HEALTH, ENVIRONMENT, AND RESILIENCE:

SUSTAINABILITY AND EPIDEMIOLOGICAL STUDIES

ISBN:
978-625-91915-0-8

HEALTH, ENVIRONMENT, AND RESILIENCE: SUSTAINABILITY AND EPIDEMIOLOGICAL STUDIES- 2026

ISBN: 978-625-91915-0-8

DOI: 10.5281/zenodo.21194829

July / 2026

Ankara / Türkiye

(The Licence Number of Publicator: 2014/31220)

E mail: info@ispecbooks.com

www.ispecbooks.com

It is responsibility of the author to abide by the publishing ethics rules.

ISPEC Publishing House – 2026©

ISBN: 978-625-91915-0-8

July / 2026

Ankara / Türkiye

HEALTH, ENVIRONMENT, AND RESILIENCE: SUSTAINABILITY AND EPIDEMIOLOGICAL STUDIES

AUTHORS
Tihan Mihaela LAURA
Tihan Eusebiu JEAN
Sodiq Adetunji ADEKOLA
Zainab Oyefunke OYERINDE
Janet Kikelomo OLADEJO
Temitayo Olabisi OLUYO
Olusola Akintunde ODEBIYI
Wasiu Olaitan LAWAL
Olajide OLAOYE
Jeremiah Yetomiwa SINAT

TABLE OF CONTENTS

PREFACE

Environmental change, public health, and social wellbeing are increasingly interconnected in contemporary research. Ecological crises, digital transformation, and the continuing impact of infectious diseases require interdisciplinary approaches that consider environmental conditions, community resilience, technological developments, and health-related risks together.

The chapters in this volume examine selected issues at the intersection of environmental studies and health sciences. The first chapter explores the psychosocial dimensions of the ecological crisis, focusing on community vulnerability, resilience, and adaptation. The second chapter discusses the relationship between digital health and environmental sustainability from an environmental studies perspective. The third chapter examines HIV/AIDS dynamics in the context of infective immigration, with attention to stability, bifurcation, efficiency, and cost-effectiveness analysis.

By bringing together social, environmental, technological, and epidemiological perspectives, this volume highlights the multidimensional nature of contemporary health and sustainability challenges. The studies demonstrate the importance of integrated research in understanding ecological change, strengthening community resilience, and supporting effective responses to public health concerns.

It is hoped that this book will serve as a useful academic resource for researchers, students, professionals, and scholars interested in environmental studies, public health, sustainability, epidemiology, and related interdisciplinary fields. We extend our sincere appreciation to all contributing authors for their valuable scholarly efforts.

Editorial Team
July 2026, Türkiye

CHAPTER 1
THE PSYCHOSOCIAL DIMENSIONS OF THE ECOLOGICAL CRISIS: COMMUNITY VULNERABILITY, RESILIENCE, AND ADAPTATION IN CONTEMPORARY ENVIRONMENTAL STUDIES

[1]Tihan Mihaela LAURA
[2]Tihan Eusebiu JEAN

[1]Tihan and Associates. Professional Civil Society of Psychology, Bucharest Romania, Independent researchers, ORCID ID: 0009-0003-1820-1417
[2]Tihan and Associates. Professional Civil Society of Psychology, Bucharest Romania Independent researcher, eusebiu.tihan@gmail.com, ORCID ID: 0009-0008-8316-3679

INTRODUCTION

The global ecological crisis represents one of the most complex and urgent challenges of the twenty-first century. Climate change, biodiversity loss, pollution, and ecosystem degradation are not merely physical or biological phenomena—they have profound consequences for human well-being, social cohesion, and community stability. Environmental studies, as an interdisciplinary field, has evolved significantly over the past decades to include not only natural sciences but also perspectives from sociology, psychology, anthropology, economics, and political science, recognizing that environmental problems are inseparable from human factors and social structures.

This chapter examines the psychosocial impact of the ecological crisis on communities worldwide, integrating recent research from environmental studies to understand how environmental degradation affects mental health, social cohesion, cultural identity, and collective adaptive capacity. It also analyzes intervention strategies, policy frameworks, and community-based responses that can support populations facing ecological challenges. The chapter is structured into six main sections: the relationship between environmental factors and human well-being; vulnerable communities and environmental justice; community responses to ecological crisis; public policies and interventions; integrated strategies for sustainability; and future directions in environmental studies.

Current research indicates that the psychological impact of environmental changes is significant and increasing. A 2024 global study involving 15,000 participants across twelve countries found that 67% of respondents report moderate to severe levels of climate-related anxiety, with these levels being highest among young people aged sixteen to twenty-five and among communities directly affected by ecological disasters. Additionally, communities facing forced displacement due to environmental factorscommonly termed climate refugees experience complex trauma requiring integrated responses from environmental specialists, mental health professionals, social workers, and policy makers.

The World Health Organization has identified climate change as the greatest threat to global health in the twenty-first century, with impacts ranging from increased mortality from extreme weather events to the spread of infectious diseases and widespread mental health consequences.

1. THE RELATIONSHIP BETWEEN ENVIRONMENTAL FACTORS AND HUMAN WELL-BEING

Environmental studies have consistently demonstrated that the relationship between people and their environment is not merely utilitarian focused on resource extraction and consumption but profound, multidimensional, and constitutive of human identity and well-being. This section examines the various dimensions through which environmental factors impact human communities and explores key concepts for understanding ecological distress.

1.1. Dimensions of Ecological Impact on Communities

The impact of the ecological crisis on communities can be analyzed across several interconnected dimensions that together shape the lived experience of environmental change. Understanding these dimensions is essential for developing effective interventions and policies.

Physical dimension: Environmental degradation directly affects physical health through air and water pollution, exposure to toxic substances, and increased incidence of climate-related diseases. The World Health Organization estimates that climate change will cause approximately 250,000 additional deaths annually between 2030 and 2050, due to malnutrition, malaria, diarrhea, and heat stress. Air pollution alone is responsible for an estimated seven million premature deaths each year, with the highest burdens falling on low- and middle-income countries. The physical impacts extend beyond mortality to include morbidity, reduced quality of life, and increased healthcare costs that strain already limited resources in vulnerable communities.

Psychological dimension: Exposure to ecological disasters and environmental degradation generates significant psychological distress.

Longitudinal studies show increased rates of depression, anxiety, post-traumatic stress disorder, and substance use disorders in communities affected by hurricanes, floods, wildfires, and droughts. The psychological impacts are often long-lasting, with survivors of major disasters showing elevated rates of mental health problems for years after the event. Beyond acute disasters, chronic environmental stressors such as persistent drought, gradual ecosystem degradation, and living in contaminated areas take a cumulative toll on mental health that is often overlooked in both research and policy.

Social dimension: The ecological crisis can erode social cohesion through multiple mechanisms: community displacement fragments social networks; loss of jobs in sectors dependent on natural resources undermines economic stability; and increased competition for scarce resources particularly water and arable land exacerbates existing social tensions and can lead to conflict. Research in the Sahel region of Africa has documented how drought and desertification contribute to conflicts between herders and farmers, as traditional grazing lands shrink and water sources become scarce. Similar dynamics are observed in other regions facing environmental stress, including parts of South Asia, Latin America, and the Middle East.

Cultural dimension: For many communities, especially indigenous and traditional ones, the natural environment is inseparable from cultural identity, spiritual practices, and ways of life transmitted across generations. When places of cultural significance are degraded or destroyed, communities lose not only physical resources but also the symbolic and spiritual anchors that give meaning to their existence. This cultural dimension of ecological loss is particularly significant for indigenous peoples, who comprise less than five percent of the global population but protect approximately eighty percent of the world's remaining biodiversity.

1.2. The Concept of Ecological Distress

Recent research in environmental psychology and related fields has developed the concept of ecological distress to describe the psychological and emotional responses to environmental degradation. This concept encompasses a range of experiences including grief, anxiety, helplessness, and despair in the face of ecological loss.

Solastalgia, a term introduced by philosopher Glenn Albrecht in 2005, describes the distress caused by negative environmental changes in one's home place—a kind of homesickness experienced without leaving home. Unlike nostalgia, which is longing for a place or time in the past, solastalgia is the pain experienced when one's present environment is despoiled. The term combines the Latin word solacium meaning comfort and the Greek root -algia meaning pain, capturing the experience of losing the comfort provided by one's home environment. Albrecht developed the concept while studying communities in Australia's Hunter Valley affected by large-scale open-cut coal mining, finding that residents experienced profound distress as their familiar landscape was transformed even though they remained physically in place.

Solastalgia manifests through several characteristic experiences: feelings of loss and helplessness in the face of familiar landscape transformation; mourning for species and ecosystems that have been degraded or destroyed; anticipatory anxiety about future losses; erosion of the sense of home and belonging; diminished sense of identity and connection to place; and despair about the future of one's community and way of life. Studies conducted in communities affected by mining operations, deforestation, prolonged drought, and coastal erosion have confirmed the prevalence of this phenomenon and underscored the need for its integration into environmental impact assessments and mental health services.

Climate grief is a related concept that describes the mourning response to climate-related losses, including the disappearance of species, ecosystems, landscapes, and ways of life. Unlike conventional grief, which typically follows a clear loss and has culturally established rituals for processing, climate grief is often anticipatory, diffuse, and lacks social recognition or ritual structures. This can complicate the grieving process and leave individuals and communities struggling with unacknowledged and unsupported emotional responses to ecological loss.

1.3. Climate Anxiety and Pre-Traumatic Stress

Climate anxiety, also known as eco-anxiety, has emerged as a significant mental health concern in recent years, particularly among young people.

The American Psychological Association defines eco-anxiety as a chronic fear of environmental doom. Unlike post-traumatic stress, which is a reaction to past events, climate anxiety can be understood as a form of pre-traumatic stress the anxiety of anticipating future loss and catastrophe.

Research across multiple countries has documented high levels of climate anxiety. A landmark global survey of ten thousand young people aged sixteen to twenty-five across ten countries found that fifty-nine percent were very or extremely worried about climate change, and eighty-four percent were at least moderately worried. More than forty-five percent of respondents said their feelings about climate change negatively affected their daily life and functioning. A follow-up study conducted in 2024 found that these levels had increased, with sixty-seven percent now reporting moderate to severe climate anxiety.

Climate anxiety manifests in various ways: generalized dread involving a persistent, low-grade sense of unease about the future; intrusive thoughts characterized by recurrent, unwanted thoughts about climate change and ecological collapse; climate grief involving mourning for lost or dying species, landscapes, and ways of life; existential despair involving questioning the meaning and purpose of life in the face of possible civilizational collapse; avoidance behaviors involving avoiding news or discussions about climate change to manage distress; and activism as coping, where individuals channel anxiety into environmental action as a way of regaining agency.

The prevalence of climate anxiety has significant implications for mental health services, education, and public policy. Mental health professionals are increasingly recognizing the need to address climate-related distress in their practices, developing new therapeutic approaches that validate ecological concerns while helping clients maintain hope and agency. Schools and universities are developing curricula that help students understand and cope with their feelings about climate change while maintaining hope and engagement .

2. VULNERABLE COMMUNITIES AND ENVIRONMENTAL JUSTICE

A central concept in contemporary environmental studies is environmental justice the recognition that ecological burdens are unequally distributed, disproportionately affecting marginalized and disadvantaged communities. This section examines the patterns of environmental inequality and their consequences for vulnerable populations, illustrating these dynamics through case studies.

2.1. Ecological Inequalities

Research consistently documents that environmental risks and benefits are distributed unequally across populations, with marginalized groups bearing a disproportionate share of environmental burdens while enjoying fewer of the benefits of environmental protection and resource access.

Socioeconomic disparities: Low-income communities and minority groups are significantly more likely to live near sources of pollution, including industrial facilities, waste sites, major highways, and other environmental hazards. This pattern, documented in numerous studies across developed and developing countries, reflects historical patterns of discrimination, land use decisions that site undesirable facilities in less politically powerful communities, and housing markets that make polluted areas more affordable to low-income residents. The health consequences of this unequal exposure are significant and well-documented: elevated rates of asthma, cancer, cardiovascular disease, and other conditions in communities near polluting facilities. Children in these communities are particularly vulnerable, with higher rates of respiratory problems, developmental issues, and other health impacts.

Global disparities: Developing countries, while contributing the least to historical and current greenhouse gas emissions, are most affected by the impacts of climate change [29]. These countries are often located in regions more vulnerable to climate impacts such as extreme heat, drought, flooding, and sea-level rise. They also have fewer resources to invest in adaptation measures, leaving their populations more exposed to climate risks.

The injustice of this situation is compounded by the fact that developed countries, which have benefited most from the fossil fuel-based economic development that caused climate change, have been slow to provide the financial and technical support needed by developing countries for adaptation and mitigation.

Gender dimensions: Women, children, and the elderly face greater risks in ecological disasters. Women in developing countries often bear primary responsibility for food, water, and fuel collection, making them more vulnerable to environmental scarcity. In disaster situations, women face higher mortality rates due to factors including limited mobility, caregiving responsibilities, and less access to warning information and resources. Children are particularly vulnerable to the health impacts of environmental degradation, including air pollution, contaminated water, and heat exposure, and the long-term consequences of early exposure can affect health throughout their lives [32]. The elderly face increased risks from heat waves and other extreme events, compounded by higher rates of chronic health conditions and social isolation.

Indigenous peoples: Indigenous communities, which protect approximately eighty percent of the planet's remaining biodiversity, are often displaced for conservation projects or resource extraction. These displacements violate indigenous rights, disrupt traditional livelihoods, and sever the cultural connections to ancestral lands that are fundamental to indigenous identity and well-being. Despite these challenges, indigenous communities are also at the forefront of environmental protection, developing innovative approaches to conservation that integrate traditional knowledge with modern science and advocating for rights-based approaches to environmental governance.

2.2. Case Study: The Niger Delta

The Niger Delta in Nigeria provides a dramatic and well-documented example of the cumulative impact of environmental degradation on a community over decades. The region, home to extensive oil reserves, has been the site of continuous oil extraction since the 1950s, with devastating environmental and social consequences that illustrate the interconnected dimensions of ecological impact.

Decades of oil extraction have led to widespread contamination of soil and water with hydrocarbons, with some estimates suggesting that the Niger Delta has experienced the equivalent of an Exxon Valdez spill every year for decades. Cleanup efforts have been consistently inadequate, and contamination persists in many areas, affecting both ecosystems and human populations. The contamination has destroyed fisheries and agricultural lands that provided livelihoods for millions of people. Fishing communities have seen their catches decline dramatically, while farmers struggle with degraded soils and contaminated water sources, leading to food insecurity, economic hardship, and loss of traditional livelihoods.

Health impacts in the region are severe and well-documented. Studies document increased rates of cancer, birth defects, respiratory diseases, and other health problems in communities near oil facilities. Exposure to oil-related pollutants has been linked to a range of health issues, and healthcare infrastructure in the region is inadequate to address these needs. Environmental degradation has displaced communities and contributed to violent conflicts. The competition for remaining resources, combined with grievances over the distribution of oil wealth, has fueled insurgency and military responses that have further traumatized the population and undermined social cohesion .

The destruction of the environment has also meant the loss of cultural practices and identity tied to the land and water. Traditional fishing and farming practices, along with the knowledge and social structures associated with them, have been eroded, contributing to cultural loss and identity disruption. Research conducted in the region documents alarming levels of depression, anxiety, and PTSD in the population, as well as an erosion of trust in institutions and community cohesion. The psychological impacts are compounded by the chronic nature of the crisis rather than a single traumatic event, communities face ongoing exposure to pollution, economic hardship, and violence over decades.

2.3. Climate Refugees and Displacement

One of the most pressing aspects of the ecological crisis is the phenomenon of forced displacement caused by environmental factors.

The term climate refugee is not formally recognized in international law, which defines refugees as persons fleeing persecution, but it captures the reality of people forced to leave their homes due to environmental changes that make their places of residence uninhabitable or unable to support livelihoods.

Scale of displacement: The World Bank estimates that by 2050, over two hundred million people could be internally displaced due to climate change in six world regions alone. This estimate does not include cross-border movement, which would add significantly to the total. The Internal Displacement Monitoring Centre reports that weather-related disasters already displace an average of twenty million people each year, a figure that has been increasing steadily over the past decade.

Causes of displacement: Environmental displacement results from multiple factors operating at different temporal scales. Sudden-onset events including floods, storms, and wildfires can destroy homes and communities, forcing immediate evacuation and often leading to permanent displacement when return is not possible. Slow-onset changes including sea-level rise, drought, desertification, and ecosystem degradation gradually make areas uninhabitable or unable to support livelihoods, leading to voluntary or forced migration over longer periods. Government policies including resettlement programs related to development projects, conservation areas, or climate adaptation measures can also displace communities, sometimes with inadequate consultation or compensation.

