater management are not only scientifically justified, but also aligned with current policy priorities for coastal sustainability and climate resilience [25].

A solution to tackling global warming can be achieved by leveraging nature-based approaches, such as mangrove planting and sustainable industrial waste management [26–28]. Mangrove forests are vital coastal ecosystems with an exceptional ability to absorb carbon dioxide (CO_2) from the atmosphere. Planting and restoring mangroves function as carbon sinks, protect coastal ecosystems, and help reduce local surface temperatures [29–31]. Mangroves can store substantial CO_2 in biomass and sediment, supporting habitat provision and local environmental stability; by lowering atmospheric CO_2, they mitigate GHG impacts and slow warming [28, 32].

On the other hand, environmentally compliant industrial waste and wastewater management can help reduce pollution pressure and maintain water quality within acceptable environmental standards, thereby supporting marine primary productivity and ecosystem balance [33]. Plankton play a central role in the global carbon cycle through photosynthetic CO_2 uptake, therefore, enhancing plankton growth can increase carbon absorption, improve oxygen availability, and help maintain food-web stability [34–36].

Accordingly, the combined use of mangrove restoration and industrial waste and wastewater management provides an ecosystem-based strategy for reducing GHG impacts while improving biodiversity and supporting coastal communities. This approach contributes not only to SDG 13 (Climate Action) through climate-change mitigation, but also to SDG 14 (Life Below Water) by supporting marine ecosystem health and to SDG 8 (Decent Work and Economic Growth) by helping sustain coastal tourism and local livelihoods.

The impacts of GHG require a comprehensive mitigation framework that integrates dynamic modeling and optimal control [37]. This study offers a novel approach to coastal climate mitigation by combining mangrove planting and industrial waste management within a single dynamic framework, while also explicitly considering ocean oxygen as an essential ecological component. It explains how GHG concentration, temperature, plankton, fish, and ocean oxygen are interconnected, allowing the role of ecosystem-based interventions to be evaluated more comprehensively.

Mangrove planting is considered to enhance natural CO_2 absorption, reduce GHG concentration, and lower surface temperature, while also helping maintain coastal environmental stability. Industrial waste management is incorporated to support plankton growth, which can increase CO_2 uptake through photosynthesis, improve oxygen availability in the ocean, and help sustain fish populations. Within this framework, optimal control theory is used to determine effective intervention strategies over time under given constraints and objectives [38–40].

2. LITERATURE REVIEW

In an effort to understand marine ecosystem dynamics and their contribution to the global carbon cycle, various studies have developed mathematical approaches to describe interactions among biological and environmental factors [41]. These approaches provide insights into how marine organisms, particularly plankton communities, respond to climate-driven changes such as temperature increases, atmospheric warming, and GHG concentrations. Mathematical models have been applied to analyze ecosystem responses, predict environmental scenarios, and evaluate mitigation strategies for maintaining ecosystem stability. Table 1 summarizes previous studies on the impact of temperature variations and GHGs on marine plankton ecosystems, including research objectives, analyzed parameters, and solution methods.

Table 1. Summary of Literature on the Impact of Temperature and GHG on Marine Plankton Ecosystems

No	Study Title	Research Focus	Analyzed Parameters	Solution Method
1	Modeling the Impact of Carbon Dioxide on Marine Plankton [42]	Influence of CO_2 on phytoplankton growth	CO_2 concentration, plankton density	Mathematical and numerical analysis
2	Modeling and Analytical Analysis of the Effect of Atmospheric Temperature to the Planktonic Ecosystem in Oceans [43]	Influence of temperature on photosynthetic activity	Temperature, plankton density, dissolved oxygen	Non-linear model, numerical simulation
3	A mathematical model applied to investigate the potential impact of global warming on marine ecosystems [44]	Influence of GHG on marine ecosystems	GHG concentration, atmospheric temperature, plankton density	Deterministic model, bifurcation analysis
4	Modeling with strategies to control the adverse effects of global warming on marine ecosystems [45]	Control strategies for mitigating global warming effects on plankton and fish populations	Coastal reforestation, plankton nutrients, fish and plankton density, atmospheric temperature	Deterministic model, optimal control and simulation analysis
5	Climate change and the shifting dynamics of marine ecology [46]	Influence of climate change on plankton dynamics with explicit oxygen involvement	Sea surface temperature, dissolved oxygen, phytoplankton, zooplankton	Mathematical modeling, stability analysis, delayed and non-delayed simulations

A series of studies [44, 45] provided an important mathematical basis for describing how CO_2, temperature, and ecological interactions influence marine plankton systems [47]. Their works showed that changes in carbon dioxide and atmospheric temperature affect plankton growth, photosynthetic activity, and marine ecosystem balance, and were later extended to a control framework involving coastal reforestation and nutrient enhancement [42–45]. More recently, [46] emphasized the importance of dissolved oxygen as a key ecological variable that interacts with temperature and plankton dynamics under climate change.

Table 1 shows that previous studies have gradually progressed from basic plankton–CO_2 models to global-warming models and control-based mitigation strategies, with more recent attention given to oxygen dynamics. However, an important gap remains. Existing optimal control models mainly focus on Greenhouse Gases, temperature, plankton, and fish, whereas oxygen has not been explicitly incorporated as a state variable within the control framework. Conversely, studies that explicitly examine oxygen generally focus on ecological dynamics rather than optimal intervention design [48, 49].

This study addresses that gap by developing a dynamic optimal control model that explicitly incorporates ocean oxygen together with greenhouse gas concentration, temperature, plankton, and fish [50]. The model integrates mangrove planting and industrial waste management within a single ecosystem-based control framework for coastal climate mitigation [51]. Therefore, the novelty of this study lies both conceptually and methodologically, conceptually, it treats oxygen as an essential ecological component of the controlled system;

methodologically, it embeds oxygen dynamics within an optimal control framework to evaluate coordinated mitigation strategies in coastal ecosystems. Figure 1 presents the proposed compartment diagram, illustrating the interactions among greenhouse gases, temperature, plankton, fish, and oxygen components considered in the ecosystem model.