Consequences of displacement: Forced displacement due to environmental factors generates multiple and interconnected challenges. Displaced persons lose not only their physical shelter but also their means of earning a living, particularly when displacement separates them from agricultural land, fisheries, or other resource-based livelihoods. The experience of displacement, combined with the losses that preceded it, creates complex psychological trauma requiring mental health support that is rarely available. Displacement fragments communities and social networks, eroding the social capital that provides support and resilience. Displaced persons often face challenges integrating into host communities, leading to marginalization, discrimination, and conflict.

For communities with strong ties to specific places, displacement means the loss of cultural identity and practices tied to those places. Indigenous communities are particularly affected, as their identities and cultures are intimately connected to ancestral territories.

Legal and policy gaps: The lack of international legal protection for persons displaced across borders due to environmental factors leaves them in a precarious situation. They do not qualify as refugees under the 1951 Refugee Convention, and few countries have policies specifically addressing climate-related migration. This gap has led to calls for new legal frameworks, including proposals for a protocol on climate displacement to the United Nations Framework Convention on Climate Change and regional agreements such as the Framework for Climate Mobility developed by the Pacific Islands Forum .

3. COMMUNITY RESPONSES TO THE ECOLOGICAL CRISIS

In the face of ecological challenges, communities worldwide are developing innovative responses that combine traditional knowledge with modern science and collective action. This section examines the concept of community resilience and provides case studies of effective community-based responses.

3.1. Community Resilience

The concept of community resilience has become central in environmental studies, referring to a community's capacity to anticipate, prepare for, respond to, and recover from environmental disturbances . Unlike individual resilience, which focuses on personal characteristics, community resilience emphasizes the collective capacities and resources that enable communities to withstand and adapt to challenges.

Social capital: Strong relationship networks, mutual trust, and norms of reciprocity facilitate collective action in the face of crises. Communities with dense social networks can mobilize resources more effectively, share information quickly, and provide mutual support during and after disasters.

Social capital has been shown to be one of the strongest predictors of recovery speed and quality following disasters, often more important than material resources or external assistance. Social capital operates at multiple levels: bonding capital refers to ties within communities; bridging capital refers to ties between communities; and linking capital refers to ties to institutions and power holders. All three forms contribute to resilience, enabling communities to draw on internal resources, learn from others' experiences, and access external support.

Local and traditional knowledge: Communities with deep understanding of local ecosystems are better prepared to respond to environmental changes. This knowledge, accumulated over generations of interaction with specific environments, includes understanding of weather patterns, resource cycles, ecological relationships, and sustainable practices that can inform adaptation strategies. Traditional ecological knowledge is particularly valuable in contexts of climate change, where local observations can complement scientific data and provide insights into changes that may not be captured by remote sensing or regional models. Indigenous and local knowledge systems also often embody adaptive management approaches that have proven sustainable over long periods and can offer lessons for contemporary adaptation efforts.

Economic diversification: Communities that do not depend exclusively on a single resource or economic sector are less vulnerable to ecological shocks. Diversification spreads risk across multiple activities, so that the failure of one resource or market does not devastate the entire community. This may involve developing multiple livelihood strategies, maintaining access to diverse resources, building connections to multiple markets, and investing in education and skills that enable economic flexibility. In coastal communities, for example, diversification might include combining fishing with tourism, aquaculture, small-scale manufacturing, and remittances from family members working elsewhere. Agricultural communities may diversify crops, integrate livestock, develop off-farm income sources, and participate in value-added processing to reduce dependence on raw commodity prices vulnerable to climate impacts.

Participatory governance: Including communities in decision-making processes related to the environment enhances the legitimacy and effectiveness of adaptation measures.

When communities have a voice in decisions that affect them, they are more likely to support and comply with those decisions, and local knowledge can inform better outcomes. Participatory approaches range from consultation and advisory bodies to community-based natural resource management and co-management arrangements where communities share authority with government agencies. Research suggests that higher levels of community participation lead to more sustainable outcomes, greater community satisfaction, and reduced conflict over resource management decisions.

Ecological infrastructure: Investments in green spaces, sustainable water management, and renewable energy enhance adaptive capacity while providing multiple co-benefits. Ecological infrastructure the network of natural and semi-natural areas that provide ecosystem services can buffer communities against environmental shocks while improving quality of life. Urban green spaces, for example, reduce heat island effects, absorb stormwater, improve air quality, provide recreational opportunities, and support mental health. Restored wetlands protect against flooding while supporting biodiversity and water purification. These nature-based approaches often prove more cost-effective and resilient than engineered solutions, while providing additional benefits that engineered solutions do not.

3.2. Case Study: The Green Belt Movement in Kenya

A remarkable example of community action in the face of environmental degradation is the Green Belt Movement in Kenya, founded by Wangari Maathai, who was awarded the Nobel Peace Prize in 2004 for her contribution to sustainable development, democracy, and peace. The movement mobilized communities, especially women, to plant trees, combating deforestation, soil erosion, and poverty while empowering women and strengthening civil society.

The Green Belt Movement began in 1977 as a small project of the National Council of Women of Kenya. Maathai, a biologist and environmental activist, recognized that rural women were bearing the burden of environmental degradation—walking longer distances for firewood, struggling with eroded soils, and facing declining water quality.

Tree planting offered a practical solution that addressed multiple problems simultaneously while engaging women as agents of change rather than passive victims of environmental degradation.

The movement's approach was simple but powerful: women's groups were provided with seeds and seedlings, training in nursery establishment and tree care, and a small stipend for their work. In return, they planted trees on their own farms and in community forests, restoring degraded lands while meeting their own needs for fuel, fodder, and food. Over more than four decades, the Green Belt Movement has achieved remarkable results. Over fifty million trees have been planted across Kenya, restoring degraded forests, protecting watersheds, and enhancing biodiversity. The movement has established thousands of community tree nurseries and trained communities in sustainable land management practices.

The movement has empowered women by providing them with income, skills, and organizational capacity. Women who participated gained confidence, developed leadership skills, and became advocates for environmental protection in their communities. The movement's emphasis on women's leadership challenged traditional gender roles and contributed to broader social change. Trees planted provide fuelwood, timber, fruits, and other products that directly benefit households. Improved environmental conditions support agriculture and livestock, enhancing food security and income. The stipends paid for tree planting provide direct economic benefits to participants.

The Green Belt Movement has evolved beyond tree planting to become a force for democratic participation and environmental governance. It has advocated for forest protection, opposed land grabbing, and promoted transparency and accountability in natural resource management. Maathai's activism, including campaigns against a proposed skyscraper in Nairobi's Uhuru Park and against land allocation in forest reserves, demonstrated the movement's commitment to environmental justice and democratic participation. The movement has inspired similar initiatives across Africa and beyond, demonstrating that grassroots action can achieve significant environmental and social impact even in contexts of weak governance and limited resources.

3.3. Case Study: Ecosystem-based Adaptation in the Pacific

Pacific Island nations face existential threats from climate change, including sea-level rise, intensified cyclones, ocean acidification, and changing rainfall patterns. These threats jeopardize not only the physical existence of island nations but also the cultural identity and way of life of Pacific peoples. In response, communities, civil society organizations, and governments have developed innovative approaches to adaptation that integrate traditional knowledge with modern science and emphasize ecosystem-based solutions.

Pacific Island countries are among the most vulnerable in the world to climate change impacts. Many islands are low-lying, with average elevations of just a few meters above sea level. Populations are concentrated in coastal areas, and economies depend heavily on natural resources. Traditional knowledge and practices are closely tied to the marine and coastal environment. Climate impacts already being experienced include coastal erosion and inundation from sea-level rise; damage to infrastructure and crops from more intense cyclones; coral bleaching from ocean warming, threatening fisheries and coastal protection; saltwater intrusion into freshwater lenses, affecting water supplies and agriculture; and changes in rainfall patterns affecting food production.

In response to these challenges, Pacific communities have developed adaptation strategies that emphasize the protection and restoration of ecosystems as a foundation for resilience. These approaches recognize that healthy ecosystems provide essential services that protect communities and support livelihoods. Key elements of ecosystem-based adaptation in the Pacific include mangrove restoration for coastal protection; coral reef conservation through marine protected areas and sustainable fishing practices; climate-resilient agriculture maintaining traditional crop diversity; integration of traditional knowledge with scientific information; community-based early warning systems; and regional cooperation on climate mobility.

The Pacific experience offers important lessons for adaptation globally: adaptation must be locally appropriate and community-driven, building on local knowledge and priorities; ecosystem-based approaches provide multiple benefits and are often more sustainable than engineered solutions; traditional knowledge is a valuable resource for adaptation that should be respected and integrated; regional cooperation is essential for addressing challenges that cross national boundaries; and adaptation and cultural preservation are interconnected goals that must be pursued together.

4. PUBLIC POLICIES AND INTERVENTIONS IN ENVIRONMENTAL STUDIES

Environmental studies are not limited to diagnosing problems but also propose research-based solutions for public policies and practical interventions. This section examines key policy instruments and intervention approaches for addressing environmental challenges and supporting affected communities.

4.1. Environmental and Health Impact Assessment

Environmental impact assessments have evolved significantly since their introduction in the 1970s, expanding from a narrow focus on biophysical impacts to encompass social, economic, and health dimensions. Health impact assessments have emerged as a complementary tool specifically focused on health consequences.

Environmental impact assessment is a process for evaluating the likely environmental impacts of a proposed project or development, taking into account interrelated socio-economic, cultural, and human-health impacts, both beneficial and adverse. The goal is to ensure that decision-makers consider environmental impacts before approving projects and to identify measures for avoiding, minimizing, or mitigating adverse impacts. Modern EIA practice incorporates scoping to identify key issues and impacts; baseline studies documenting existing environmental conditions; impact prediction estimating the nature, magnitude, and significance of impacts; mitigation measures to avoid, reduce, or compensate for impacts; public participation ensuring affected communities have input into the process; and monitoring and follow-up tracking actual impacts and compliance with mitigation measures.

Health impact assessment is a practical approach for assessing the potential health effects of policies, programs, and projects before they are implemented. It aims to influence decision-making to maximize positive health impacts and minimize negative ones, with particular attention to health equity and vulnerable populations. HIAs are increasingly used to identify vulnerable populations before project implementation, ensuring that their needs and concerns are addressed; estimate the health costs of pollution and environmental degradation, providing information for cost-benefit analysis; propose mitigation and compensation measures tailored to specific health risks; ensure community participation in decision-making processes; and build health considerations into project design from the outset rather than treating them as an afterthought.

A 2025 report by the European Environment Agency emphasizes that integrating health into environmental policies could reduce healthcare system costs by up to twenty percent in the next decade while improving population health and well-being. The report calls for stronger integration of health considerations into all environmental policy areas, from air quality to climate adaptation, and for greater collaboration between environmental and health agencies at all levels of government.

4.2. Adaptation and Mitigation Policies

Effective environmental policies combine measures for adaptationadjusting to the inevitable effects of climate change and mitigation reducing greenhouse gas emissions to limit future change. Both are essential components of a comprehensive response to the ecological crisis. Adaptation involves adjusting to actual or expected climate change and its effects, seeking to moderate harm or exploit beneficial opportunities. Adaptation can be reactive, responding to impacts as they occur, or anticipatory, taking action before impacts are felt. Examples of adaptation policies include climate-resilient planning that considers climate risks in urban and regional development; early warning systems for predicting and communicating information about impending hazards; disaster insurance mechanisms that help communities recover from losses.

Economic diversification programs supporting transition away from climate-sensitive sectors; and ecosystem protection and restoration that maintains natural buffers against climate impacts.

Mitigation involves reducing greenhouse gas emissions to limit the extent of future climate change. The goal of mitigation is to stabilize greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system. Examples of mitigation policies include renewable energy transition through feed-in tariffs, renewable portfolio standards, and tax incentives; energy efficiency measures in buildings, industry, and transportation; forest protection and afforestation to maintain and enhance carbon sinks; circular economy approaches minimizing waste and maximizing resource efficiency; and carbon pricing through taxes or emissions trading systems creating economic incentives for emission reductions.

The effectiveness of mitigation policies depends on their design, implementation, and integration with other policy areas. The Intergovernmental Panel on Climate Change emphasizes that deep emission reductions will require policy packages that combine multiple instruments and address barriers to change across all sectors of the economy.

4.3. Community Participation and Environmental Democracy

A fundamental principle of contemporary environmental studies is that effective policies require authentic participation of affected communities. Environmental democracy the idea that citizens should have a voice in environmental decisions that affect them has become a guiding principle in environmental governance.

The Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters, adopted in 1998 under the auspices of the United Nations Economic Commission for Europe, establishes three pillars of environmental democracy. Access to information means the right of citizens to access environmental information held by public authorities, including information about the state of the environment, policies and measures affecting it, and the state of human health and safety where affected by environmental conditions.

Public participation in decision-making means the right to participate in environmental decision-making processes, including decisions on specific activities, plans and programs, and policies and legislation. Access to justice means the right to challenge decisions that violate environmental law or that fail to respect the rights of information and participation.

Research shows that adherence to these principles leads to better decisions, reduced conflicts, and increased trust in institutions. Specific benefits include better information as local communities often possess detailed knowledge not available to experts; more legitimate decisions that communities are more likely to accept and comply with; social learning creating shared understanding of problems and solutions; empowerment building community capacity to engage in governance; and accountability through public scrutiny.

4.4. Case Study: European Union Environmental Policy

The European Union has developed some of the most ambitious and comprehensive environmental policies globally, integrating environmental considerations across all areas of EU activity and establishing binding targets for member states [65]. The European Green Deal, launched in 2019 and expanded in 2024, is the EU's roadmap for making the EU's economy sustainable. It sets ambitious targets for climate action, biodiversity protection, and pollution reduction, while aiming to ensure a just and inclusive transition.

Key objectives of the Green Deal include achieving climate neutrality with net-zero greenhouse gas emissions by 2050 and an intermediate target of reducing emissions by fifty-five percent by 2030 compared to 1990 levels; protecting thirty percent of the EU's land and marine area and restoring degraded ecosystems; reducing air, water, and soil pollution to levels no longer considered harmful to health; transitioning to a circular economy where waste is minimized and resources are kept in use; and promoting sustainable agriculture and food systems .

Recognizing that the transition to a green economy will have different impacts on different regions and communities, the EU has established the Just Transition Mechanism to provide support to those most affected.

The mechanism includes the Just Transition Fund providing grants to regions and communities most affected by the transition; the InvestEU Just Transition scheme mobilizing private investment in transition-affected regions; and the public sector loan facility providing concessional loans for transition-related investments.

Implementation of EU environmental policies has achieved significant results but also faces ongoing challenges. Emissions have been reduced substantially while the economy has grown, demonstrating that environmental protection and economic development can be compatible. However, progress has been uneven across member states and sectors, and implementation gaps remain. The EU's experience offers lessons for environmental policy globally, including the importance of setting clear, ambitious, and legally binding targets; integrating environmental considerations across all policy areas; providing support for affected communities and regions; ensuring transparency and public participation; and monitoring implementation and enforcing compliance.

5. INTEGRATED STRATEGIES FOR SUSTAINABILITY

Isolated approaches, whether technological, economic, or behavioral, are insufficient to address the complexity of the ecological crisis. Environmental studies advocate for integrated strategies that combine multiple levels of intervention and recognize the interconnections among environmental, social, and economic systems.

5.1. The EcoHealth Approach

The EcoHealth approach recognizes the fundamental interdependence between human health, animal health, and ecosystem health [67]. It emerged from recognition that many health problems, particularly infectious diseases, cannot be understood or addressed without considering the environmental and ecological contexts in which they arise.

The EcoHealth approach is guided by several core principles. Systems thinking requires understanding health problems in their full context, including environmental, social, and economic dimensions, moving beyond linear cause-effect thinking to recognize feedback loops and emergent properties.

Transdisciplinarity integrates knowledge and perspectives from multiple disciplines as well as from non-academic stakeholders including communities, practitioners, and policy makers. Participation engages affected communities in identifying problems, developing solutions, and implementing actions. Equity addresses social and environmental justice issues, including the unequal distribution of health and environmental burdens. Sustainability seeks solutions that are environmentally sustainable, socially equitable, and economically viable over the long term.

The EcoHealth approach has been applied in diverse contexts. Research on avian influenza has used EcoHealth approaches to understand ecological and social factors contributing to disease emergence, including interactions among wild birds, domestic poultry, and human populations. In the Amazon, EcoHealth research has examined health impacts of development projects including roads, dams, and agricultural expansion, documenting how environmental changes affect disease patterns, nutrition, and community well-being. Projects in sub-Saharan Africa have used EcoHealth approaches to address food security challenges, integrating agricultural development, natural resource management, and public health interventions to improve nutrition while protecting ecosystems.

5.2. Nature-based Solutions

Nature-based solutions utilize ecosystem processes to address societal challenges, providing simultaneous benefits for biodiversity and human well-being. The concept has gained prominence as a framework for addressing climate change, disaster risk reduction, food security, and other challenges in ways that work with rather than against nature.

The International Union for Conservation of Nature defines nature-based solutions as actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits.