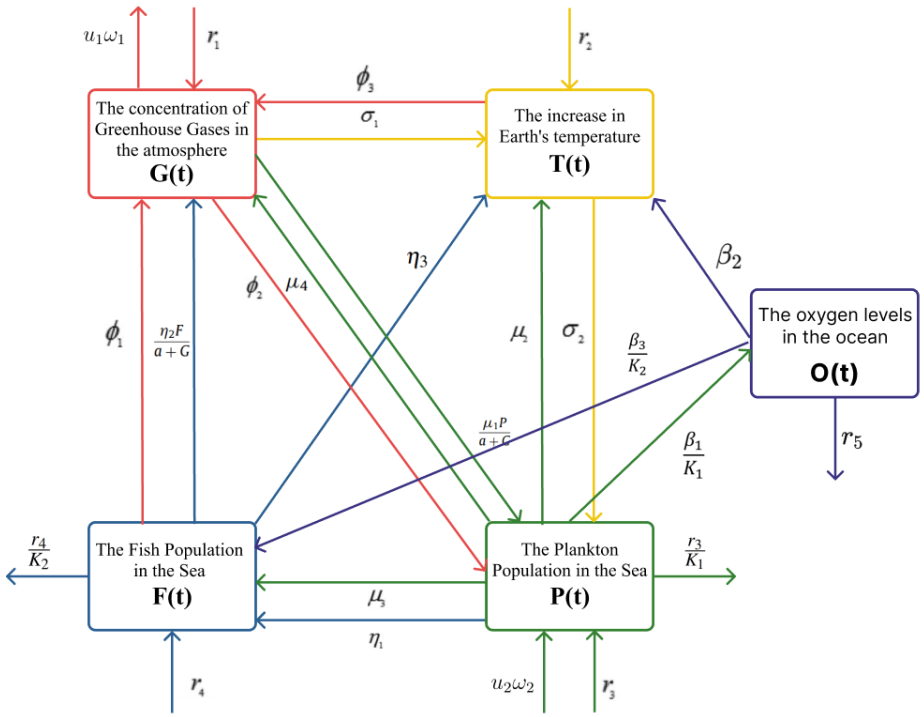


Figure 1. Compartment Diagram of the GHG Emissions Problem

Figure 1 illustrates the compartment structure of the proposed ecosystem model, where greenhouse gas concentration, temperature, plankton, fish, and ocean oxygen are represented as interconnected components [52]. The model describes the dynamic interactions among environmental and biological variables, including the influence of greenhouse gas emissions on temperature changes, the role of temperature and oxygen availability in plankton growth, and the relationship between plankton and fish populations. By incorporating oxygen as an explicit state variable, the framework provides a more comprehensive representation of marine ecosystem responses and enables the evaluation of integrated mitigation strategies for coastal climate management.

3. PROBLEM FORMULATION

To address coastal environmental challenges, this study develops a mathematical model based on [44, 45] by extending the existing framework with ocean oxygen concentration as an additional state variable. The model describes interactions among GHG concentration, surface temperature, plankton, fish populations, and oxygen dynamics, while incorporating optimal control measures to reduce GHG concentration and regulate temperature for climate-change mitigation. The relationships among the main variables and system flows, including GHG concentration (G), surface temperature (T), plankton population (P), fish population (F), and oxygen concentration (O), are illustrated through the compartmental diagram in Figure 1.

3.1. Model Development with The Oxygen Variable and Objective Functional

This study adopts the baseline climate–marine ecosystem model from [44], which describes the interactions among GHG concentration $G(t)$, Earth's surface temperature $T(t)$, plankton population $P(t)$, and fish population $F(t)$. These four variables are retained as the fundamental framework, while this study extends the

model by incorporating ocean oxygen concentration $O(t)$ as an additional state variable to represent marine ecosystem health.

The inclusion of $O(t)$ expands the system from a four-dimensional to a five-dimensional ecological control model. Oxygen dynamics consider four main processes: natural loss through diffusion and microbial consumption represented by $-r_5 O$, oxygen production by plankton photosynthesis represented by $\beta_1 O\frac{P}{K_1}$, temperature-induced oxygen reduction represented by $-\beta_2 OT$, and oxygen consumption by fish activity represented by $-\beta_3 O\frac{F}{K_2}$. Accordingly, the oxygen dynamics are formulated as:

$$\frac{dO}{dt} = -r_5 O + \beta_1 O\frac{P}{K_1} - \beta_2 OT - \beta_3 O\frac{F}{K_2}. \tag{1}$$

3.2. Formulation of the Optimal Control Problem

The control variables considered in this study are the mangrove planting effort, denoted by $u_1(t)$, and industrial waste management, denoted by $u_2(t)$. The first control is intended to reduce GHG concentration through additional carbon absorption, while the second control is used to support plankton growth through improved environmental management. Although the newly introduced oxygen variable is not explicitly included in the objective functional, it plays an important ecological role in evaluating the indirect impact of the controls on marine environmental quality. To balance environmental mitigation and implementation cost, the objective functional is defined as:

$$\min_{(u_1,u_2)\in U} J(u_1,u_2) = \int_{t_0}^{t_f}\left(G(t) + \frac{1}{2}Au_1^2(t) + \frac{1}{2}Bu_2^2(t)\right)dt. \tag{2}$$

This objective reflects the policy goal of minimizing GHG concentration over the control horizon while keeping the economic costs of the two interventions at reasonable levels. The coefficients A and B represent the relative weights associated with mangrove planting and industrial waste management, respectively. Therefore, the objective functional captures the trade-off between environmental benefit and policy cost, while the extended state system enables the effects of the controls to be assessed not only on GHG reduction but also on marine ecosystem balance through the oxygen dynamics.

Based on the compartment diagram in Figure 1 and by extending the baseline subsystem in [44] with an additional oxygen equation, the proposed optimal control model is formulated as follows:

$$\begin{aligned}
\min_{(u_1,u_2)\in U} \quad & J(u_1,u_2) = \textstyle\int_{t_0}^{t_f}\left(G(t) + \frac{1}{2}Au_1(t)^2 + \frac{1}{2}Bu_2(t)^2\right)dt,\\
\text{subject to} \quad \tfrac{dG}{dt} &= r_1 G + \phi_1 FG - \phi_2 PG + \phi_3 T - u_1\omega_1 G,\\
\tfrac{dT}{dt} &= r_2 T + \sigma_1 GT - \sigma_2 PT,\\
\tfrac{dP}{dt} &= r_3 P\left(1 - \tfrac{P}{K_1}\right) + \tfrac{\mu_1 P}{a+G} - \mu_2 TP - \mu_3 FP - \mu_4 GP\\
&\quad + u_2\omega_2 P,\\
\tfrac{dF}{dt} &= r_4 F\left(1 - \tfrac{F}{K_2}\right) + \eta_1 PF - \tfrac{\eta_2 F}{a+G} - \eta_3 TF,\\
\tfrac{dO}{dt} &= -r_5 O + \beta_1 O\tfrac{P}{K_1} - \beta_2 OT - \beta_3 O\tfrac{F}{K_2},
\end{aligned} \tag{3}$$

with the control constraints $0 \le u_1(t), u_2(t) \le 1$.