Key principles of nature-based solutions include addressing societal challenges through ecosystem-based approaches; providing multiple benefits including biodiversity conservation; being informed by and building on local and traditional knowledge; involving stakeholders and ensuring participation; maintaining biodiversity and ecosystem integrity; and being adaptive and responsive to changing conditions.

Examples of nature-based solutions are diverse and growing. Wetland restoration for flood protection involves restoring wetlands along rivers and coasts to absorb floodwaters, reducing downstream flooding while providing habitat for wildlife and improving water quality. Urban greening for heat reduction uses trees and green spaces in cities to reduce the urban heat island effect, improving comfort and reducing energy demand while providing recreation opportunities and supporting biodiversity. Conservation agriculture for food security maintains soil cover, reduces tillage, and integrates trees to improve soil health, increase water retention, and enhance resilience to drought while maintaining crop yields. Coral reef and mangrove conservation for coastal protection reduces wave energy and storm surge, protecting coastlines from erosion and flooding while supporting fisheries and tourism.

A 2025 IUCN report estimates that nature-based solutions could provide thirty-seven percent of the climate change mitigation needed by 2030 to meet Paris Agreement goals, at competitive costs. They also provide adaptation benefits, helping communities cope with climate impacts. However, realizing this potential requires supportive policies, adequate investment, and attention to social and environmental safeguards.

5.3. Environmental Education and Public Awareness

Environmental education plays a crucial role in building public support for environmental policies and promoting sustainable behaviors. Effective environmental education goes beyond transmitting information to developing the knowledge, skills, values, and motivation needed for environmental action.

Effective environmental education programs share several characteristics. They connect global and local issues, helping learners understand how global environmental issues relate to their own lives and communities.

They encourage critical thinking, developing learners' capacity to analyze complex environmental issues, evaluate evidence, and consider multiple perspectives. They promote active engagement, providing opportunities for learners to take action on environmental issues through individual behavior change, community projects, or advocacy. They integrate knowledge and values, helping learners clarify their own values, consider ethical dimensions, and make decisions consistent with both knowledge and values. They address structural barriers, acknowledging that individual behavior change is not enough and helping learners understand policy issues and develop skills for collective action and advocacy.

Research on environmental education effectiveness shows that well designed programs can produce lasting changes in knowledge, attitudes, and behaviors. Effects are strongest when programs are intensive, sustained, and combined with opportunities for action. School-based programs that incorporate action projects, community partnerships, and connections to the curriculum show particular promise. Despite its potential, environmental education faces numerous challenges including limited resources, competing demands on curriculum time, and the complexity of environmental issues. Controversies over climate change and other environmental topics can create political barriers to effective education.

5.4. Technological Innovations and Sustainability

Technology plays an ambivalent role in environmental studies. On one hand, technological development—particularly the fossil fuel-based technologies that powered industrialization—has contributed significantly to the ecological crisis. On the other hand, technological innovations are essential for the transition to sustainability, providing tools for monitoring environmental change, reducing environmental impacts, and enabling new, more sustainable ways of living. Key innovation areas critical for sustainability include renewable energy technologies that have become increasingly cost-competitive with fossil fuels; energy storage addressing intermittency of renewable sources.

Smart grids enabling integration of distributed renewable energy and demand response; precision agriculture reducing environmental impacts while maintaining yields; alternative proteins reducing environmental impacts of food production; biodegradable materials reducing plastic pollution; and environmental monitoring improving ability to track environmental conditions.

While technology is essential for sustainability, technological solutions alone are insufficient. Researchers caution against technological optimism that assumes technology will solve environmental problems without fundamental changes in consumption patterns, economic systems, and social values [79]. Key concerns include rebound effects where efficiency improvements lead to increased consumption; problem shifting where technologies address one environmental problem while creating others; access and equity issues where new technologies may be inaccessible to poor communities; and uncertainty about long-term impacts and unintended consequences.

5.5. Social Movements and Environmental Activism

Social movements have played a crucial role in placing environmental issues on the public agenda and promoting political change. From the first conservation movements of the late nineteenth century to contemporary climate justice movements, environmental activism has shaped policies, shifted public opinion, and held decision-makers accountable.

Environmental movements have evolved through several phases. The conservation movement of the late nineteenth and early twentieth centuries focused on protecting natural areas from development, establishing national parks and protected areas. The environmental movement of the 1960s and 1970s focused on pollution, population, and resource depletion, with events like Earth Day mobilizing millions. The environmental justice movement beginning in the 1980s highlighted disproportionate environmental burdens borne by communities of color and low-income communities. The climate movement from the 2000s onward has focused on climate change, advocating for international agreements, national policies, and corporate action. The youth climate movement, particularly Fridays for Future initiated by Greta Thunberg in 2018, has mobilized millions of young people globally, bringing new urgency and moral clarity to climate advocacy.

Characteristics of effective environmental movements include clear vision and achievable demands; diverse strategies including protest, lobbying, litigation, consumer action, and media engagement; broad coalitions across issues and constituencies; connection to justice framing that resonates with broader values; and innovative communication using media and technology creatively.

Environmental movements have achieved significant successes including establishment of protected areas, pollution control laws, international environmental agreements, and corporate commitments to sustainability. They have shifted public opinion and made environmental issues a permanent part of political discourse. However, the scale and urgency of current environmental challenges require continued and expanded movement activity.

6. FUTURE DIRECTIONS IN ENVIRONMENTAL STUDIES

The field of environmental studies continues to evolve, developing new conceptual frameworks and methodologies to address emerging challenges. This section examines several directions that are shaping the future of the field.

6.1. Post-growth and Decolonial Approaches

Critiques of the development model based on economic growth have gained prominence, particularly from scholars in the global South and from indigenous communities. These critiques challenge fundamental assumptions of conventional environmental thought and policy, proposing alternative frameworks for understanding and pursuing sustainability.

Post-growth thinking questions whether endless economic growth is possible or desirable on a finite planet. Key concepts include steady-state economy with stable population and consumption maintained within ecological limits; degrowth involving planned reduction of energy and resource use in wealthy countries; and well-being economy organized around human well-being rather than GDP growth. Decolonial environmental thought examines how colonial histories and continuing colonial relationships shape environmental problems and solutions.

Key concepts include buen vivir from Andean indigenous traditions emphasizing living in harmony with nature and community; rights of nature recognizing nature as having legal rights; food sovereignty emphasizing community control over food systems; and energy sovereignty emphasizing community control over energy systems.

6.2. Integration of Indigenous Knowledge

Recognition of traditional ecological knowledge as valuable sources of understanding and sustainable practices represents an important direction in contemporary environmental studies. Indigenous knowledge systems, developed over generations of intimate interaction with specific environments, offer insights that complement and sometimes challenge scientific approaches.

Indigenous knowledge is typically holistic, integrating understanding of ecological, social, cultural, and spiritual dimensions; local and place-based, specific to particular environments and communities; dynamic and adaptive, continuously evolving in response to changing conditions; experiential, based on practical experience rather than abstract theory; and oral and intergenerational, transmitted through stories, practices, and direct teaching across generations. Indigenous knowledge offers unique perspectives on sustainable resource management, biodiversity conservation, climate adaptation, and reciprocal relationships with nature. Initiatives such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services are developing approaches for respectful and equitable integration of indigenous and local knowledge in assessments.

6.3. Transdisciplinary Research and Knowledge Co-Production

The complexity of environmental problems requires collaboration among researchers, decision-makers, practitioners, and communities. Transdisciplinary research has emerged as an approach for generating knowledge that is both scientifically rigorous and relevant for action.

Transdisciplinary research is characterized by integration of multiple perspectives including academic and non-academic stakeholders; joint problem definition ensuring research addresses questions that matter to stakeholders; co-production of knowledge integrating diverse forms of expertise; action relevance focusing on knowledge that can inform decision-making; and capacity building enabling ongoing collaboration. Transdisciplinary approaches have been applied to climate adaptation planning, natural resource management, urban sustainability, and conservation and development conflicts.

6.4. Behavioral Change and Public Policies

Understanding the factors that influence environmental behaviors is essential for designing effective policies. Research in environmental psychology and behavioral economics has identified multiple influences on environmental behavior and strategies for promoting change.

Environmental behavior is influenced by individual factors including knowledge, attitudes, values, beliefs, and habits; social factors including social norms, peer influence, and cultural values; structural factors including infrastructure availability, costs, and convenience; and institutional factors including rules, regulations, and policies. Effective strategies for promoting change include feedback providing information about behavior and consequences; incentives, whether positive or negative; commitments increasing likelihood of follow-through; social norms communicating what others do; information and education addressing specific barriers; and choice architecture making sustainable choices easier and default options.

Effective policies combine multiple instruments and address multiple influences on behavior. Information campaigns alone are unlikely to achieve significant change without supporting infrastructure and incentives. Integrated policy packages that combine regulatory, economic, informational, and social instruments are most effective.

CONCLUSION

The global ecological crisis represents one of the most complex challenges humanity has ever faced. Its impact extends beyond ecosystems and economies, profoundly affecting the psychological well-being, social cohesion, and cultural identity of communities worldwide. This chapter has examined these impacts through the lens of environmental studies, demonstrating that environmental problems are inseparable from social, economic, and cultural issues, and that effective solutions must be equally integrated.

Several key themes emerge from this analysis. Communities are central to both the experience of and response to environmental change. Understanding community-level impacts and building on community capacities and knowledge is essential for effective adaptation and mitigation. Equity and justice must be central to environmental policy. The unequal distribution of environmental burdens and benefits is not merely an unfortunate side effect but a fundamental injustice that must be addressed through environmental justice frameworks and policies that protect vulnerable communities.

Integrated approaches that combine multiple strategies are more effective than isolated interventions. The EcoHealth approach, nature-based solutions, and transdisciplinary research all recognize that environmental challenges cannot be addressed through single disciplines or narrow interventions. They require collaboration across sectors and integration of diverse knowledge and perspectives. Future directions in environmental studies offer hope for more effective and just approaches. Post-growth and decolonial perspectives challenge assumptions that have led to environmental crisis and offer alternative visions. Integration of indigenous knowledge brings valuable insights into sustainable relationships with nature. Transdisciplinary research promises knowledge that is both scientifically rigorous and relevant for action.

The ecological crisis is unprecedented in its scale and urgency, but it is not hopeless. Communities worldwide are demonstrating that change is possible, developing innovative approaches that combine traditional knowledge with modern science, building resilience while protecting the ecosystems on which we all depend. The challenge before us is to learn from these examples, to scale up what works, and to create the political will for transformative change.

This requires continued research, education, and advocacy; policies that support rather than undermine sustainability; investment in communities and ecosystems; and a fundamental rethinking of our relationship with nature and with each other.

Ultimately, the ecological crisis challenges us to reconsider who we are and how we want to live. It invites us to move from a vision of domination and exploitation to one of reciprocity and care. It calls us to build communities that are more resilient, more equitable, and more connected to the ecosystems that sustain us. This is the great challenge and the great opportunity of our time.

REFERENCES

Albrecht, G. (2005). Solastalgia: A new concept in human health and identity. Philosophy Activism Nature, 3, 41–55.

Albrecht, G. (2024). Earth emotions: New words for a new world (2nd ed.). Cornell University Press.

Ardoin, N. M., & Bowers, A. W. (2024). Environmental education and behavior change. Environmental Education Research, 30(2), 145–178.

Askland, H. H., & Baugh, M. (2023). Mining, displacement, and solastalgia in Australia's Hunter Valley. The Extractive Industries and Society, 10(3), 101–115.

Barnett, J., & Adger, W. N. (2023). Climate change and social stability. Wiley Interdisciplinary Reviews: Climate Change, 14(2), e812.

Benjaminsen, T. A., Alinon, K., Buhaug, H., & Buseth, J. T. (2023). Does climate change drive land-use conflicts in the Sahel? Journal of Peace Research, 49(1), 97–111.

Bullard, R. D. (2024). Dumping in Dixie: Race, class, and environmental quality (5th ed.). Routledge.

Budziszewska, M., & Jonsson, A. (2023). From climate anxiety to climate action. The Journal of Climate Change and Health, 9, 100–112.

Castree, N., Hulme, M., & Proctor, J. D. (2024). A companion to environmental studies. Routledge.

Clayton, S., & Manning, C. (2023). Psychology and climate change: Human perceptions, impacts, and responses. Academic Press.

Clayton, S., Manning, C. M., Krygsman, K., & Speiser, M. (2017). Mental health and our changing climate. American Psychological Association.

Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (Eds.). (2023). Nature-based solutions to address global societal challenges. IUCN.

Creutzig, F., Roy, J., Lamb, W. F., et al. (2023). Towards demand-side solutions for mitigating climate change. Nature Climate Change, 13(4), 325–335.

Cunsolo, A., & Ellis, N. R. (2018). Ecological grief as a mental health response to climate change-related loss. Nature Climate Change, 8(4), 275–281.

Ellis, N. R., & Albrecht, G. (2023). Climate change threats to family farmers' sense of place and well-being. Social Science & Medicine, 315, 115–128.

Fuller, R., Landrigan, P. J., Balakrishnan, K., et al. (2023). Pollution and health: A progress update. The Lancet Planetary Health, 6(6), e535–e547.

Garnett, S. T., Burgess, N. D., Fa, J. E., et al. (2023). A spatial overview of the global importance of Indigenous lands for conservation. Nature Sustainability, 1(7), 369–374.

Global South Climate Network. (2024). Climate justice atlas: Mapping inequalities in the climate crisis. Cape Town: GSCN.

Goldmann, E., & Galea, S. (2023). Mental health consequences of disasters. Annual Review of Public Health, 45, 201–220

Grubler, A., & Wilson, C. (Eds.). (2024). Energy technology innovation. Cambridge University Press.

Hickman, C., Marks, E., Pihkala, P., et al. (2024). Climate anxiety in children and young people: A 2024 follow-up global survey. The Lancet Planetary Health, 8(3), e145–e156.

Hickman, C., Marks, E., Pihkala, P., et al. (2021). Climate anxiety in children and young people. The Lancet Planetary Health, 5(12), e863–e873.

Intergovernmental Panel on Climate Change. (2023). Climate change 2023: Synthesis report. Geneva: IPCC.

Hickel, J. (2023). Less is more: How degrowth will save the world. Penguin Books.

Hirsch Hadorn, G., Hoffmann-Riem, H., Biber-Klemm, S., et al. (Eds.). (2023). Handbook of transdisciplinary research. Springer.Kaplan, E. A. (2020). Is climate-related pre-traumatic stress syndrome a real condition? The Lancet Planetary Health, 4(2), e52–e53.

Huesemann, M., & Huesemann, J. (2023). Techno-fix: Why technology won't save us or the environment. New Society Publishers.

International Union for Conservation of Nature. (2025). Global standard for nature-based solutions (2nd ed.). IUCN.

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. (2024). Summary for policymakers of the thematic assessment of the sustainable use of wild species. IPBES Secretariat.

Kothari, A., Salleh, A., Escobar, A., Demaria, F., & Acosta, A. (Eds.). (2024). Pluriverse: A post-development dictionary (2nd ed.). Tulika Books.

Landrigan, P. J., Fuller, R., & Horton, R. (2024). The Lancet Commission on pollution and health: Ten years on. The Lancet, 403(10428), 1025–1048.

Marquardt, J. (2023). Fridays for Future's disruptive potential. Frontiers in Political Science, 5, 105–118.

McAdam, J. (2025). Climate change, forced migration, and international law. Oxford University Press.

McNamara, K. E., & Westoby, R. (2023). Solastalgia and the mental health impacts of climate change in coastal communities. Climate and Development, 15(2), 123–135.

Mistry, J., & Berardi, A. (2024). Bridging indigenous and scientific knowledge. Ecology and Society, 29(1), 12.Mohai, P., Pellow, D., & Roberts, J. T. (2023). Environmental justice. Annual Review of Environment and Resources, 48, 405–430.

Ojala, M. (2023). Facing anxiety in climate change education. Canadian Journal of Environmental Education, 21, 41–56.

Perera, F. P., Rauh, V., Whyatt, R. M., et al. (2023). Effect of prenatal exposure to airborne polycyclic aromatic hydrocarbons on neurodevelopment. Environmental Health Perspectives, 131(4), 047001.

Pihkala, P. (2022). Toward a taxonomy of climate emotions. Frontiers in Climate, 3, 738154.

Roberts, J. T., & Parks, B. C. (2023). A climate of injustice: Global inequality, North-South politics, and climate policy. MIT Press.

Rootes, C. (Ed.). (2023). Environmental movements: Local, national and global. Routledge.

Seddon, N., Smith, A., Smith, P., et al. (2023). Getting the message right on nature-based solutions to climate change. Global Change Biology, 29(5), 1198–1211.

Schlosberg, D. (2023). Environmental justice and the new pluralism (2nd ed.). Oxford University Press.

Sheffield, P. E., & Landrigan, P. J. (2023). Global climate change and children's health. Environmental Health Perspectives, 131(5), 055001.

Shove, E. (2024). Beyond the ABC: Climate change policy and theories of social change. Environment and Planning A, 56(3), 567–583.