Each variable and associated parameter in this model is defined in Table 2 to provide a clear understanding of their roles and influences within the system.

Table 2. Initial Values, Parameter Values, and Descriptions

Symbol	Value	Source	Description
$G(t_0)$	0.04	[44]	Initial GHG concentration
$T(t_0)$	0.07	[44]	Initial temperature
$P(t_0)$	17.5	[44]	Initial plankton population
$F(t_0)$	7.8	[44]	Initial fish population
$O(t_0)$	12	[53]	Initial oxygen concentration
r_1	0.00095	[44]	Natural rate of GHG (GHG) increase
ϕ_1	0.0029	[44]	GHG production rate due to fish respiration

Symbol	Value	Source	Description
ϕ_2	0.00099	[44]	GHG absorption rate due to plankton photosynthesis
ϕ_3	1	[44]	GHG production rate due to temperature-driven phenomena
r_2	0.099	[44]	Natural rate of atmospheric temperature increase
σ_1	0.00025	[44]	Rate of temperature increase due to GHG
σ_2	0.00565	[44]	Temperature absorption rate by plankton
r_3	0.00225	[44]	Natural growth rate of plankton population
μ_1	0.00108	[44]	Growth rate of plankton population due to CO_2
μ_2	0.00001	[44]	Rate of plankton population inhibition due to global warming
μ_3	0.0031	[44]	Rate of plankton decrease due to fish predation
μ_4	0.00001	[44]	Rate of plankton population inhibition due to ocean acidification
r_4	0.0002	[44]	Natural growth rate of fish population
η_1	0.000175	[44]	Growth rate of fish population due to plankton consumption
η_2	0.000190	[44]	Rate of fish population inhibition due to ocean acidification
η_3	0.000061	[44]	Rate of fish population inhibition due to global warming
a	0.01	[44]	Saturation constant for dissolved CO_2
K_1	1,000,000	[44]	Carrying capacity of plankton population in the ocean
K_2	10,000	[44]	Carrying capacity of fish population in the ocean
r_5	0.00005	Scenario (scaled), this study [48]	Natural oxygen loss through diffusion and microbial consumption
β_1	0.02	Scenario (scaled), this study [48]	Rate of oxygen production due to plankton photosynthesis
β_2	0.03	Scenario (scaled), this study [49]	Rate of oxygen depletion caused by thermal effects
β_3	0.04	Scenario (scaled), this study [54]	Rate of oxygen consumption associated with fish respiration and biological activity

Table 2 presents the parameters and initial values used in the proposed oxygen-integrated climate–marine ecosystem model. The parameters represent interactions among greenhouse gases, temperature, plankton, fish, and oxygen dynamics, including biological rates, environmental coefficients, and carrying capacities. The additional oxygen parameters (β_1, β_2, and β_3) describe oxygen production, temperature-driven depletion, and fish-related consumption, supporting the numerical simulation and optimal control analysis.

4. MODEL EVALUATION AND CONTROL STRATEGY

A deeper understanding of the system dynamics is needed to evaluate how environmental interventions affect coastal ecosystems over time. This section highlights the main properties of the model, particularly the preservation of positive and realistic values of GHG concentration, sea surface temperature, plankton and fish populations, and dissolved oxygen, all of which are essential for marine ecosystem stability. It also examines the role of the proposed controls, namely mangrove planting and nutrient waste management, in reducing environmental degradation and guiding the coastal system toward a more balanced and sustainable state.

4.1. Analysis of Positivity

Climate change driven by GHG emissions affects marine ecosystems through changes in GHG concentration, temperature, plankton, fish, and oxygen dynamics. A mathematical model is developed to describe these interactions, where all state variables must remain nonnegative to ensure physical and ecological feasibility. Therefore, positivity analysis is performed to verify that the model produces realistic trajectories under positive initial conditions.

It can be seen from Equation 3 that the model is valid if it has a positive solution for any time t. Thus, if $G(t_0)$, $T(t_0)$, $P(t_0)$, $F(t_0)$, and $O(t_0)$ have positive values, then $G(t)$, $T(t)$, $P(t)$, $F(t)$, and $O(t)$ remain positive for all $t \geq t_0$. Assuming the existence of a unique solution, the positivity of these variables is established through the following theorem.

Theorem 4.1. If G, T, P, F and O are solutions of Equation 3 and $G(t_0)$, $T(t_0)$, $P(t_0)$, $F(t_0)$ and $O(t_0)$ have

positive values, then $G(t)$, $T(t)$, $P(t)$, $F(t)$ and $O(t)$ are positive numbers for all $t \geq t_0$.

This study illustrate the argument for $T(t)$. From the temperature equation:

$$\frac{dT}{dt} = r_2 T + \sigma_1 GT - \sigma_2 PT = \Big(r_2 + \sigma_1 G(t) - \sigma_2 P(t)\Big)\, T(t), \tag{4}$$

Where the time-dependent coefficient is $a_2(t) = r_2 + \sigma_1 G(t) - \sigma_2 P(t)$. Using the integrating-factor form, Equation 4 implies

$$\frac{d}{dt}\left(T(t)\exp\Big(-\int_{t_0}^{t} a_2(\tau)\,d\tau\Big)\right) = 0.$$

hence,

$$T(t)\exp\Big(-\int_{t_0}^{t} a_2(\tau)\,d\tau\Big) = T(t_0),$$

and therefore

$$T(t) = T(t_0)\exp\left(\int_{t_0}^{t} \big(r_2 + \sigma_1 G(\tau) - \sigma_2 P(\tau)\big)\,d\tau\right). \tag{5}$$

Because $T(t_0) > 0$ and the exponential term is strictly positive for all t, it follows from 5 that $T(t) > 0$ for every $t \in [t_0, t_f]$.

Applying the same integrating-factor representation to the equations of $G(t)$, $P(t)$, $F(t)$, and $O(t)$ yields $G(t) > 0$, $P(t) > 0$, $F(t) > 0$, and $O(t) > 0$ on $[t_0, t_f]$.