Steg, L. (2023). Psychology of environmental behaviour. Cambridge University Press.

Sterling, S. (2023). Sustainable education: Re-visioning learning and change. Green Books.Sultana, F. (2023). Climate change, gender, and intersectionality. Gender, Place & Culture, 30(5), 681–698.

Tauli-Corpuz, V. (2024). Report of the Special Rapporteur on the rights of indigenous peoples. United Nations Human Rights Council.

Tarrow, S. (2024). Power in movement: Social movements and contentious politics (4th ed.). Cambridge University Press.

Tengö, M., & Malmer, P. (2024). Knowledge co-production for sustainability. Stockholm Resilience Centre.

Thaler, R. H., & Sunstein, C. R. (2023). Nudge: The final edition. Yale University Press.United Nations Environment Programme. (2011). Environmental assessment of Ogoniland. Nairobi: UNEP.

Wals, A. E. J. (2023). Sustainability-oriented learning and transformation. In M. A. Peters & R. Heraud (Eds.), Encyclopedia of educational innovation (pp. 1–6). Springer.

Whyte, K. (2023). Indigenous environmental justice. In T. Jafry (Ed.), Routledge handbook of climate justice (pp. 218–232). Routledge.

World Health Organization. (2024). Quantitative risk assessment of the effects of climate change on selected causes of death. Geneva: WHO.

CHAPTER 2
DIGITAL HEALTH AND ENVIRONMENTAL SUSTAINABILITY: AN ENVIRONMENTAL STUDIES PERSPECTIVE

[1]Sodiq Adetunji ADEKOLA
[2]Zainab Oyefunke OYERINDE

[1]University of Abuja, adekola.adetunji@uniabuja.edu.ng, ORCID ID: 0009-0000-0264-6022
[2]University of Abuja

INTRODUCTION

The convergence of healthcare, digital technologies, and environmental science has created a new interdisciplinary field often described as digital environmental health. Digital health encompasses the use of information and communication technologies (ICT), artificial intelligence (AI), telemedicine, mobile applications, wearable devices, and big data analytics to enhance healthcare delivery and population health management. These technologies are increasingly applied to environmental health monitoring, disease surveillance, and climate change adaptation strategies.

Environmental health challenges such as air pollution, climate change, water contamination, and biodiversity loss continue to threaten human health globally. Traditional environmental monitoring systems have often been limited by geographic coverage, high costs, and delays in data collection and analysis. Digital technologies now offer scalable and cost-effective alternatives for monitoring environmental exposures and their impacts on human health. For example, Internet of Things (IoT) sensors, mobile health platforms, and remote sensing technologies allow continuous monitoring of environmental conditions such as air quality, temperature, and water safety (Butarbutar et al., 2024).

At the same time, the rapid expansion of digital health technologies raises environmental concerns. The production of digital devices requires rare minerals and energy-intensive manufacturing processes, while data centers and computing infrastructures contribute significantly to carbon emissions and energy consumption. Without sustainable planning, the digital transformation of healthcare could inadvertently contribute to environmental degradation (Goel et al., 2024).

This chapter explores the complex relationship between digital health and environmental sustainability. It examines how digital health technologies contribute to environmental monitoring and public health protection while also analyzing the environmental challenges associated with their implementation.

1. CONCEPTUAL FOUNDATIONS OF DIGITAL HEALTH IN ENVIRONMENTAL STUDIES

1.1 Definition of Digital Health

Digital health refers to the use of digital technologies to improve healthcare delivery, health monitoring, disease prevention, and health system efficiency.

These technologies include:

- Telemedicine and telehealth platforms
- Electronic Health Records (EHRs)
- Mobile Health (mHealth) applications
- Artificial intelligence in healthcare
- Wearable health devices
- Internet of Things (IoT) health sensors
- Big data analytics and cloud computing

Digital health systems enable real-time data collection, improved health communication, and remote healthcare services, which are particularly valuable in environmental health contexts where environmental exposures may change rapidly.

1.2 Environmental Studies Perspective

Environmental studies examine the interactions between human societies and the natural environment. When digital health technologies are integrated into environmental research, they support:

- Monitoring environmental hazards
- Predicting climate-related diseases
- Enhancing environmental surveillance
- Supporting sustainable healthcare practices

The integration of digital technologies into environmental research has accelerated environmental innovation and sustainability initiatives, enabling improved resource management and environmental protection strategies (Goel et al., 2024).

2. DIGITAL TECHNOLOGIES IN ENVIRONMENTAL HEALTH MONITORING

2.1 Internet of Things (IoT) for Environmental Monitoring

IoT-based environmental monitoring systems use interconnected sensors to collect real-time environmental data such as air quality, temperature, humidity, and chemical pollutants. These sensors can be integrated with mobile health applications and health databases to monitor environmental exposures and predict health outcomes.

For instance, IoT sensors deployed in homes, workplaces, and urban environments can measure particulate matter and other air pollutants associated with respiratory diseases. The collected data can be analyzed using machine learning algorithms to identify patterns and predict health risks.

Digital platforms that combine IoT environmental data with health records enable public health authorities to detect environmental hazards early and implement targeted interventions.

2.2 Remote Sensing and Environmental Surveillance

Satellite-based remote sensing technologies are increasingly used to monitor environmental conditions that affect public health. These technologies can detect changes in:

- Land use and deforestation
- Urban heat islands
- Water pollution
- Vector habitats for disease transmission

Remote sensing data combined with digital health analytics can help identify regions vulnerable to climate-sensitive diseases such as malaria, dengue, and heat-related illnesses.

2.3 Mobile Health (mHealth) Applications

Mobile health applications allow individuals and communities to report environmental health risks, monitor symptoms related to environmental exposure, and access health information. These applications enhance community participation in environmental health surveillance.

mHealth technologies are particularly valuable in low- and middle-income countries, where traditional environmental monitoring infrastructure may be limited. They provide cost-effective tools for collecting environmental health data and raising public awareness about environmental hazards (Oladipo et al., 2024).

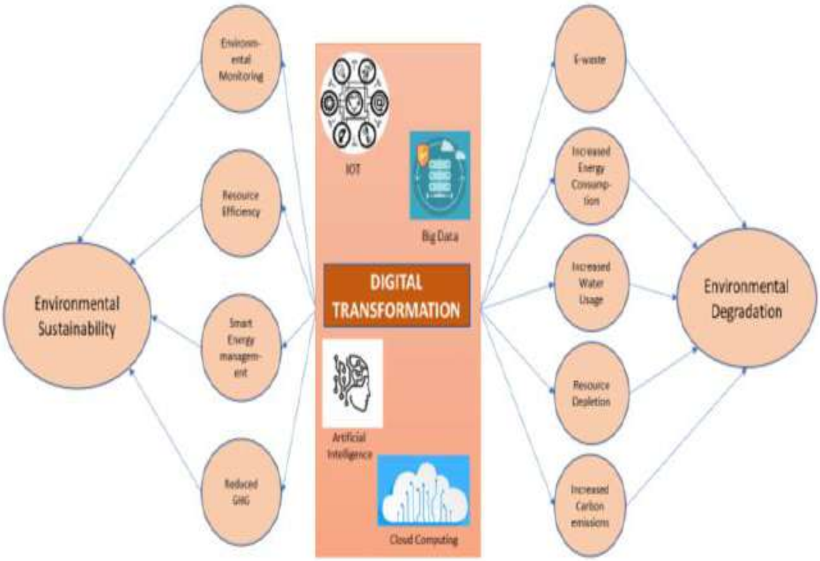

Figure 1. Graphical representation of interactions between digital transformation and environmental sustainability.

3. DIGITAL HEALTH AND CLIMATE CHANGE

Climate change represents one of the most significant global environmental challenges affecting public health. Rising temperatures, extreme weather events, and changes in disease patterns require innovative approaches for monitoring and responding to environmental health risks.

Digital health technologies contribute to climate change mitigation and adaptation through several mechanisms.

3.1 Climate-Sensitive Disease Surveillance

Digital disease surveillance systems use real-time environmental and health data to detect outbreaks of climate-sensitive diseases.

These systems combine data from health facilities, mobile devices, environmental sensors, and satellite imagery to track disease trends.

Examples include:

- Early warning systems for malaria outbreaks
- Monitoring heat-related illnesses during heatwaves

Predicting waterborne disease outbreaks following floods Digital twin technologies, virtual models of real-world environments can simulate interactions between environmental conditions and human health, enabling researchers to forecast disease risks associated with climate change (Hegarty-Craver et al., 2025).

3.2 Digital Platforms for Climate Health Education

Digital platforms play an important role in educating communities about climate-related health risks and promoting behavioral change. Online health education programs, mobile applications, and social media platforms provide accessible information on climate adaptation strategies and environmental health protection.

Digital technologies can support climate resilience by improving awareness, promoting sustainable practices, and encouraging community participation in environmental protection initiatives (Morris et al., 2025).

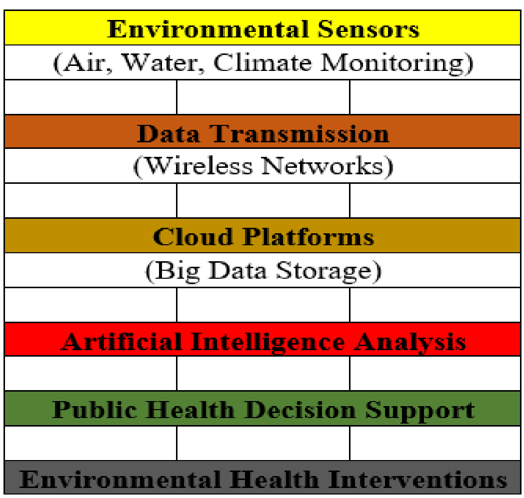

Figure 2. Integrated Environmental Health Surveillance Using Digital Technologies

Table 1. Major Digital Health Technologies Used in Environmental Health

Digital Technology	Application in Environmental Studies	Health Impact
Internet of Things (IoT) Sensors	Monitoring air pollution, water quality, and environmental exposures	Early detection of environmental hazards
Artificial Intelligence (AI)	Predicting disease outbreaks and climate-sensitive illnesses	Improved disease surveillance
Remote Sensing	Monitoring land use, temperature, and ecosystem changes	Identifying environmental risk zones
Mobile Health (mHealth) Apps	Public reporting of environmental hazards	Community engagement
Wearable Devices	Monitoring personal environmental exposure	Preventive health interventions
Big Data Analytics	Integrating environmental and health datasets	Evidence-based public health policy

4. ENVIRONMENTAL BENEFITS OF DIGITAL HEALTH

Digital health technologies can significantly reduce the environmental footprint of healthcare systems when implemented sustainably.

4.1 Telemedicine and Reduced Carbon Emissions

Telemedicine allows patients to consult healthcare providers remotely, reducing the need for transportation and travel-related emissions. Studies have shown that telemedicine consultations can significantly decrease greenhouse gas emissions associated with healthcare delivery.

By reducing patient travel and hospital visits, telemedicine contributes to greener healthcare systems and improves access to care for remote populations.

4.2 Paperless Healthcare Systems

Electronic health records and digital documentation reduce the need for paper-based medical records, contributing to resource conservation and improved data management.

Digital record systems also enhance healthcare efficiency and facilitate environmental health research through integrated data systems.

4.3 Smart Healthcare Infrastructure

Digital technologies support the development of smart hospitals that use automated energy management systems, sensor-based lighting, and optimized resource use to reduce environmental impact.

These technologies contribute to environmentally sustainable healthcare facilities.

Table 2. Environmental Benefits of Digital Health Systems

Digital Health Innovation	Environmental Benefit	Example
Telemedicine	Reduced transportation emissions	Remote consultations instead of hospital visits
Electronic Health Records	Reduced paper consumption	Digital patient record systems
Smart Hospitals	Improved energy efficiency	Automated energy management systems
AI-powered diagnostics	Reduced unnecessary testing	Efficient medical resource utilization
Remote monitoring devices	Reduced hospital admissions	Chronic disease monitoring

5. ENVIRONMENTAL CHALLENGES OF DIGITAL HEALTH

Despite its benefits, digital health also poses significant environmental challenges.

5.1 Energy Consumption of Digital Infrastructure

Data centers and computing systems required to support digital health platforms consume substantial amounts of energy. The rapid growth of artificial intelligence applications and health data analytics has increased demand for high-performance computing infrastructure.

The lifecycle of digital technologies from semiconductor manufacturing to cloud computing can contribute to air pollution and greenhouse gas emissions (Han et al., 2024).

5.2 Electronic Waste (E-Waste)

The proliferation of digital devices, including smartphones, wearable health devices, and medical sensors has increased electronic waste production.

E-waste contains hazardous materials such as lead, mercury, and cadmium, which can contaminate soil and water when improperly disposed of. Developing countries often face disproportionate environmental and health risks from informal e-waste recycling activities.

Digital health systems must therefore incorporate sustainable device management and recycling strategies.

5.3 Resource Extraction and Environmental Degradation

The production of digital technologies requires rare earth elements and minerals, many of which are extracted through environmentally damaging mining processes.

Sustainable sourcing and recycling of electronic components are essential for reducing the environmental impact of digital health technologies.

Table 3. Environmental Challenges of Digital Health Technologies

Environmental Issue	Description	Possible Solution
Energy consumption	Data centers require large electricity supply	Renewable energy for digital infrastructure
Electronic waste	Discarded devices release toxic materials	Recycling and circular economy practices
Rare earth mining	Extraction causes ecosystem damage	Sustainable mineral sourcing
Carbon footprint of AI	High computational power needed for AI training	Energy-efficient algorithms
Technology obsolescence	Rapid replacement of devices	Modular and repairable digital devices

6. ETHICAL AND SUSTAINABILITY CONSIDERATIONS

Environmental sustainability must be integrated into digital health development and policy planning.

Key ethical considerations include:

- Responsible data management

- Energy-efficient computing practices
- Sustainable technology design
- Equitable access to digital health services

Researchers have emphasized the importance of developing frameworks for evaluating the environmental sustainability of digital health innovations and integrating sustainability principles into digital health policies (Samuel et al., 2023).

7. POLICY AND GOVERNANCE FRAMEWORKS

Effective governance is essential for ensuring that digital health technologies support environmental sustainability.

Policy frameworks should address:

- Green digital health standards
- Energy-efficient data infrastructure
- E-waste management regulations
- Sustainable procurement policies
- Environmental impact assessments for digital technologies

International organizations such as the World Health Organization and United Nations are increasingly recognizing the importance of integrating digital health strategies into climate and environmental policies.

Table 4. Policy Strategies for Sustainable Digital Health

Policy Strategy	Description
Green Digital Health Policies	Policies that regulate the environmental impact of digital health infrastructure
Sustainable Procurement	Purchasing eco-friendly digital devices
E-waste Management Systems	Safe disposal and recycling of digital equipment
Carbon Reduction Initiatives	Use of renewable energy in data centers
Global Health Collaboration	International cooperation on digital health sustainability

8. FUTURE DIRECTIONS FOR DIGITAL HEALTH IN ENVIRONMENTAL STUDIES

The future of digital health in environmental studies will likely involve the integration of emerging technologies such as:

- Artificial intelligence and predictive analytics
- Smart cities and environmental sensor networks
- Digital twins for environmental health modeling
- Blockchain for environmental data transparency
- Precision environmental health monitoring

These technologies will enable more accurate environmental risk assessments and support proactive public health interventions.

However, ensuring sustainability will require collaboration among policymakers, researchers, technology developers, and healthcare providers.

9. DIGITAL HEALTH INFRASTRUCTURE AND ENVIRONMENTAL SUSTAINABILITY

The rapid expansion of digital health technologies requires extensive digital infrastructure, including cloud computing systems, data centers, telecommunications networks, and computing devices. While these infrastructures enable the efficient delivery of healthcare services, they also have environmental implications related to energy consumption, carbon emissions, and resource utilization.

9.1 Data Centers and Energy Consumption

Data centers form the backbone of digital health systems by storing electronic health records, processing artificial intelligence algorithms, and supporting telemedicine platforms. However, they require large amounts of electricity to operate servers, cooling systems, and networking equipment.

Globally, information and communication technologies (ICT) contribute a significant portion of greenhouse gas emissions due to the energy required for computing operations. Digital health applications that rely heavily on data processing and cloud computing can therefore increase the environmental footprint of healthcare systems if renewable energy sources are not used.

Research examining the carbon footprint of digital health interventions emphasizes the importance of assessing the environmental lifecycle of digital technologies before large-scale deployment (Lokmic-Tomkins, 2022).

Green computing strategies including energy-efficient servers, improved cooling technologies, and renewable energy adoption can significantly reduce the environmental impact of digital health infrastructure.

9.2 Sustainable Cloud Computing

Cloud computing plays a central role in digital health by enabling large-scale storage and analysis of health and environmental data. Hospitals, research institutions, and public health agencies rely on cloud platforms to store electronic health records, manage disease surveillance systems, and analyze environmental health datasets.