4.2. Existence of Optimal Control

Model Equation 3 is developed to describe the impact of global warming on the marine ecosystem through the interactions among GHG concentration, temperature, plankton, fish population, and ocean oxygen. To mitigate these effects, two control variables are introduced: mangrove planting u_1, which enhances carbon sequestration, and nutrient waste management u_2, which supports marine environmental balance. In this section, this study establish the existence of an optimal control for system Equation 3, showing that there exist admissible strategies u_1 and u_2 that minimize the adverse effects of global warming while preserving the system within realistic and sustainable bounds.

Based on, the existence of an optimal control for system Equation 3 can be established by verifying the following standard conditions.

- **The Admissible Control set is Nonempty.**
  Define
  $$\mathcal{U} := \{(u_1, u_2) \text{ measurable} \mid 0 \leq u_1(t) \leq 1,\ 0 \leq u_2(t) \leq 1,\ \forall t \in [0, t_f]\}.$$
  Clearly, $(u_1, u_2) \equiv (0, 0) \in \mathcal{U}$ (the problem without control), hence $\mathcal{U} \neq \emptyset$.

- **$\mathcal{U}$ is closed and convex.**
  Let $v_1 = (u_{11}, u_{21})$, $v_2 = (u_{12}, u_{22}) \in \mathcal{U}$ and $\lambda \in [0, 1]$. Then
  $$\lambda v_1 + (1-\lambda)v_2 = \big(\lambda u_{11} + (1-\lambda)u_{12},\ \lambda u_{21} + (1-\lambda)u_{22}\big),$$
  and since $[0, 1]$ is convex, this study have $0 \leq \lambda u_{11} + (1-\lambda)u_{12} \leq 1$ and $0 \leq \lambda u_{21} + (1-\lambda)u_{22} \leq 1$ a.e. on $[0, t_f]$. Thus $\mathcal{U}$ is convex. Moreover, if $(u_{1n}, u_{2n}) \to (u_1, u_2)$ in L^∞ (or uniformly a.e.), then the bounds $0 \leq u_{in} \leq 1$ imply $0 \leq u_i \leq 1$ a.e., hence $(u_1, u_2) \in \mathcal{U}$ and $\mathcal{U}$ is closed.

- **Well Posedness and Boundedness of the State System.**
  For any $(u_1, u_2) \in \mathcal{U}$, the right-hand side of (3) is continuous in the state variables and measurable in t (with bounded controls), and it is locally Lipschitz in (G, T, P, F, O) on the positive region. Therefore, (3) admits a unique solution on $[0, t_f]$. Furthermore, since G, T, P, F, O are continuous on the compact interval $[0, t_f]$, they are bounded:

  $$0 < G(t) \leq G_{\max}, \quad 0 < T(t) \leq T_{\max}, \quad 0 < P(t) \leq P_{\max}, \quad 0 < F(t) \leq F_{\max}, \quad 0 < O(t) \leq O_{\max}.$$

  Consequently, the vector field is bounded on $[0, t_f]$; e.g.

  $$\dot{G} \leq r_1 G_{\max} + \phi_1 F_{\max} G_{\max} + \phi_3 T_{\max}, \qquad \dot{T} \leq r_2 T_{\max} + \sigma_1 G_{\max} T_{\max},$$

  and similarly for $\dot{P}, \dot{F}, \dot{O}$.

- **Convexity of the Running Cost in the Controls.**
  Consider the standard performance index

$$J(u_1, u_2) = \int_0^{t_f} \left(z_1 G(t) + \frac{1}{2}\left(A u_1^2(t) + B u_2^2(t)\right) \right) dt.$$

  The control-dependent term $q(u_1, u_2) := \frac{1}{2} A u_1^2 + \frac{1}{2} B u_2^2$ is convex since its Hessian is

$$\nabla^2 q = \begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix} \succeq 0 \qquad (A, B \geq 0).$$

  Moreover, $G(t)$ is bounded on $[0, t_f]$, hence J is well-defined and bounded below on $\mathcal{U}$.

- **Affine Dependence on the Controls.**
  The controlled system (3) can be written in the affine form

$$\dot{x} = f(x) + u_1 g_1(x) + u_2 g_2(x), \qquad x = (G, T, P, F, O),$$

  So the state dynamics are linear (affine) in the controls and bounded for bounded states.

Thus, all hypotheses of the existence theorem in Fleming and Rishel are satisfied; hence, there exists an optimal control $(u_1^*, u_2^*) \in \mathcal{U}$ that minimizes J subject to Equation 3.

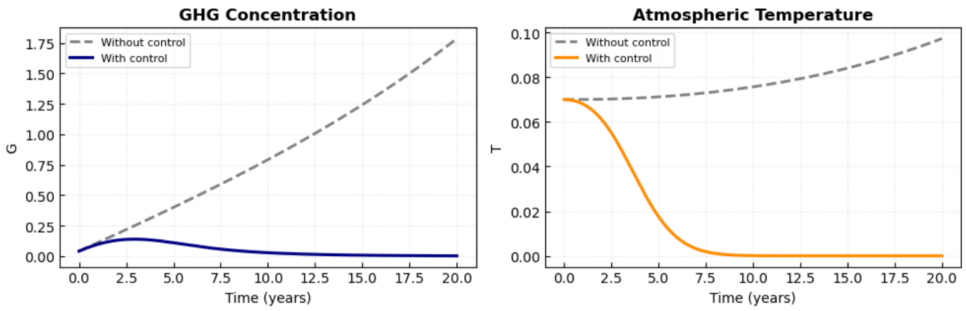
5. NUMERICAL SOLUTION

This section presents the numerical results of the proposed optimal control model using the PMP–RK4 scheme. The simulations are carried out to illustrate the dynamic behavior of the state variables and control functions over the prescribed time horizon. In particular, the numerical study is used to compare the uncontrolled and controlled scenarios and to examine how moderate variations in selected scaled parameters affect the resulting system behavior. The definitions and numerical values of the parameters used in the simulations are listed in Table 2.

5.1. Controlled and Uncontrolled Dynamics

The numerical results in Figure 2 show a clear contrast between the uncontrolled and controlled scenarios. Without control, the GHG concentration $G(t)$ increases continuously from about 0.04 to 1.75 at $t = 20$, while the atmospheric temperature $T(t)$ rises from about 0.07 to nearly 0.10, indicating progressive environmental deterioration due to sustained emission accumulation and warming.

Under the optimal control strategy, the system exhibits markedly improved behavior. The temperature $T(t)$ decreases from the beginning of the simulation and approaches zero around years 8–10, whereas $G(t)$ increases slightly in the early stage, peaks around year 3, and then declines steadily to a value close to zero. This indicates that temperature is controlled immediately, while GHG concentration is reduced after a short transient phase.