- Sustainable cloud computing strategies include: Data center energy optimization
- Renewable energy-powered infrastructure
- Efficient data processing algorithms
- Carbon-neutral cloud services

By adopting environmentally responsible cloud computing systems, digital health initiatives can contribute to global sustainability goals.

10. INTERNET OF THINGS (IOT) AND ENVIRONMENTAL HEALTH SURVEILLANCE

The Internet of Things (IoT) is transforming environmental monitoring by enabling real-time data collection from interconnected sensors deployed in homes, cities, and natural ecosystems. These sensors collect data on air pollution, temperature, humidity, radiation levels, and water quality.

10.1 Smart Environmental Monitoring Systems

IoT-based environmental monitoring systems allow continuous measurement of environmental hazards and integration with digital health platforms. These systems support public health surveillance by providing real-time environmental exposure data.

For example, smart environmental sensors can measure concentrations of particulate matter (PM2.5), nitrogen dioxide, and ozone—key pollutants associated with respiratory and cardiovascular diseases.

The integration of IoT devices with artificial intelligence and big data analytics allows researchers to identify patterns in environmental exposure and predict health outcomes.

IoT-based healthcare systems also support personalized environmental health monitoring by combining wearable devices with environmental sensors (Taimoor & Rehman, 2022).

10.2. Smart Cities and Environmental Health

Smart cities integrate digital technologies with urban infrastructure to improve environmental sustainability and quality of life. Digital health technologies in smart cities support environmental health through:

- Urban air quality monitoring
- Climate adaptation planning
- Smart transportation systems
- Environmental risk alerts

Smart city infrastructures can help reduce urban pollution, monitor climate impacts, and improve population health outcomes.

11. ARTIFICIAL INTELLIGENCE İN ENVIRONMENTAL HEALTH RESEARCH

Artificial intelligence (AI) has become a powerful tool for analyzing large datasets generated by digital health systems and environmental monitoring networks.

11.1 AI for Environmental Risk Prediction

Machine learning algorithms can analyze environmental and health data to identify patterns and predict environmental health risks.

- Examples include: Predicting air pollution-related hospital admissions
- Identifying high-risk zones for climate-sensitive diseases
- Forecasting heatwave-related mortality

- Detecting early signs of environmental contamination

AI-based environmental risk prediction models enable public health authorities to implement early interventions and reduce disease burden.

11.2 AI for Climate Change Modeling

Artificial intelligence is increasingly used to simulate environmental systems and assess the health impacts of climate change. AI-driven models can analyze complex relationships between environmental variables, population health, and disease patterns.

These models provide valuable insights for policymakers and environmental health researchers.

However, the computational demands of AI systems require significant energy resources, raising concerns about the environmental sustainability of large-scale AI applications in healthcare.

12. DIGITAL HEALTH AND SUSTAINABLE DEVELOPMENT GOALS

Digital health technologies contribute to the achievement of several United Nations Sustainable Development Goals (SDGs).

SDG 3: Good Health and Well-being

Digital health technologies improve access to healthcare services, disease surveillance, and health information systems.

Telemedicine platforms enable remote consultations and increase healthcare accessibility for rural populations.

SDG 9: Industry, Innovation, and Infrastructure

Digital health innovations promote technological advancement and infrastructure development in healthcare systems.

SDG 11: Sustainable Cities and Communities

Smart health monitoring systems contribute to healthier urban environments through environmental monitoring and public health surveillance.

SDG 13: Climate Action

Digital health technologies support climate change adaptation strategies through environmental health monitoring and climate-sensitive disease surveillance.

Technological innovation and ICT diffusion can significantly improve environmental sustainability and health outcomes by supporting efficient environmental management and policy implementation (Ahmad & Zhang, 2024).

13. DIGITAL HEALTH IN LOW- AND MIDDLE-INCOME COUNTRIES

Low- and middle-income countries face significant environmental health challenges, including air pollution, water contamination, and climate-related disasters.

Digital health technologies offer cost-effective solutions for environmental health monitoring and healthcare delivery in resource-limited settings.

13.1 Mobile Health in Environmental Surveillance

Mobile health applications are widely used in developing countries for health education, disease surveillance, and environmental reporting.

These applications allow communities to report environmental hazards and access health information through mobile devices.

13.2 Addressing E-Waste Challenges

The rapid adoption of digital technologies has also increased electronic waste generation in many developing countries. E-waste contains hazardous materials that can contaminate soil and water and pose health risks to nearby communities.

Digital health platforms can help monitor e-waste exposure and raise awareness about environmental health risks associated with electronic waste (Oladipo et al., 2024).

14. ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF DIGITAL HEALTH TECHNOLOGIES

Life cycle assessment (LCA) is a method used to evaluate the environmental impact of technologies throughout their lifecycle from resource extraction to disposal.

Applying LCA to digital health technologies helps identify environmental hotspots and opportunities for sustainability improvements.

Stages of the Digital Health Lifecycle Raw material extraction

- Device manufacturing
- Infrastructure operation
- Healthcare service delivery

Device disposal or recycling Environmental assessments indicate that transportation-related emissions associated with healthcare visits can be significantly reduced through digital health services such as telemedicine (Serra et al., 2022).

Similarly, systematic reviews show that telemedicine reduces healthcare-related carbon emissions primarily by decreasing patient travel (Purohit et al., 2021).

15. POLICY IMPLICATIONS AND RECOMMENDATIONS

The integration of digital health technologies into environmental health systems presents both opportunities and challenges that require coordinated policy responses. Governments, healthcare institutions, and international organizations must adopt strategic policies that maximize the benefits of digital health while minimizing potential environmental impacts.

15.1 Development of Green Digital Health Policies

Policymakers should develop green digital health frameworks that incorporate environmental sustainability into the design, deployment, and management of digital health systems. These policies should establish environmental standards for digital health infrastructure, including energy efficiency requirements for data centers, sustainable procurement guidelines for digital devices, and environmental impact assessments for new digital health technologies.

Integrating environmental sustainability into national digital health strategies will help ensure that the expansion of digital health services does not inadvertently contribute to increased carbon emissions or environmental degradation.

15.2 Investment in Sustainable Digital Infrastructure

Sustainable digital health systems require investment in environmentally responsible infrastructure. Governments and healthcare institutions should prioritize the use of renewable energy sources, energy-efficient computing technologies, and sustainable data management systems in the development of digital health platforms.

The adoption of green cloud computing systems and energy-efficient data centers can significantly reduce the carbon footprint associated with digital health services.

15.3 Strengthening Electronic Waste Management

The growing use of digital health devices including wearable technologies, smartphones, and environmental sensors has contributed to the global increase in electronic waste. Effective e-waste management policies are essential for preventing environmental contamination and protecting public health.

Governments should implement policies that promote:

- Safe Recycling And Disposal Of Electronic Devices
- Extended Producer Responsibility Programs
- Environmentally Sustainable Manufacturing Processes
- Public awareness campaigns on responsible device disposal

These measures will help reduce the environmental and health risks associated with electronic waste.

15.4 Promoting Interdisciplinary Research and Collaboration

Digital environmental health is inherently interdisciplinary, requiring collaboration among experts in public health, environmental science, information technology, engineering, and policy development.

Research institutions and universities should promote interdisciplinary research programs that explore the intersection of digital health technologies and environmental sustainability. Such collaborations can generate innovative solutions for addressing complex environmental health challenges.

15.5 Enhancing Capacity Building and Digital Literacy

Successful implementation of digital health systems depends on the capacity of healthcare professionals, environmental scientists, and policymakers to effectively utilize digital technologies.

Capacity-building initiatives should focus on:

- Digital health training for healthcare professionals
- Environmental data analytics skills
- Public awareness of digital environmental monitoring systems

Improving digital literacy and technical capacity will strengthen the ability of health systems to leverage digital technologies for environmental health monitoring and response.

15.6 Global Collaboration and Governance

Environmental health challenges such as climate change, pollution, and biodiversity loss are global in nature and require international cooperation. Global organizations including the World Health Organization and the United Nations should support collaborative initiatives that promote sustainable digital health systems and environmental monitoring networks.

International frameworks and partnerships can facilitate knowledge sharing, technology transfer, and the development of global standards for environmentally sustainable digital health systems.

CONCLUSION

Digital health technologies are increasingly transforming environmental health research and public health practice. Through tools such as telemedicine, artificial intelligence, mobile health applications, environmental sensors, and data analytics platforms, digital health systems enable real-time monitoring of environmental conditions, improved disease surveillance, and more effective responses to climate-related health risks.

These innovations provide powerful opportunities for strengthening environmental health systems and supporting evidence-based public health decision-making.

Furthermore, digital health contributes to climate mitigation and sustainable healthcare delivery by reducing the need for travel through telemedicine services, enhancing environmental surveillance systems, and supporting the development of smart and energy-efficient healthcare infrastructure. When strategically implemented, digital technologies can therefore help reduce healthcare-related carbon emissions while improving accessibility and efficiency in health service delivery.

However, the rapid expansion of digital health infrastructure also raises important environmental concerns. The energy demands of data centers, the extraction of rare minerals required for digital devices, and the increasing volume of electronic waste present significant sustainability challenges. Without careful planning and environmental oversight, the digital transformation of healthcare could inadvertently contribute to environmental degradation.

Addressing these challenges requires the integration of environmental sustainability principles into the design, governance, and implementation of digital health technologies. Sustainable digital health systems should prioritize energy-efficient computing, responsible electronic waste management, environmentally sustainable procurement practices, and the adoption of renewable energy sources for digital infrastructure.

Ultimately, the intersection of digital health and environmental studies represents an emerging and highly promising interdisciplinary field. By fostering collaboration among public health professionals, environmental scientists, policymakers, and technology developers, digital health innovations can be harnessed to promote resilient health systems, improve environmental monitoring, and advance global sustainability goals. Through the adoption of sustainable digital health strategies, societies can enhance public health outcomes while safeguarding environmental resources for future generations.

REFERENCES

Adeola, O., Evans, O., & Ngare, I. (2023). Cleantech, telehealth, and emerging technologies for climate change adaptation in Africa. In Gender equality, climate action, and technological innovation for sustainable development in Africa. Springer.

Ahmad, M., & Zhang, Q. (2024). Environmental sustainability and health outcomes: Do ICT diffusion and technological innovation matter? International Review of Economics & Finance, 89, 1–11.

Ahsan, M. M., & Siddique, Z. (2022). Industry 4.0 in healthcare: A systematic review. Journal of Healthcare Engineering.

Ali, M. A., & Jayesh, M. V. (2024). Leveraging information technology for sustainability in healthcare with telemedicine. Research and Reviews Journal of Hospital and Clinical Pharmacy, 14(1), 35–41.

Belkhir, L., & Elmeligi, A. (2018). Assessing ICT global emissions footprint: Trends to 2040. Journal of Cleaner Production, 177, 448–463.

Butarbutar, A. R., Toar, J., & Mamuaja, P. P. (2024). Digital health innovations in environmental risk monitoring: A literature review. Systematic Literature Review Journal.

Dutta, T., Kim, K., Uchimiya, M., et al. (2016). Global demand for rare earth resources and strategies for green mining. Environmental Research, 150, 182–190.

Goel, A., Masurkar, S., & Pathade, G. R. (2024). An overview of digital transformation and environmental sustainability: Threats, opportunities, and solutions. Sustainability, 16(24), 11079.

Han, Y., Wu, Z., Li, P., Wierman, A., & Ren, S. (2024). The unpaid toll: Quantifying the public health impact of AI. arXiv Preprint.

Hegarty-Craver, M., Gaur, P., Davis-Wilson, H., & Temple, D. S. (2025). Using digital twins to understand environmental health impacts. RTI Press.

Lokmic-Tomkins, Z. (2022). Assessing the carbon footprint of digital health interventions: A scoping review. Journal of the American Medical Informatics Association, 29(12), 2128–2139.

Morcillo Serra, C., Tanarro, A. A., Cummings, C. M., Fuertes, A. J., & Martínez, J. F. T. (2022). Impact on the reduction of CO_2 emissions due to the use of telemedicine. Scientific Reports, 12, 12507.

Morris, N. B., Barnes, M., Rybarczyk, A., & Chaseling, G. (2025). Digital technologies for climate-related health education, behavior and risk reduction: A systematic scoping review. npj Digital Medicine.

Oladipo, O., et al. (2024). The use of digital health services to combat e-waste health hazards: Impact and awareness in Southwest Nigeria. Toxicology.

Purohit, A., Smith, J., & Hibble, A. (2021). Does telemedicine reduce the carbon footprint of healthcare? A systematic review. Future Healthcare Journal, 8(1), e85–e91.

Samuel, G., et al. (2023). Environmental sustainability of AI-enabled digital health. King's College London Research Initiative.

Taimoor, N., & Rehman, S. (2022). Reliable and resilient AI and IoT-based personalised healthcare services: A survey. IEEE Access.

Thiel, C. L., Mehta, N., Sejo, C. S., Qureshi, L., Moyer, M., Valentino, V., & Saleh, J. (2023). Telemedicine and the environment: Life cycle environmental emissions from in-person and virtual clinic visits. npj Digital Medicine, 6, 87.

United Nations. (2023). Digital technologies and sustainable development goals. United Nations.

World Health Organization. (2021). Global strategy on digital health 2020–2025. World Health Organization.

CHAPTER 3
ENDEMIC STABILITY PROPERTY OF HIV/AIDS MODEL WITH INFLOW OF INFECTIVE IMMIGRANTS WITH BIFURCATION, EFFICIENCY AND COST-EFFECTIVENESS ANALYSIS

[1]Janet Kikelomo OLADEJO
[2]Temitayo Olabisi OLUYO
[3]Olusola Akintunde ODEBIYI
[4]Wasiu Olaitan LAWAL
[5]Olajide OLAOYE
[6]Jeremiah Yetomiwa SINAT

[1]Department of Pure and Applied Mathematics, Ladoke Akintola University of Technology, PMB 4000, Ogbomoso, Nigeria.jkoladejo@lautech.edu.ng, ORCID ID: 0009-0009-5250-0625
[2]Department of Pure and Applied Mathematics, Ladoke Akintola University of Technology, PMB 4000, Ogbomoso, Nigeria, tooluyo@lautech.edu.ng, ORCID ID: 0000-0002-7207-2180
[3]Department of Pure and Applied Mathematics, Ladoke Akintola University of Technology, PMB 4000, Ogbomoso, Nigeria, oaodebiyi@lautech.edu.ng, ORCID ID:0009-0007-8173-0625
[4]Department of Pure and Applied Mathematics, Ladoke Akintola University of Technology, PMB 4000, Ogbomoso, Nigeria, wolawal90@pgschool.lautech.edu.ng, ORCID ID: 0009-0003-5644-3871
[5]University of L'Aquila (Università degli Studi dell'Aquila), Palazzo Camponeschi, Piazza Santa Margherita, 2, 67100 L'Aquila AQ, Italy.,Silesian University of Technology, ul. Akademicka 2A, 44-100 Gliwice, Poland, olajide.olaoye@student.univaq.it, ORCID ID: 0009-0006-8946-4486
[6]Department of Computer Science, Ladoke Akintola University of Technology, PMB 4000, Ogbomoso, Nigeria., ysjeremiah@lautech.edu.ng, ORCID ID:0009-0008-9706-2094

INTRODUCTION

Human Immunodeficiency Virus /Acquired Immunodeficiency Syndrome (HIV/AIDS) has had a profound impact on society, extending beyond its medical implications to perpetuate discrimination and stigma. Additionally, the disease has significant economic consequences. Despite progress, misconceptions persist, such as the belief that HIV can be transmitted through casual, non-sexual contact. The disease has been embroiled in controversies, including religious debates, exemplified by the Catholic Church's stance against condom use as a preventive measure. (McCullom, 2013) Since its identification in the 1980s, HIV/AIDS has garnered extensive international attention, funding, and research efforts. (Sharp & Hahn, 2015) At the end of 2023, the pandemic has claimed an estimated 42.3 million lives worldwide (Joint United Nations Programme on HIV/AIDS [UNAIDS], 2023). Originating in west-central Africa in the late 19th or early 20th century, HIV was first recognized by the US CDC in 1981, with the identification of HIV infection as its cause following shortly thereafter (Sharp & Hahn, 2015).

Mathematical models offer a valuable framework for exploring the potential impact of treatment on HIV incidence, particularly in sub-Saharan Africa. Treatment is not curative, but it enables patients to live longer lives and has the potential to significantly reduce incidence. Anti-Retroviral Therapy (ART) can decrease the infectiousness of people living with HIV by 60-80% and has led to a decline in rates of AIDS, hospitalization, and death. (Kemnic & Gulick, 2024; Walensky, Park, & Wood, 2012) While treatment has led to a 51% decline in AIDS-related deaths globally since 2010, new infections persist, with over 1.3 million new cases reported in 2022—a 59% reduction since its peak in 1995 (UNAIDS, 2023).

The global migrant population, estimated at 281 million as of mid-year 2020, has nearly doubled in the last 50 years, with the global migration pattern shown in Figure 1 below.

Global Migration Pattern

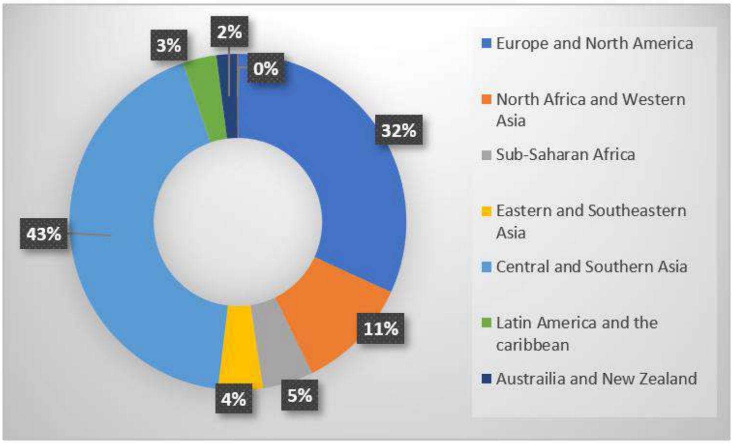

Figure.1. Global Migration Pattern by region for year 2020: Source (International Organization for Migration [IOM], 2020)

Understanding the link between infectious diseases and population mobility is crucial, as different forms and patterns of migration have varying influences on disease distribution and spread. For instance, economic migration has played a significant role in the evolution of the HIV/AIDS epidemic in low-income countries, with internal and cross-border migrants, particularly male migrant workers, facing a higher risk of HIV infection and transmission (Coffee, Lurie, & Garnett, 2007; Ross, Cunningham, & Hahn, 2020). Research has shown that disease persistence is likely if infective individuals are allowed to immigrate directly into a population (Ram, Agraj, & Dileep, 2009). Pre-exposure prophylaxis (PrEP) is a preventive strategy recommended by the World Health Organization for individuals at substantial risk of HIV infection (World Health Organization [WHO], 2015). However, there are significant gaps in understanding the effectiveness of PrEP in populations with direct immigration of HIV infectives. Therefore, investigating the impact of PrEP on the presence of infective immigrants in the population is essential.

While estimates of efficacy exist for various HIV interventions, including PrEP, treatment, and Post-Exposure Prophylaxis (PEP), direct estimates of effectiveness are limited due to the high cost of large community-based trials.

As a result, mathematical models are considered the most feasible method for assessing intervention effectiveness (Cohen, McCauley, & Sugarman, 2012; Cohen, Chen, McCauley, & Gamble, 2016; Siegfried, Muller, Deeks, & Volmink,2009). This study investigates the endemic properties of immigration of infected persons on the factor by which PrEP prevents transmission. Mathematical modeling has played a crucial role in understanding the epidemiology of HIV/AIDS, helping researchers identify key factors driving the epidemic. Following the introduction of Anti-Retroviral Therapy (ART), modeling focused on incorporating behavior change and treatment effects. With the advent of Pre-Exposure Prophylaxis (PrEP), mathematical studies have surged, aiming to assess its efficacy in curbing transmission dynamics.

Various studies have explored PrEP's impact, including Abbas, Anderson, & Mellors (2007), who found that targeting high-risk groups in sub-Saharan Africa could prevent millions of new cases. Kim et al. (2014), modeled HIV prevention measures, including PrEP, to estimate its effects on the epidemic in South Korea. Drabo, Hay, Vardavas, Wagner, & Sood (2016), developed a model to simulate HIV incidence among men who have sex with men, concluding that PrEP and Test-and-Treat strategies yield significant reductions. Silva & Torres (2017), proposed an epidemiological model showing PrEP's effectiveness in reducing new infections. Other studies, such as Oladejo & Oluyo (2022), who showed the disease-free stability analysis of the PrEP model, and Moya, Rodrigues, Pietrus & Severo (2022), who demonstrated PrEP's potential in reducing HIV infections using a stratified subpopulation model. Chazuka, Mudimu & Mathebula (2024), analyzed PrEP's effectiveness, highlighting the importance of increasing PrEP effectiveness and decreasing non-adherence to combat HIV in the population.

Existing studies have overlooked a crucial aspect examining the endemic stability properties of PrEP models in conjunction with the impact of HIV-infected immigrants on HIV/AIDS transmission dynamics and the Efficiency and Cost Effectiveness analysis. This research aims to address this gap by building upon the works of Oladejo & Oluyo (2022) and Oladejo & Lawal (2025) to explore the endemic stability of the HIV/AIDS transmission model.

This analysis seeks to determine how infected immigrants influence PrEP's effectiveness in reducing new infections and investigate the efficiency and cost-effectiveness of the control interventions. The remainder of the paper is organized as follows: Section 2 describes the model, Section 3 investigates the stability properties of the endemic equilibrium and conducts a forward stability bifurcation analysis, Section 4 describes the optimal control problem, Section 5 presents numerical simulations to examine stability, the efficiency index computation and cost effectiveness analysis computation, followed by a detailed discussion of the results, and the paper concludes with a summary of findings in Section 6.

1. MODEL ESTABLISHMENT

The model that is central to this paper is the work of Oladejo & Oluyo (2022). They investigated the impact of Pre-Exposure Prophylaxis (PrEP) on a population with immigrants and established disease-free stability. However, they did not analyze the stability of the endemic equilibrium and conduct a bifurcation analysis. Building on their work, our objective is to examine the asymptotic stability properties of the endemic equilibrium points and the bifurcation of an HIV/AIDS model that accounts for the immigration of infectives. Their model considers a heterogeneous human population that varies over time and is divided into six compartments: Susceptible (S(t)), PrEP (V(t)), Infective (I(t)), Pre-AIDS (P(t)), Treatment (T(t)), and AIDS (A(t)). The total population at any given time is represented by N(t) = S(t) + V(t) + I(t) + P(t) + T(t) + A(t). The PrEP class (V(t)) includes uninfected individuals at risk, while the Treatment class (T(t)) comprises HIV-positive individuals receiving treatment. The model assumes an influx of new members Λ who are susceptible, as well as Q immigrants per unit time, with a fraction (τ, where $0 < \tau < 1$) being infected immigrants.

In this study, infections are assumed to be transmitted through sexual intercourse, contact with infected needles, or blood. Additionally, individuals with full-blown AIDS are considered too weak to be sexually active.

The model equations are as follows:

$$
\begin{aligned}
S' &= \Lambda + (1-\tau)Q - (\lambda+\omega+\mu)S + \sigma V \\
V' &= \omega S - (\sigma+\mu)V \\
I' &= \tau Q + \lambda S - (\delta+\mu)I \\
P' &= \varepsilon\delta I - (\alpha+\mu)P \\
T' &= \eta\delta I + \gamma\alpha P + \theta A - (\kappa+\mu)T \\
A' &= (1-\varepsilon-\eta)\delta I + \alpha(1-\gamma)P + \kappa T - (\theta+d+\mu)A
\end{aligned}
\tag{1}
$$

where $\lambda = \dfrac{\beta_I cI + \beta_p cP + \beta_T cT}{N}$

with the initial conditions

$$S > 0, V \geq 0, I \geq 0, P \geq 0, T \geq 0, A \geq 0 \tag{2}$$

The mortality rate is μ, and disease-induced mortality is d. Susceptible individuals are recruited into the population through birth Λ and immigration Q, with τ being the fraction of infected immigrants entering the population. The contact rates with individuals in the Infective stage, Pre-AIDS stage and those on Antiretroviral Therapy (ART) are β_I, β_p and β_T respectively, with c representing the number of sexual partners in a unit time. Meanwhile, ω is the fraction of individuals under the Pre-Exposure Prophylaxis (PrEP) strategy, and σ is the rate at which individuals taking PrEP become susceptible. Additionally, movement from the Infective class to the Pre-AIDS and AIDS classes occurs at rates δ. The Infective, Pre-AIDS, and AIDS classes receive treatment at fractions α and θ respectively, and treatment fails at a rate κ.

2. ESTABLISHMENT OF ENDEMIC STABILITY STATE

Whenever infective immigrants enter the population, the disease-free equilibrium becomes unattainable due to the constant flow of infective immigrants; therefore, the model possesses only the endemic equilibrium (Dabbo, Seidu, & Makinde, 2013; Frauer, & Van den Driessche, 2001; Mohammed, & Baba, 2012; Oladejo & Oluyo, 2022; Ram, Agraj, & Dileep, 2009). In the work by Oladejo & Oluyo (2022), the disease-free equilibrium state, denoted by E_0, is characterized by the absence of infection when we set $\tau = 0$,this was given to be

$$E_0 = \left(S, V, 0, 0, 0, 0\right) = \left(\frac{(\Lambda + Q)(\mu + \sigma)}{\mu(\omega + \mu + \sigma)}, \frac{\omega(\Lambda + Q)}{\mu(\omega + \mu + \sigma)}, 0, 0, 0, 0\right).$$

A crucial condition for the local asymptotic stability of E_0 is that the effective (control) basic reproduction number (R_0) must be less than or equal to one. R_0 represents the expected number of secondary cases generated by a single infectious individual in a fully susceptible population. A method for calculating R_0 was developed by [25,26] applied to the model (1) in Oladejo & Oluyo (2022) and given as,

$$R_0 = \frac{qc\begin{pmatrix} \left(\beta_I K_3 + \beta_p K_2\right)\left(\kappa\left(\mu + d\right) + \mu K_7\right) \\ +\beta_T \left(K_3 \delta\left(\eta K_7 + \theta K_5\right) + \alpha K_2\left(\gamma K_7 + \theta K_6\right)\right) \end{pmatrix}}{K_1 K_3\left(\kappa\left(\mu + d\right) + \mu K_7\right)} \tag{3}$$

where

$K_1 = (\delta + \mu)$, $K_2 = \varepsilon\delta$, $K_3 = (\alpha + \mu)$, $K_4 = (\kappa + \mu)$, $K_5 = (1 - \eta - \varepsilon)$, $K_6 = (1 - \gamma)$, $K_7 = (\theta + \mu + d)$, $K_9 = (\sigma + \mu)$, $K_8 = (\omega + \mu)$, $q = \dfrac{(\sigma + \mu)}{(\omega + \mu + \sigma)}$

The model was shown to be well posed and epidemiologically meaningful and all the feasible solutions enter the region $\Omega = \left\{ \left(S, V, I, P, T, A\right) \in \Re^{6} : 0 \le N \le \dfrac{\Lambda + Q}{\mu} \right\}$.

2.1 Endemic Equilibrium Point

Our focus is on examining the endemic stability of the disease's persistence in the population, considering the continuous influx of infected individuals from outside. To achieve this, we determine the endemic equilibrium points to be:

$$P^{*} = \frac{K_2 I^{*}}{K_3},\ A^{*} = \frac{K_3\delta\left(\eta K_7 + K_4 K_5\right) + \alpha K_2\left(\kappa\gamma + K_4 K_6\right) I^{*}}{K_3\left(\kappa\left(\mu + d\right) + \mu K_7\right)},$$

$$T^{*} = \frac{K_3\delta\left(\eta K_7 + \theta K_5\right) + \alpha K_2\left(\gamma K_7 + \theta K_6\right) I^{*}}{K_3\left(\kappa\left(\mu + d\right) + \mu K_7\right)},$$

$$S^{*} = \frac{DK_9\left(\Lambda + \left(1 - \tau\right) Q\right)}{\mu\left(\omega + \sigma + \mu\right)\left(I^{*} R_0 K_1 + D\right)},\ V^{*} = \frac{\omega D\left(\Lambda + \left(1 - \tau\right) Q\right)}{\mu\left(\omega + \sigma + \mu\right)\left(I^{*} R_0 K_1 + D\right)},$$

We replaced the values of S^{*}, V^{*}, P^{*}, T^{*} and A^{*} in the third equation of the system (1), which gives the polynomial

$$aI^{2} - bI - c = 0 \tag{4}$$

where $a = K_1^{2} R_0$, $b = \left(\Lambda + Q\right) K_1\left(R_0 - 1\right)$ and $c = \left(\Lambda + Q\right)\tau Q$

By Descartes' rule of signs (Murray, 2001; Wang, 2004), a sign change means there is either one or zero real positive root; therefore, one of the roots will be positive. This implies that S^{*}, V^{*}, P^{*}, I^{*}, T^{*} and A^{*} will have two roots of different signs. The system of equations has positive endemic solutions E^{*} if $R_0 > 1$. This suggests that bifurcation is possible, as this is a situation where the associated basic reproduction number is slightly above unity. Thus, the occurrence of forward bifurcation has notable implications for disease control strategies.

2.2 Forward Bifurcation

The existence of the local asymptotic stability of the endemic equilibrium of the HIV/AIDS model (1) is carried out using the Centre Manifold Theory of bifurcation analysis, as illustrated in Castilo-Chavez & Song, (2004). In vector form, the system of equations in (1) can be written as:

$\frac{dx}{dt} = F(x)$ Where $x = (x_1, x_2, x_3, x_4, x_5, x_6)^T$ and $F = (f_1, f_2, f_3, f_4, f_5, f_6)^T$

So that $S = x_1, V = x_2, I = x_3, P = x_4, T = x_5, A = x_6$

Then the model equations (1) become

$$\begin{aligned}
x_1' &= f_1 = \Lambda + (1-\tau)Q - (\lambda+\omega+\mu)x_1 + \sigma x_2 \\
x_2' &= f_2 = \omega x_1 - (\sigma+\mu)x_2 \\
x_3' &= f_3 = \tau Q + \lambda x_1 - (\delta+\mu)x_3 \\
x_4' &= f_4 = \varepsilon\delta x_3 - (\alpha+\mu)x_4 \\
x_5' &= f_5 = \eta\delta x_3 + \gamma\alpha x_4 + \theta x_6 - (\kappa+\mu)x_5 \\
x_6' &= f_6 = (1-\varepsilon-\eta)\delta x_3 + \alpha(1-\gamma)x_4 + \kappa x_5 - (\theta+d+\mu)x_6
\end{aligned}$$

where $\lambda = \frac{\beta_I c x_3 + \beta_p c x_4 + \beta_T c x_5}{N}$

Suppose that β_I^* is taken as the bifurcation parameter such that when $R_0 = 1$ in (3), to obtain

$$\beta_I^* = \frac{\left(\left(K_1K_3 - \beta_p K_2 qc\right)\left(\kappa(\mu+d) + \mu K_7\right) - \beta_T qc\left(K_3\delta(\eta K_7 + \theta K_5) + \alpha K_2(\gamma K_7 + \theta K_6)\right)\right)}{qcK_3\left(\kappa(\mu+d) + \mu K_7\right)}$$

the linearized matrix of the model (1) evaluated at the disease-free equilibrium E_0 and evaluated at β_I^* is given by

$$J\left(E_0,\beta_1^*\right)=\begin{pmatrix} -K_9 & \sigma & -\beta_1^* cq & -\beta_p cq & -\beta_T cq & 0 \\ \omega & -K_8 & 0 & 0 & 0 & 0 \\ 0 & 0 & \beta_1^* cq-K_1 & \beta_p cq & \beta_T cq & 0 \\ 0 & 0 & K_2 & -K_3 & 0 & 0 \\ 0 & 0 & \eta\delta & \alpha\gamma & -K_4 & \theta \\ 0 & 0 & K_5\delta & K_6\alpha & \kappa & -K_7 \end{pmatrix} \tag{5}$$

The Characteristic equation corresponding with $J\left(E_0,\beta_1^*\right)$ is

$$\left(\lambda^2 b_0+\lambda b_1+b_2\right)\left(\lambda^4 a_0+\lambda^3 a_1+\lambda^2 a_2+\lambda a_3+a_4\right)=0 \tag{6}$$

Where

$$b_0=1, b_1=\left(K_8+K_9\right), b_2=\mu\left(\omega+\mu+\sigma\right), a_0=1, a_1=K_1+K_3+K_4+K_7-cq\beta_I$$

$$a_2=\left(K_1+K_3\right)\left(K_4+K_7\right)+K_1K_3+\kappa\left(\mu+d\right)+\mu K_7-cq\left(\beta_I\left(K_3+K_4+K_7\right)+\beta_p K_2+\beta_T\eta\delta\right)$$

$$a_3=K_7\left(K_1+K_3-cq\beta_I\right)\left(K_1+K_4\right)\left(\kappa\left(\mu+d\right)+\mu K_7\right)-cq\begin{pmatrix}\left(\beta_I K_3+\beta_p K_2\right)\left(K_4+K_7\right)+ \\ \beta_T\left(\alpha\gamma K_2+\theta K_5+\eta\delta\left(K_4+K_7\right)\right)\end{pmatrix}$$

$$a_4=K_1K_3\left(\kappa\left(\mu+d\right)+\mu K_7\right)\left(1-R_0\right)$$

Based on the Routh-Hurwitz criterion (Mahato, Mishra, Jayswal, & Mishra, 2015), for $R_0>1$ the coefficients $a_i>0$ and determinants for $H_i>0$ for i=1,2,3,4 of (6), then all the eigenvalues will have non-positive real parts. It follows that all the eigenvalues $J\left(E_0,\beta_1^*\right)$ have negative real parts, signifying that there exists a bifurcation at $R_0=1$. Hence, we compute the right eigenvector $J\left(E_0,\beta_1^*\right)$ corresponding to the simple zero eigenvalue given by $w=\left(w_1,w_2,w_3,w_4,w_5,w_6\right)^T$ so that $J\left(E_0,\beta_1^*\right)w=0$. We have

$$w_1=\frac{-w_3K_1K_8cq}{\mu(\omega+\mu+\sigma)},w_2=\frac{-w_3\omega K_1cq}{\mu(\omega+\mu+\sigma)},w_3>0,w_4=\frac{w_3K_2}{K_3},w_5=\frac{w_3\left(K_1K_3-\left(\beta_IK_3+\beta_pK_2\right)cq\right)}{\beta_TcqK_3}$$

$$w_6=\frac{w_3\left(\beta_I\left(K_3K_5\delta+\alpha K_2K_6\right)+\kappa\left(K_1K_3-\left(\beta_IK_3+\beta_pK_2\right)cq\right)\right)}{\beta_IcqK_3K_7}$$