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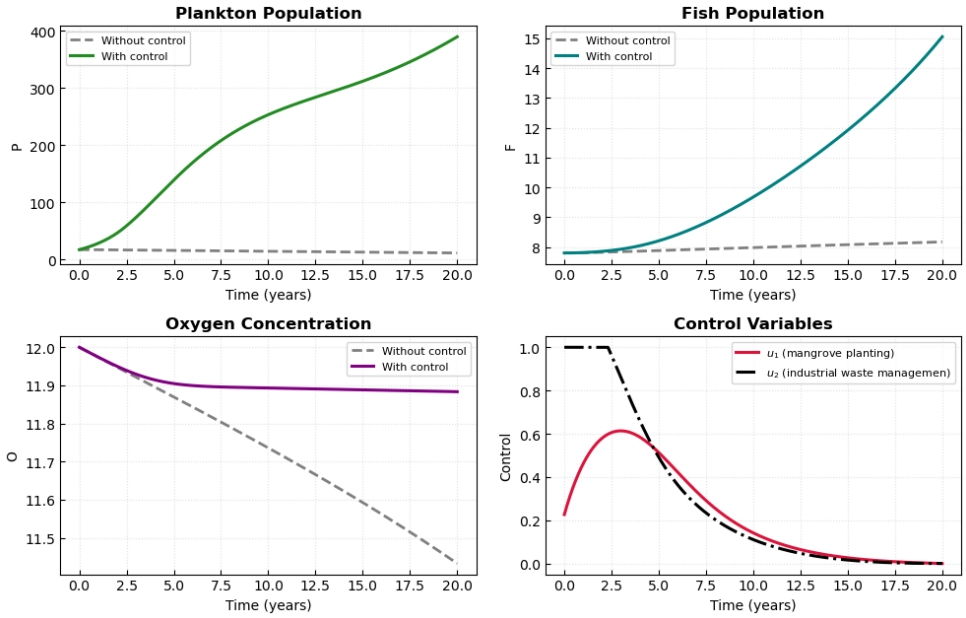


Figure 2. Controlled and Uncontrolled Dynamics of the Coastal Ecosystem Model and the Corresponding Optimal Control Profiles

The ecological variables show a similar improvement. Under control, the plankton population $P(t)$ increases substantially from about 17.5 to nearly 390, whereas in the uncontrolled case it remains almost stagnant. The fish population $F(t)$ also responds positively, rising only slightly without control but reaching about 15 under intervention. Likewise, the oxygen level $O(t)$ declines persistently in the uncontrolled case, from about 12.0 to 11.43, but under control it decreases only slightly at the beginning and then remains nearly stable around 11.89. These results suggest that reducing GHG concentration and temperature not only limits environmental degradation, but also promotes marine productivity and maintains ecosystem balance.

The control profiles further explain this mechanism. The control $u_2(t)$ remains high in the early stage and then gradually declines, indicating that waste-management intervention is most effective at the beginning to support plankton growth. Meanwhile, $u_1(t)$ increases in the initial stage, reaches its maximum around years 2–3, and then decreases gradually, showing that mangrove planting is particularly important in the early-to-middle phase for suppressing GHG accumulation.

Overall, the results indicate that early and intensive intervention is crucial for improving both environmental and ecological conditions. Once recovery begins, the control effort can be reduced gradually while maintaining system stability.

5.2. Effect of Parameter Variations

To examine how the numerical results change under moderate variations of the scaled parameters, this study vary each selected parameter by $\pm 20\%$ while keeping the others fixed. The resulting terminal states and objective functional values are reported in Table 3.

Table 3. One-at-a-Time Sensitivity Analysis Results

Parameter	**Perturb.**	$G(t_f)$	$T(t_f)$	$P(t_f)$	$F(t_f)$	$O(t_f)$	J
r_5	-20%	0.070825	0.002317	102.563662	8.800289	11.880321	1.822242
r_5	$+20\%$	0.070825	0.002317	102.563662	8.800289	11.878420	1.822242
β_1	-20%	0.070825	0.002317	102.563662	8.800289	11.879333	1.822242
β_1	$+20\%$	0.070825	0.002317	102.563662	8.800289	11.879407	1.822242
β_2	-20%	0.070825	0.002317	102.563662	8.800289	11.901705	1.822242
β_2	$+20\%$	0.070825	0.002317	102.563662	8.800289	11.857078	1.822242

Parameter	Perturb.	$G(t_f)$	$T(t_f)$	$P(t_f)$	$F(t_f)$	$O(t_f)$	J
β_3	-20%	0.070825	0.002317	102.563662	8.800289	11.880148	1.822242
β_3	$+20\%$	0.070825	0.002317	102.563662	8.800289	11.878593	1.822242

The results in Table 3 indicate that the controlled system is numerically robust under moderate $\pm 20\%$ perturbations of the selected scaled parameters. For all tested cases, the terminal values of $G(t_f)$, $T(t_f)$, $P(t_f)$, $F(t_f)$, and the objective functional J remain unchanged to the reported numerical precision. By contrast, the terminal oxygen level $O(t_f)$ shows a small response, varying from 11.857078 to 11.901705. Among the tested parameters, β_2 has the strongest influence on $O(t_f)$, with $O(t_f) = 11.901705$ for a -20% perturbation and $O(t_f) = 11.857078$ for a $+20\%$ perturbation. The effects of the other parameters are smaller, for r_5, $O(t_f)$ varies from 11.878420 to 11.880321, for β_1, from 11.879333 to 11.879407, and for β_3, from 11.878593 to 11.880148. These results suggest that the selected parameters mainly affect the oxygen dynamics, while the overall controlled behavior of the system remains stable over the considered time horizon.

6. DISCUSSION

The numerical results demonstrate that the proposed optimal control strategy provides environmental and ecological benefits by reducing GHG concentration and temperature while improving plankton, fish, and oxygen dynamics. The sensitivity analysis indicates that the controlled system remains robust under moderate parameter variations, with only minor changes observed in the oxygen state. This finding suggests that the model maintains stable qualitative behavior and that the proposed interventions remain effective under reasonable parameter uncertainty.

The integration of oxygen dynamics strengthens the ecological relevance of the proposed model. To avoid unrealistic fluctuations, the oxygen variable is formulated in normalized form, while oxygen-related parameters are introduced through scaled scenarios based on previous studies. This approach maintains ecological plausibility while allowing the model to capture the qualitative role of oxygen in coastal ecosystem dynamics. Recent studies have highlighted the importance of oxygen responses under climate stress, particularly through plankton oxygen interactions and dissolved oxygen changes caused by warming. Compared with previous studies, the present framework provides a more comprehensive approach by integrating oxygen dynamics, optimal control, mangrove planting, and industrial waste management into a unified coastal climate-mitigation model.