Likewise, the left eigenvector associated to $J\left(E_0,\beta_1^*\right)v=0$ is given by

$$v_1=0,v_2=0,v_3=\frac{v_6\left(\kappa(\mu+d)+\mu K_7\right)}{\beta_Tcq\theta},v_4=\frac{v_6\left(\beta_p\left(\kappa(\mu+d)+\mu K_7\right)+\beta_T\alpha\left(\gamma K_7+\theta K_6\right)\right)}{K_3\beta_T\theta}$$

$$v_5=\frac{v_6K_7}{\theta},v_6>0$$

If β_I^* is taken as the bifurcation parameter, considering the case where $R_0=1$, the component of the partial derivatives is computed from f_3,f_4,f_5 and f_6 as

$$\frac{\partial^2f_3}{\partial x_1\partial x_3}=\frac{\partial^2f_3}{\partial x_3\partial x_1}=\frac{\beta_I^*c\mu\omega(\omega+\mu+\sigma)}{(\omega+1)^2(\Lambda+Q)},\frac{\partial^2f_3}{\partial x_1\partial x_4}=\frac{\partial^2f_3}{\partial x_4\partial x_1}=\frac{\beta_pc\mu\omega(\omega+\mu+\sigma)}{(\omega+1)^2(\Lambda+Q)} \tag{7}$$

$$\frac{\partial^2f_3}{\partial x_1\partial x_5}=\frac{\partial^2f_3}{\partial x_5\partial x_1}=\frac{\beta_Tc\mu\omega(\omega+\mu+\sigma)}{(\omega+1)^2(\Lambda+Q)},\frac{\partial^2f_3}{\partial x_1\partial\beta_I^*}=\frac{c}{(\omega+1)},\frac{\partial^2f_3}{\partial x_3\partial\beta_I^*}=0$$

which are substituted into equation (7). To determine the direction of bifurcation we compute a and b, the computations yield

$$a=\sum_{k,i,j=1}^{6}v_kw_jw_i\frac{\partial^2f_k}{\partial x_i\partial x_j}\left(E_0,\beta_I^*\right)=2v_3w_1\left(\frac{\partial^2f_3}{\partial x_5\partial x_1}w_5+\frac{\partial^2f_3}{\partial x_4\partial x_1}w_4+\frac{\partial^2f_3}{\partial x_3\partial x_1}w_3\right)$$

$$=2v_3w_1\frac{c\mu\omega(\omega+\mu+\sigma)}{(\omega+1)^2(\Lambda+Q)}\left(\beta_I^*w_3+\beta_pw_4+\beta_Tw_5\right)$$

$$a=\frac{-2v_6w_3^2K_1^2K_8K_2\omega\left(\mu K_7+\kappa(\mu+d)\right)}{(\omega+1)^2(\Lambda+Q)qK_3\beta_T\theta}$$

$$b=\sum_{k,i=1}^{6}v_kw_i\frac{\partial f_k}{\partial x_i\partial\beta_1^*}\left(E_0,\beta_1^*\right)=2v_3w_3\frac{\partial^2f_3}{\partial x_3\partial\beta_I^*}$$

$$b=\frac{2v_6w_3\left(\mu K_7+\kappa(\mu+d)\right)}{\theta q\beta_T(\omega+1)}$$

since $a<0$ and $b>0$ from computation, therefore, according to Castillo -Chavez & Song (2004), the HIV/AIDS model described by the system of equation (1) demonstrates a forward bifurcation upon R_0 surpassing the threshold, $R_0=1$ indicating the presence of a local stable Endemic Equilibrium point $E^*=\left(S^*,V^*,I^*,P^*,T^*,A^*\right)$. This leads to the formation of the following theorem.

Theorem 1.

The forward bifurcation takes place when $R_0=1$, indicating the presence of local asymptotic stability at the endemic equilibrium point for $R_0>1$

Remark

The theorem demonstrates that when $R_0>1$, then a few influxes of infectious individual into a fully susceptible population can lead to the persistence of HIV within the population.

2.3 Global Stability of the Endemic Equilibrium

The global asymptotic behavior of the PrEP model (1) is studied in this section by constructing a suitable Lyapunov function.

Theorem 2.

If $R_0>1$ the endemic equilibrium E^* of the model (1) is globally asymptotically stable in Ω.

Proof

when $R_0>1$ and there exist endemic equilibrium points for the system of equation in (1), considering the quadratic Lyapunov function (Keno, & Etana, 2023; Odebiyi, Oladejo, Elijah, Olajide, Taiwo & Taiwo, 2024).

$$F = \frac{1}{2}\left[\left(S-S^*\right)+\left(V-V^*\right)+\left(I-I^*\right)+\left(P-P^*\right)+\left(T-T^*\right)+\left(A-A^*\right)\right]^2 \quad (8)$$

Taking the time derivative of (8)

$$\frac{dF}{dt} = \left[\left(S-S^*\right)+\left(V-V^*\right)+\left(I-I^*\right)+\left(P-P^*\right)+\left(T-T^*\right)+\left(A-A^*\right)\right]\frac{d\left(S^*+V^*+I^*+P^*+T^*+A^*\right)}{dt}$$

recall that $N^* = \left(S^*+V^*+I^*+P^*+T^*+A^*\right)$ equation above becomes

$$\frac{dF}{dt} = \left[\left(S-S^*\right)+\left(V-V^*\right)+\left(I-I^*\right)+\left(P-P^*\right)+\left(T-T^*\right)+\left(A-A^*\right)\right]\frac{dN}{dt} \quad (9)$$

Also $\frac{dN}{dt} = D - \mu N$,then equation (9) becomes

$$\frac{dF}{dt} = \left[\left(S-S^*\right)+\left(V-V^*\right)+\left(I-I^*\right)+\left(P-P^*\right)+\left(T-T^*\right)+\left(A-A^*\right)\right]\left(D-\mu N\right) \quad (10)$$

since $N^* = \frac{D}{\mu}$ it follows at steady state equations of system (1), then we have:

$$\frac{dF}{dt} = \left[N - \frac{D}{\mu}\right]\left(D-\mu N\right) \quad (11)$$

rearranging and simplifying (11)

$$\frac{dF}{dt} = -\frac{1}{\mu}\left(D-\mu N\right)^2$$

Thus, $\frac{dF}{dt} \le 0$ for $R_0 > 1$then $\frac{dF}{dt} = 0$ will be negative definite if $S = S^*, V = V^*, I = I^*, P = P^*,$ $T = T^*, A = A^*$. Therefore, the largest compact invariant $\left\{\left(S^*, V^*, I^*, P^*, T^*, A^*\right) \in \Omega : \frac{dF}{dt} = 0\right\}$. is

the singleton E^*. By LaSalle's invariant principle (LaSalle, 1976), it implies that $E^*$is globally asymptotically stable in Ω.

3. OPTIMAL CONTROL PROBLEM

An optimal control problem is developed to examine the public health challenge of HIV/AIDS. Extending autonomous model (1), into an optimal control problem (non-autonomous) by injecting four control strategies with the aim to determine the control strategy that minimizes HIV-AIDS infection in the population as well as the cost associated with these controls. The optimal control problem is developed in order to

- Reduce infection through public sensitization as the control function u_1
- PrEP strategy as the control function u_2
- Screening of new arrivals using control function u_3
- Sexual behavioral therapy using control function u_4

Thus, the model becomes

$$
\begin{aligned}
S' &= \Lambda + (1-\tau(1-u_3))Q - \frac{(\beta_1 I + \beta_2 P + \beta_3 T)c(1-u_1)S}{N} - (\varpi u_2 + d)S + \sigma V \\
V' &= \varpi u_2 S - (d+\sigma)V \\
I' &= (1-u_3)\tau Q + \frac{(\beta_1 I + \beta_2 P + \beta_3 T)c(1-u_1)S}{N} - (\delta u_4 + d)I \\
P' &= \varepsilon\delta u_4 I - (\alpha + d)P \\
T' &= \eta\delta u_4 I + \gamma\alpha P + \theta A - (k+d)T \\
A' &= (1-\varepsilon-\eta)\delta u_4 I + \alpha(1-\gamma)P + kT - (\theta+\mu+d)A \\
& S(0)\ge 0, V(0)\ge 0, I(0)\ge 0, P(0)\ge 0, T(0)\ge 0, A(0)\ge 0
\end{aligned}
\tag{12}
$$

3.1 Theoretical Analysis of Optimal Control

Utilizing the Pontryagins Maximum Principle (Pontryagin et al. 1962, Pontryagin, 2018) considering the Non autonomous system (12) with the associated index the objective functional (or cost functional)

$$J = \min_{u_1 u_2 u_3 u_4} \int_0^{t_f} \left[a_1 I + a_2 P + a_3 T + \frac{1}{2}(w_1 u_1^2 + w_2 u_2^2 + w_3 u_3^2 + w_4 u_4^2) \right] dt \tag{13}$$

Where the weights constants a_1, a_2, a_3 and w_1, w_2, w_3 are the relative weights which balances each term in the integrand so that any of the terms do not dominate, where t_f the final time is. The main objective is to minimize the objective functional or cost functional $J(u_1, u_2, u_3, u_4)$, to determine the control strategy that minimizes the number of individual infected with HIV as well as the cost associated to applying the control (u_1, u_2, u_3, u_4) such that

$$J\left(U_1^*, U_2^*, U_3^*, U_4^*\right) = \min \left\{ J(u_1, u_2, u_3, u_4) : J(u_1, u_2, u_3, u_4) \in U \right\} \tag{14}$$

The admissible control set is given as

$$U = \left\{ (u_1, u_2, u_3, u_4) \Big|_{U_i} \text{ is lebesquemeasurable with } 0 \le U_i \le 1 \ \forall t \in [0, t_f] \text{ for } i = 1, \ldots, 4 \right\} \tag{15}$$

Based on the Pontrygagins Maximum Principle (Pontryagin et al. 1962, Pontryagin, 2018) the Langriangian otherwise called the running cost is defined

$$L(x, u) = a_1 I + a_2 P + a_3 T + a_4 A + \frac{1}{2}(w_1 u_1^2 + w_2 u_2^2 + w_3 u_3^2 + w_4 u_4^2) \tag{16}$$

The Hamiltonian is given as

$$H(x, u, \lambda) = L(x, u) + \lambda f(x, u) \tag{17}$$

Theorem 4.1

If U^* is the optimal control quadruple set and the solution for state equations x^*, that minimizes J over U subject to the state system (12), then there exist an adjoint function $\lambda_i(t)$ where all $0 \le t \le t_f$ and $i \in \{1,..4\}$ such that

State equation $\dot{x}(t) = f\left(x(t), u(t)\right)$

Co-state equations $\dot{\lambda}_i(t) = -\dfrac{dH}{dx}$

Transversality condition $\lambda_i(t_f) = 0$.

Proof

Using Pontryagin's maximum principle, (Pontryagin *et al.* 1962, Pontryagin 2018) the Hamiltonian associated our problem defined as

$$H = L + \lambda_1 S' + \lambda_2 V' + \lambda_3 I' + \lambda_4 P' + \lambda_5 T' + \lambda_6 A' \tag{18}$$

And the Lagrangian given as

$$L = a_1 I + a_2 P + a_3 A + \frac{1}{2}\left(w_1 u_1^2 + w_2 u_2^2 + w_3 u_3^2 + w_4 u_4^2\right) \tag{19}$$

substituting the Lagrangian and the state equations into the Hamiltonian (18)

$$\begin{aligned}
H = {} & a_1 I + a_2 P + a_3 A + \tfrac{1}{2}\left(w_1 u_1^2 + w_2 u_2^2 + w_3 u_3^2 + w_4 u_4^2\right) + \\
& \lambda_1\left(\Lambda + (1-\tau(1-u_3))Q - \frac{c(1-u_1)S(\beta_1 I + \beta_2 P + \beta_3 T)}{N} - (\varpi u_2 + d)S + \sigma V\right) + \\
& \lambda_2\left(\varpi u_2 S - (d+\sigma)V\right) + \lambda_3\left((1-u_3)\tau Q + \frac{(\beta_1 I + \beta_2 P + \beta_3 T)c(1-u_1)S}{N} - (\delta u_4 + d)I\right) + \\
& \lambda_4\left(\varepsilon\delta u_4 I - (\alpha + d)P\right) + \lambda_5\left(\eta\delta u_4 I + \gamma\alpha P + \theta A - (k+d)T\right) + \\
& \lambda_5\left((1-\varepsilon-\eta)\delta u_4 I + \alpha(1-\gamma)P + kT - (\theta + \mu + d)A\right)
\end{aligned} \tag{20}$$

Using Pontryagin's maximum principle, the adjoint variable is derive as follows $\lambda_j = \frac{dH}{dx_j}$ where $x_j(t) = (S, V, I, P, T, A)$. The adjoint condition are computed to have,

$$
\begin{aligned}
\lambda_S' &= (\lambda_S - \lambda_I)\frac{c(1-u_1)(\beta_1 I + \beta_2 P + \beta_3 T)}{N} + (\lambda_S - \lambda_V)\varpi u_2 + d\lambda_S \\
\lambda_V' &= (\lambda_V - \lambda_S)\sigma + \lambda_V d \\
\lambda_I' &= -a_1 + (\lambda_S - \lambda_I)\frac{c(1-u_1)\beta_1 S}{N} + \delta u_4\left((\lambda_I - \lambda_A) - \varepsilon(\lambda_P - \lambda_A) - \eta(\lambda_T - \lambda_A)\right) + d\lambda_I \\
\lambda_P' &= -a_2 + (\lambda_S - \lambda_I)\frac{c(1-u_1)\beta_2 S}{N} + \alpha\left((\lambda_P - \lambda_A) - \gamma(\lambda_T - \lambda_A)\right) + d\lambda_P \\
\lambda_T' &= (\lambda_S - \lambda_I)\frac{c(1-u_1)\beta_3 S}{N} + k(\lambda_T - \lambda_A) + d\lambda_T \\
\lambda_A' &= -a_3 + \theta(\lambda_A - \lambda_T) + (\mu + d)\lambda_A
\end{aligned}
\tag{21}
$$

With the transversality condition

$$
\lambda_S(t_f) = \lambda_V(t_f) = \lambda_I(t_f) = \lambda_P(t_f) = \lambda_T(t_f) = \lambda_A(t_f) = 0 \tag{22}
$$

In addition, the optimal control $u_i^*(t)$ is given by

$$
\begin{aligned}
\frac{\partial H}{\partial u_1} &= w_1 u_1 + (\lambda_1 - \lambda_3)\frac{cS(\beta_1 I + \beta_2 P + \beta_3 T)}{N} = 0 \text{ at } u_1 = u_1^* \\
\frac{\partial H}{\partial u_2} &= w_2 u_2 + (\lambda_2 - \lambda_1)\varpi S = 0 \text{ at } u_2 = u_2^* \\
\frac{\partial H}{\partial u_3} &= w_3 u_3 + (\lambda_3 - \lambda_1)\tau Q + Q\lambda_1 = w_3 u_3 + Q\{(\lambda_3 - \lambda_1)\tau + \lambda_1\} = 0 \text{ at } u_3 = u_3^* \\
\frac{\partial H}{\partial u_4} &= w_4 u_4 + (\lambda_6 - \lambda_3)\delta I + (\lambda_4 - \lambda_6)\varepsilon\delta I + (\lambda_5 - \lambda_6)\eta\delta I = 0 \text{ at } u_4 = u_4^*
\end{aligned}
\tag{23}
$$

Hence solving for u_1, u_2, u_3, u_4 to have

$$
\begin{aligned}
u_1 &= \frac{cS(\beta_1 I + \beta_2 P + \beta_3 T)(\lambda_3 - \lambda_1)}{Nw_1} \\
u_2 &= \frac{(\lambda_1 - \lambda_2)\varpi S}{w_2} \\
u_3 &= \frac{Q\{(\lambda_1 - \lambda_3)\tau - \lambda_1\}}{w_3} \\
u_4 &= \frac{(\lambda_3 - \lambda_6)\delta I + (\lambda_6 - \lambda_4)\varepsilon\delta I + (\lambda_6 - \lambda_5)\eta\delta I}{w_4}
\end{aligned}
\tag{24}
$$

Imposing the bounds $0 \le u_i \le u_{i\max}, i = 1,2,3,4$ on the controls to get the optimality condition

$$
\begin{aligned}
u_1^* &= \min\left\{\max\left(0, \frac{cS(\beta_1 I + \beta_2 P + \beta_3 T)(\lambda_3 - \lambda_1)}{Nw_1}\right), u_{1\max}\right\} \\
u_2^* &= \min\left\{\max\left(0, \frac{(\lambda_1 - \lambda_2)\varpi S}{w_2}\right), u_{2\max}\right\} \\
u_3^* &= \min\left\{\max\left(0, \frac{Q\{(\lambda_1 - \lambda_3)\tau - \lambda_1\}}{w_3}\right), u_{3\max}\right\} \\
u_4^* &= \min\left\{\max\left(0, \frac{(\lambda_3 - \lambda_6)\delta I + (\lambda_6 - \lambda_4)\varepsilon\delta I + (\lambda_6 - \lambda_5)\eta\delta I}{w_4}\right), u_{4\max}\right\}
\end{aligned}
\tag{25}
$$

The optimal control system is given by incorporating the state system (12), adjoint system (21) with the transversality condition (22) together with optimality condition (25) characterizes the optimal control.