From a sustainability perspective, the findings contribute to SDG 13 (Climate Action) through climate-change mitigation and SDG 14 (Life Below Water) through improved marine ecosystem conditions. The study also supports SDG 8 (Decent Work and Economic Growth) indirectly, as improved coastal environmental quality can contribute to sustainable tourism and marine-resource-based livelihoods. The proposed framework is consistent with environmental protection efforts in Indonesia, particularly Government Regulation No. 22 of 2021 on environmental protection and management and Government Regulation No. 27 of 2025 on mangrove ecosystem protection and management.

The proposed model is developed as a conceptual framework rather than a site-specific empirically calibrated system. The parameters were compiled and adapted from previous studies, allowing potential transfer to other coastal environments after recalibration using local data. However, direct empirical validation using field observations has not been conducted and remains an important direction for future research.

7. MANAGERIAL IMPLICATIONS

The proposed optimal control framework provides practical insights for coastal ecosystem managers, policymakers, and environmental stakeholders in developing integrated climate mitigation strategies. The model can support decision-making by evaluating the potential impacts of mangrove restoration and industrial waste management on marine ecosystem stability. For coastal management institutions, the findings emphasize the importance of coordinating ecological conservation programs with climate mitigation actions to maintain long-term ecosystem resilience. From a management perspective, the integration of oxygen dynamics offers additional information for monitoring marine ecosystem health beyond conventional GHG and temperature indicators. Decision-makers can use this framework as a supporting tool to identify effective intervention combinations, prioritize conservation activities, and design adaptive coastal management policies. Although further

calibration with local environmental data is required before operational implementation, the model provides a foundation for evidence-based planning and sustainable coastal resource management.

8. CONCLUSION

This study developed a dynamic optimal control model for GHG mitigation in coastal ecosystems through two ecosystem-based interventions, namely mangrove restoration and environmentally compliant waste and wastewater management. By integrating GHG concentration, atmospheric temperature, plankton, fish, and oxygen into a unified framework, the model captures key ecological interactions in coastal systems. The analytical results establish the positivity of all state variables and the existence of an optimal control.

Numerical simulations show that, compared with the uncontrolled case, the optimal strategy reduces GHG concentration and temperature while improving plankton and fish populations and maintaining more stable oxygen levels. The sensitivity analysis further indicates that the controlled system remains robust under moderate parameter perturbations.

Overall, the proposed framework highlights the potential of combining mangrove restoration and responsible waste management as an ecosystem-based strategy for coastal sustainability and climate resilience. The study is particularly relevant to SDG 13 (Climate Action), SDG 14 (Life Below Water), and indirectly SDG 8 (Decent Work and Economic Growth). Future research may extend this framework through empirical validation, regional adaptation, and integration with real-time environmental monitoring data to enhance its practical value for coastal governance and sustainability planning.

9. DECLARATIONS

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9.2. Author Contributions

Conceptualization, Methodology, Formal Analysis, and Writing—original draft preparation: AA and SU; Software: AA, RM, AN, and KP; Validation: AH, SS, and NP; Writing—review and editing: SU, SS, NP, AN, and IF.

9.3. Data Availability Statement

No new dataset was generated in this study. All parameter values were adopted from previously published references and are provided in the article.

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9.5. Declaration of Conflicting Interest

The authors declare that they have no conflicts of interest, known competing financial interests, or personal relationships that could have influenced the work reported in this paper.

REFERENCES

[1] S. Gössling, A. Humpe, and Y.-Y. Sun, "On track to net-zero? large tourism enterprises and climate change," *Tourism Management*, vol. 100, p. 104842, 2024.

[2] Y. Guo and Y. Chai, "Toward green tourism: the role of renewable energy for sustainable development in developing nations," *Frontiers in Sustainable Tourism*, vol. 4, p. 1512922, 2025.

[3] S. Wang, W. Ning, J. Niu, and Z. He, "Can low-carbon city pilot policy boost tourism development? empirical evidence from china," *Environmental Science and Pollution Research*, vol. 31, no. 49, pp. 58 858–58 875, 2024.

[4] L. Li, T. Awada, Y. Zhang, and K. Paustian, "Global land use change and its impact on greenhouse gas emissions," *Global Change Biology*, vol. 30, no. 12, p. e17604, 2024.

[5] S. Baltasar and T. Marbun, "The role of artificial intelligence in human capital management: A review at pt. pos indonesia," *International Journal of Cyber and IT Service Management (IJCITSM)*, vol. 5, no. 1, pp. 31–44, 2025, https://doi.org/10.34306/ijcitsm.v5i1.175.

[6] K. E. Trenberth and L. Cheng, "Earth's energy balance and the greenhouse effect," in *Reference Module in Earth Systems and Environmental Sciences*. Elsevier, 2025, [Online]. Available: https://doi.org/10.1016/B978-0-443-15748-6.00001-0.

[7] T. Xia, Z. Wang, M. Wang, and X. Hu, "Adsorption and sensing performances of greenhouse gases (co2, ch4, sf6, n2o) on ni modified gese surface," *Materials Today Communications*, vol. 40, p. 110033, 2024.

[8] A. Ochi and A. Saidi, "Impact of governance quality, population and economic growth on greenhouse gas emissions: An analysis based on a panel var model," *Journal of Environmental Management*, vol. 370, p. 122613, 2024.

[9] Y. Zhang, J. Beardall, and K. Gao, "Combined effects of ocean acidification and warming on phytoplankton productivity and community structure in the coastal water of southern east," *Marine Environmental Research*, p. 107352, 2025.

[10] K. E. Fabricius, A. Brown, C. Collier, M.-C. Pineda, B. Robson, S. Uthicke, and J. Waterhouse, "The seven sins of climate change: A review of rates of change, and quantitative impacts on ecosystems and water quality in the great barrier reef," *Marine Pollution Bulletin*, vol. 219, p. 118267, 2025.

[11] S. Alvarez, "Regenerative management of coastal tourism destinations for the anthropocene," *Journal of Travel Research*, vol. 63, no. 3, pp. 769–774, 2024.

[12] N. Xu and H. Li, "Towards management of sustainable tourism development in coastal destinations of the bohai rim: insights from a tourism carrying capacity analysis," *Discover Sustainability*, vol. 6, no. 1, p. 168, 2025.

[13] Y. Sulistyadi, R. H. Demolingo, B. S. Latif, T. Indrajaya, P. P. Adnyana, and K. Wiweka, "The implementation of integrated coastal management in the development of sustainability-based geotourism: A case study of olele, indonesia," *Sustainability*, vol. 16, no. 3, p. 1272, 2024.

[14] E. Baltranaitė, M. Inácio, L. V. Pinto, K. Bogdziewicz, J. Rocha, E. Gomes, and P. Pereira, "Tourism impacts on marine and coastal ecosystem services: A systematic review," *Geography and Sustainability*, vol. 6, no. 2, p. 100277, 2025.

[15] C. Thiagarajan and Y. Devarajan, "The urgent challenge of ocean pollution: Impacts on marine biodiversity and human health," *Regional Studies in Marine Science*, vol. 81, p. 103995, 2025.

[16] K. S. S. Atapaththu, S. S. Herath, G. Subramaniam, Y. M. A. L. W. Yapa, W. G. S. M. Kumari, K. Masakorala, B. K. K. K. Jinadasa, and M. Wu, "Challenges in coastal ecosystem sustainability: Drivers of water quality degradation and their ecological impact," *Marine Environmental Research*, vol. 209, p. 107194, 2025.

[17] M. Teng, F. Zhang, Z. Gong, and J. H. Park, "Evaluating climate adaptation strategies for coastal resilience using multi-criteria decision-making framework," *Marine Pollution Bulletin*, vol. 217, p. 118060, 2025.

[18] M. A. I. Gazi, A. Al Masud, M. K. H. Rahman, M. B. Amin, M. Emon, A. R. bin S Senathirajah, and M. Abdullah, "Sustainable embankment contribute to a sustainable economy: the impact of climate change on the economic disaster in coastal area," *Environmental Development*, vol. 55, p. 101208, 2025.

[19] A. Karditsa, S. Niavis, T. Paramana, I. Monioudi, S. Poulos, and M. Hatzaki, "Is the insular coastal tourism of western greece at risk due to climate induced sea level rise?" *Ocean & Coastal Management*, vol. 251, p. 107088, 2024.

[20] M. Chambon, N. Wambiji, S. A. Fernandez, C. Azarian, J. N. Wandiga, J. Vialard, P. Ziveri, and V. Reyes-Garcia, "Weaving scientific and local knowledge on climate change impacts in coastal kenya, western

indian ocean," *Environmental Science & Policy*, vol. 160, p. 103846, 2024.
[21] Y. Wen, Y. Tian, N. Kato, A. Ray, Ariyaningsih, and R. Shaw, "The sustainable implementation of ecosystem-based adaptation to climate change in coastal area: Lessons from indonesia," *Prevention and Treatment of Natural Disasters*, vol. 4, no. 1, 2025. [Online]. Available: https://doi.org/10.54963/ptnd.v4i1.853
[22] S. D. Sasmito, P. Taillardat, W. C. Adinugroho, H. Krisnawati, N. Novita, L. Fatoyinbo, D. A. Friess, S. E. Page, C. E. Lovelock, D. Murdiyarso, D. Taylor, and M. Lupascu, "Half of land use carbon emissions in southeast asia can be mitigated through peat swamp forest and mangrove conservation and restoration," *Nature Communications*, vol. 16, no. 1, p. 740, 2025. [Online]. Available: https://doi.org/10.1038/s41467-025-55892-0
[23] Government of the Republic of Indonesia, "Government regulation of the republic of indonesia number 27 of 2025 on the protection and management of mangrove ecosystems," 2025, accessed March 9, 2026. [Online]. Available: https://peraturan.bpk.go.id/Details/320198/pp-no-27-tahun-2025
[24] M. Mukhlis *et al.*, "Managing institutional inclusiveness in collaborative governance climate change adaptation policy in indonesia." *International Journal of Sustainable Development & Planning*, vol. 20, no. 10, 2025.
[25] W. S. Dong, A. Ismailluddin, L. S. Yun, E. H. Ariffin, C. Saengsupavanich, K. N. A. Maulud, M. Z. Ramli, M. F. Miskon, M. H. Jeofry, J. Mohamed *et al.*, "The impact of climate change on coastal erosion in southeast asia and the compelling need to establish robust adaptation strategies," *Heliyon*, vol. 10, no. 4, 2024.
[26] B. Choudhary, V. Dhar, and A. S. Pawase, "Blue carbon and the role of mangroves in carbon sequestration: Its mechanisms, estimation, human impacts and conservation strategies for economic incentives," *Journal of Sea Research*, vol. 199, p. 102504, 2024.
[27] Y. Ji, Z. Shao, and R. Wang, "Does industrial symbiosis improve carbon emission efficiency? evidence from chinese national demonstration eco-industrial parks," *Sustainability*, vol. 16, no. 2, p. 828, 2024.
[28] S. Ali, G. Dey, N. H. K. Nuong, A. Rahman, L.-C. Wang, U. Sukul, K. Das, R. K. Sharma, S.-L. Wang, and C. Y. Chen, "Carbon sequestration in mangrove ecosystems: Sources, transportation pathways, influencing factors, and its role in the carbon budget," *Earth-Science Reviews*, vol. 269, p. 105184, 2025.
[29] I. M. Carneiro, M. T. M. de Széchy, I. Bertocci, and P. C. Paiva, "Impact of a nuclear power station effluent on marine forests: A case study in se brazil and insights for global warming scenarios," *Environmental Pollution*, vol. 344, p. 123323, 2024.
[30] S. Vaz, S. Manes, G. Khattar, M. Mendes, L. Silveira, E. Mendes, E. de Morais Rodrigues, D. Gama-Maia, M. L. Lorini, M. Macedo *et al.*, "Global meta-analysis of urbanization stressors on insect abundance, richness, and traits," *Science of the Total Environment*, vol. 903, p. 165967, 2023.
[31] H. Ray, N. Das, S. Pal, S. C. Pal, and S. Mandal, "Predicting the potential habitat suitability of mangrove bioindicator species-telescopium telescopium (linnaeus, 1758) through maxent modelling," *Regional Studies in Marine Science*, vol. 83, p. 104073, 2025.
[32] D. Juliastuti, R. Royani, I. Farida, I. N. Hikam, and A. Garcia, "Empowerment through information: How ai-driven education impacts decision-making autonomy in fertility treatment," *IAIC Transactions on Sustainable Digital Innovation (ITSDI)*, vol. 6, no. 2, pp. 196–204, 2025.
[33] T. Hartono, B. N. Henry, S. Nurm, L. Pasha, and D. Julianingsih, "The importance increasing attendance efficiency accuracy with presence system in era industrial revolution 4.0," *International Journal of Cyber and IT Service Management (IJCITSM)*, vol. 4, no. 2, pp. 133–142, 2024, https://doi.org/10.34306/ijcitsm.v4i2.168.
[34] M. Mohd-Din, K. S. Hii, N. S. Kassim, N. F. M. Azmi, S. N. Baharudin, H. Gu, C. P. Leaw, and P. T. Lim, "Diversity and distribution of micro-phytoplankton and harmful microalgae along the malaysian coasts of malacca strait and south china sea," *Regional Studies in Marine Science*, vol. 81, p. 103947, 2025.
[35] P. Kaiser, W. Hagen, A. Schukat, K. Metfies, J. Biederbick, S. Dorschner, and H. Auel, "Phytoplankton diversity and zooplankton diet across fram strait: Spatial patterns with implications for the future arctic ocean," *Progress in Oceanography*, vol. 234, p. 103423, 2025.
[36] C. Zhou, D. Liu, J. Keesing, P. Masqué, and Z. Yuan, "Distinguishing impacts of climate change and human activities on phytoplankton communities in remote coastal waters: A paleoecological perspective," *Marine Pollution Bulletin*, vol. 217, p. 118057, 2025.
[37] N. Lutfiani, S. Wijono, U. Rahardja, A. Iriani, Q. Aini, and R. A. D. Septian, "A bibliometric study:

Recommendation based on artificial intelligence for ilearning education," *Aptisi Transactions on Technopreneurship (ATT)*, vol. 5, no. 2, pp. 109–117, 2023, https://doi.org/10.34306/att.v5i2.279.

[38] R. Y. Chenavaz, M. Leocata, M. Ogonowska, and D. Torre, "Sustainable tourism," *Journal of Economic Dynamics and Control*, vol. 143, p. 104483, 2022.

[39] K. D. Hartomo, D. Manongga, A. S. Rafika, D. Julianingsih, and Z. Nanle, "Ethical governance of health data in the age of artificial intelligence," *Health, Empathy, and AI Learning (HEAL)*, vol. 1, no. 1, pp. 42–49, 2025.

[40] I. Fitria, S. Subchan, D. A. Maulina, and A. A. Hidayatullah, "Analysis and existence of rumor spreading with campaign and punishment control," *Nonlinear Dynamics and Systems Theory*, vol. 24, no. 4, pp. 380–391, 2024.

[41] U. Rahardja, P. A. Sunarya, Q. Aini, S. Millah, and S. Maulana, "Technopreneurship in healthcare: Evaluating user satisfaction and trust in ai-driven safe entry stations," *Aptisi Transactions on Technopreneurship (ATT)*, vol. 6, no. 3, pp. 404–417, 2024, https://doi.org/10.34306/att.v6i3.489.

[42] S. Mandal, M. Islam, and M. Biswas, "Modeling the impact of carbon dioxide on marine plankton," *Int. J. Math. Comput. Sci*, vol. 14, pp. 197–202, 2020, accessed March 9, 2026.

[43] S. Mandal, M. S. Islam, and M. H. A. Biswas, "Modeling and analytical analysis of the effect of atmospheric temperature to the planktonic ecosystem in oceans," in *Applications of Internet of Things: Proceedings of ICCCIOT 2020*. Springer, 2020, pp. 131–140, accessed March 9, 2026.

[44] S. Mandal, M. S. Islam, M. H. A. Biswas, and S. Akter, "A mathematical model applied to investigate the potential impact of global warming on marine ecosystems," *Applied Mathematical Modelling*, vol. 101, pp. 19–37, 2022.

[45] S. Mandal, M. S. Islam, M. H. A. Biswas, and S. Islam, "Modeling with strategies to control the adverse effects of global warming on marine ecosystems," *Modeling Earth Systems and Environment*, vol. 8, no. 3, pp. 3073–3088, 2022.

[46] A. Jana, A. Das, and S. K. Roy, "Climate change and the shifting dynamics of marine ecology," *Ecological Complexity*, vol. 63, p. 101137, 2025.

[47] U. Rusilowati, U. Narimawati, Y. R. Wijayanti, U. Rahardja, and O. A. Al-Kamari, "Optimizing human resource planning through advanced management information systems: A technological approach," *Aptisi Transactions on Technopreneurship (ATT)*, vol. 6, no. 1, pp. 72–83, 2024, https://doi.org/10.34306/att.v6i1.390.

[48] P. R. Chowdhury, M. Banerjee, and S. Petrovskii, "A two-timescale model of plankton–oxygen dynamics predicts formation of oxygen minimum zones and global anoxia," *Journal of Mathematical Biology*, vol. 89, no. 1, p. 8, 2024.

[49] B. Ma, F. Dong, W. Peng, X. Liu, and A. Huang, "Dynamics of oxygen evolution in a thermally stratified reservoir under climate warming," *Scientific Reports*, vol. 15, no. 1, p. 40419, 2025.

[50] M. Farman, R. Sarwar, E. Hincal, D. Baleanu, K. S. Nisar, A. Sambas, and M. M. Akram, "Dynamical evaluation of the mittag-leffler properties-based marine ecosystem model: M. farman et al." *Earth Systems and Environment*, vol. 10, no. 1, pp. 643–661, 2026.

[51] W. Fleming and R. Rishel, "Optimal control of markov diffusion processes," in *Deterministic and Stochastic Optimal Control*. Springer, 1975, pp. 151–197, accessed March 9, 2026.

[52] R. Haris, A. Kho, E. A. Nabila, N. S. Arasid, and A. A. Kamal, "Emotion-aware digital health platforms supporting psychological well-being through positive computing approaches," *Journal of Orange Technology*, vol. 2, no. 2, pp. 59–70, 2026.

[53] U.S. Environmental Protection Agency, "Dissolved oxygen (do) factsheet," https://www.epa.gov/system/files/documents/2021-07/parameter-factsheet_do.pdf, 2021, accessed March 9, 2026.

[54] E.-S. Khater, A. Bahnasawy, H. El-Ghobashy, Y. Shaban, F. Elsheikh, S. A. El-Reheem, and M. Aboegela, "Mathematical model for predicting oxygen concentration in tilapia fish farms," *Scientific reports*, vol. 11, no. 1, p. 24130, 2021, accessed March 9, 2026.