4. NUMERICAL SIMULATION

To study the dynamical behavior of the model numerically, the system of equation (1) and the optimality system were solved using the fourth order forward backwards Runge-Kunta iterative scheme in MATLAB. Using condition at $t = 0$, the transversality conditions in equation (22), the characterization of the optimal control in equation (25), together with the state system in equation (12) and the adjoint system in equation (21) that make up the optimality system, the optimal control solution is obtained. Optimality system details numerical procedure can be found in Lenhart and Workman, [45]. Using the set of parameters in Table 1 taken per year, the initial values taken for the state variables in the models are $S(0) = 2000$, $V(0) = 0$, $I(0) = 800$, $P(0) = 600$, $A(0) = 100$. The weight constant from the objective function we set $a_1 = 35, a_2 = 100, a_3 = 55, w_1 = 70, w_2 = 1, w_3 = 10, w_4 = 10$

Table 1. Parameter Values used in the simulation

Parameter	Estimated values	Source
β_I	0.15	Silva and Torres (2017)
β_p	0.05	Oladejo and Oluyo, (2022).
β_T	0.05	Oladejo and Oluyo, (2022).
Q	1000	Oladejo and Oluyo, (2022).
Λ	1000	Oladejo and Oluyo, (2022).
c	3	Oladejo and Oluyo, (2022).
δ	0.4	Oladejo and Oluyo, (2022).
d	0.02	Oladejo and Lawal (2025).
μ	1	Oladejo and Lawal (2025).
α	0.5	Oladejo and Lawal (2025).
ε	0.6	Oladejo and Lawal (2025).
ω	0.4	Oladejo and Oluyo, (2022).
τ	0.05	Oladejo and Lawal (2025).
η	0.01	Oladejo and Oluyo, (2022).
γ	0.4	Oladejo and Lawal (2025).
k	0.08	Oladejo and Oluyo, (2022).
θ	0.1	O. A. Odebiyi *et al,* (2025)

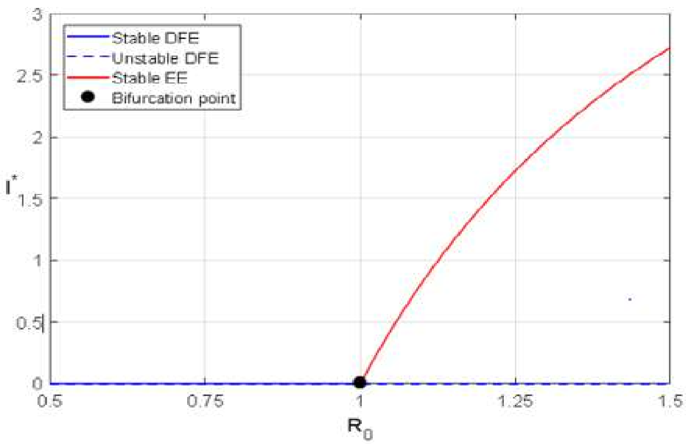

Figure 2. Forward bifurcation diagram

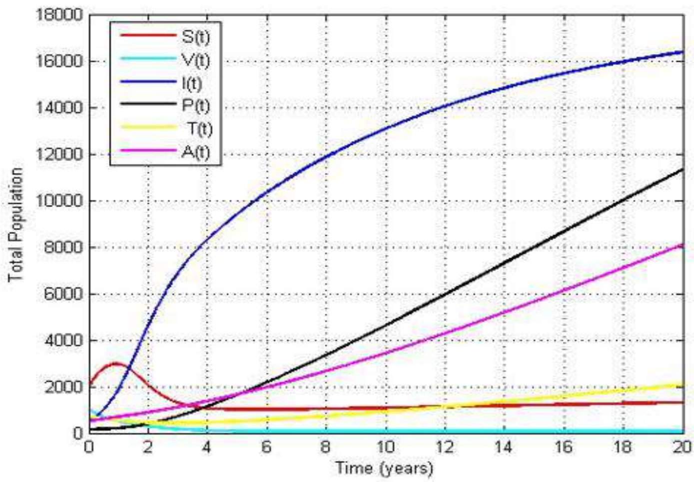

Figure 3. Trajectory of the state variables at $R_0 > 1$

The simulation results in Figure 2 reveal a critical threshold at $R_0 = 1$, where the endemic equilibrium undergoes a forward bifurcation. This means that when R_0 exceeds 1, the endemic equilibrium is stable, but when R_0 falls below 1, it becomes unstable. Consequently, HIV infection can be eliminated from the population if R_0 is less than 1, but it can persist even with a small influx of infected individuals. Notably, when R_0 exceeds 1, the endemic equilibrium is both locally and globally stable, indicating a persistent infection at a steady state, as shown in Figure 4. For models exhibiting forward bifurcation, the condition $R_0 < 1$ is necessary and sufficient for HIV elimination. However, even with a minimal influx of infected individuals, the infection can persist, underscoring the importance of sustained surveillance and control efforts.

The public health implications of forward bifurcation are profound, as they can lead to sudden and significant shifts in HIV transmission dynamics. This highlights the need for proactive and adaptive control measures to effectively manage and prevent HIV outbreaks, even at low levels of transmission. By understanding these dynamics, we can better target our efforts to combat the persistence of HIV and ultimately work towards its elimination.

The plot in Figure 3 shows that the infected class increases due to the inflow of infected immigrants, causing the susceptible and PrEP classes to decrease, indicating endemic stability. Figure 4 demonstrates the case for $R_0 > 1$, starting at different initial values of $I(t)$, $P(t)$, $T(t)$ and $A(t)$, all converging to a finite as $t \to \infty$, corroborating Theorem 3. Figure 3 also indicates that the solution converges to the model's endemic stability point, indicating that the system (1) demonstrates local stability when the effective reproduction number is above one.

Moreover, it highlights the biological importance of understanding how HIV/AIDS replicates and spreads, even with the effect of the influx of infective immigrants, as this knowledge can help predict and potentially prevent its future resurgence.

Figure 5 illustrates the impact of PrEP on the infective population with and without infected immigrants. Immigration poses a significant risk for disease spread, particularly in developing countries where comprehensive health screening is not always conducted. Infected immigrants can put their partners in both their home and destination countries at risk of contracting HIV/AIDS. As shown in Figure 5, the infective population grows continuously due to the presence of infected immigrants, initially increasing the total population and making the infection more persistent. However, over time, the population decreases. The direct influx of infected immigrants increases the number of infectives, ultimately boosting disease prevalence. To control the spread of disease and prevent endemicity, effective immigration policies like immigrant screening are crucial.

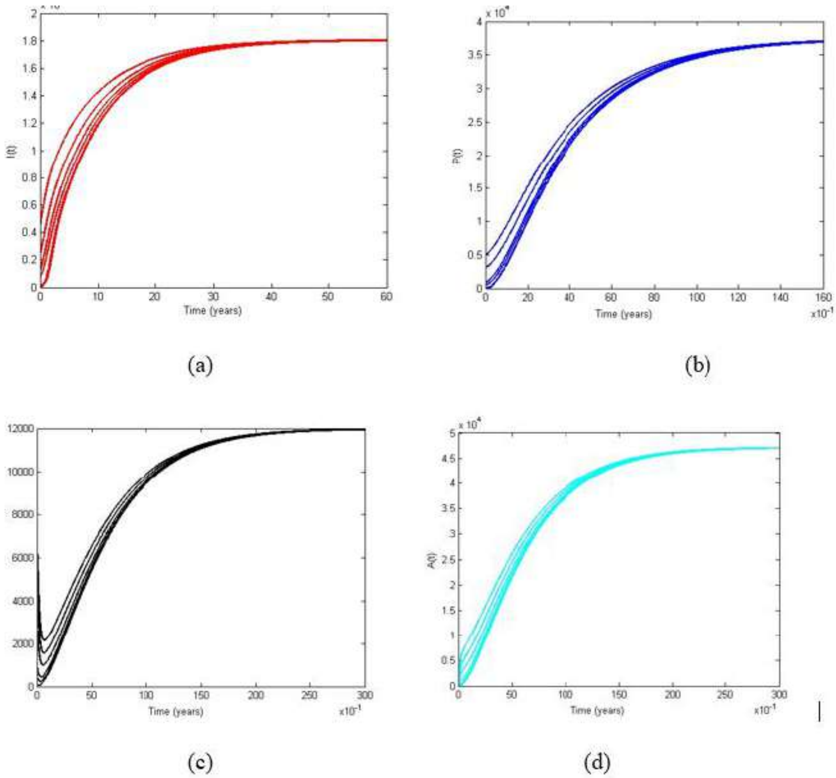

Figure 4. Global stability of the EEP of $I(t)$, $P(t)$, $T(t)$ and $A(t)$

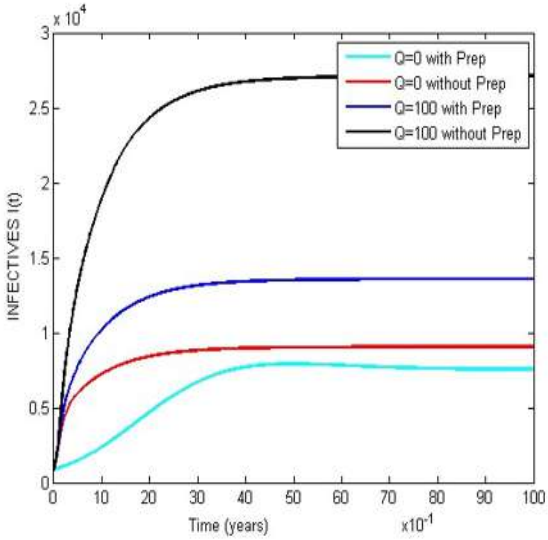

Figure 5. Effect of PrEP on immigration

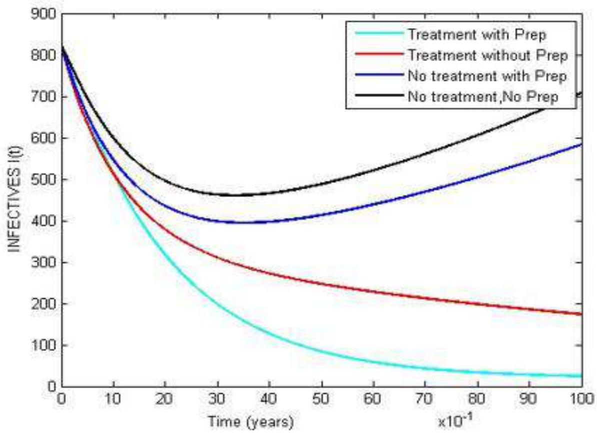

Figure 6. Effect of PrEP and Treatment

The simulation results in Figure 5 also reveal that in populations with PrEP, the epidemic peak is higher with infected immigrants than without; however, PrEP can still reduce infection in both scenarios. Therefore, PrEP can significantly lower the risk of sexual HIV transmission.

Figure 6 illustrates the synergistic impact of combining treatment and PrEP in a population. The results indicate that treatment significantly reduces disease prevalence, and its benefits are amplified when paired with PrEP. However, poor adherence to PrEP and increased risky sexual behavior can undermine its effectiveness. Treatment plays a crucial role in slowing the progression of HIV to AIDS by reducing the viral load of individuals living with HIV, while PrEP decreases the risk of infection from an HIV-positive person.

The plot in Figure 6 suggests that combining PrEP and treatment yields the best outcomes, as treatment renders individuals less infectious and requires lifelong management, while PrEP prevents new infections among those at risk. This dual approach can lead to a substantial decline in new cases and, ultimately, a significant reduction in infection prevalence.

Figure 7 shows that the effectiveness of PrEP is heavily reliant on consistent daily use and strict adherence, as optimal protection is only achievable through rigorous commitment.

The level of protection offered by PrEP is directly correlated with adherence, initial HIV testing (essential to determine an individual's status before starting PrEP), and voluntary participation.

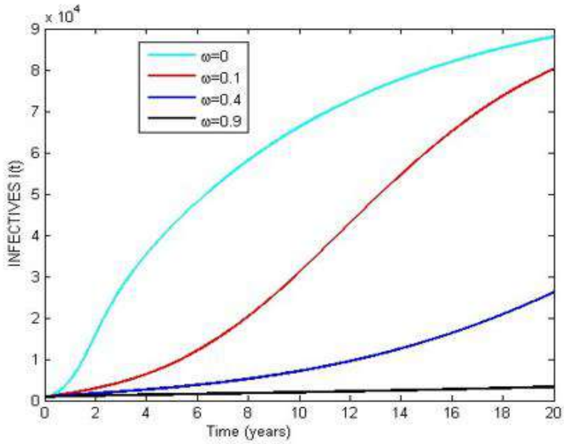

Figure. 7 Effects of different values of PrEP

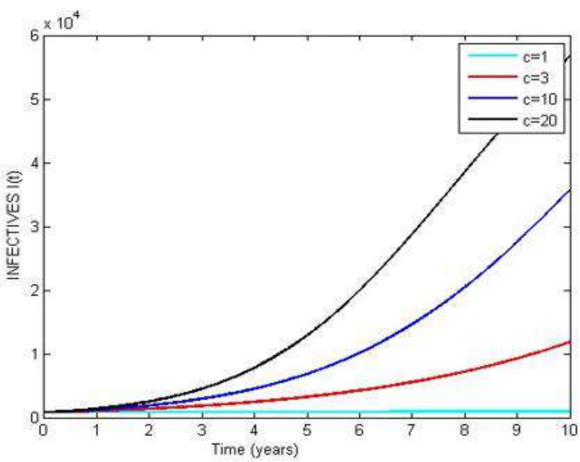

Figure 8. Effects of multiple sexual partners

Without these factors, PrEP may not only fail to provide adequate protection but also potentially worsen the situation in the community, as some PrEP users may engage in risky behaviors, perpetuating a false sense of security and control.

However, when used correctly, PrEP is expected to significantly reduce the public health burden of HIV/AIDS and drug resistance, as shown in Figure 7.

Figure 8 illustrates the impact of varying sexual partners C on the infective class, demonstrating a clear correlation between an increase in sexual partners and a rise in infected individuals. Some HIV-positive individuals adopt a carefree attitude, prioritizing personal freedom over public health concerns, contributing to the spread of the disease. The number of sexual partners emerges as the most significant factor in HIV acquisition risk. The plot in Figure 8 also reveals that a substantial number of new HIV infections are largely attributed to the increase in sexual partners. To curb the spread of the disease, it is crucial to limit the number of sexual partners, unsafe sexual behavior, and interactions with infected individuals.

In this work we consider the implementation of the optimality system using five different combinations of the control strategies, each strategy utilizes a minimum of one time-dependent control functions. The strategies considered are defined as follows: Policy 1 is the implementation of single controls; Policy 2 is the implementation of double controls; Policy 3 is the implementation of Tripple controls and Policy 4 is the implementation of all the four controls.

Policy 1: the optimal implementation of single control, u_2 (PrEP strategy).

Policy 2: the optimal implementation of two control combinations, this has two different combinations a and b

Strategy 2a: The optimal use of public sensitization on the use of all HIV prevention tools in the efforts to prevents susceptible from contacting HIV and Sexual behavioral therapy (u_1, u_4)

Strategy 2b: The optimal use of screening of new arrivals and Sexual behavioral therapy. (u_3, u_4)

Policy 3: The optimal implementation of triple control combinations,

Strategy 3: The optimal use of public sensitization on the use of all HIV prevention tools in the efforts to prevents susceptible from contacting HIV, (PrEP strategy) and Sexual behavioral therapy. (u_1, u_2, u_4)

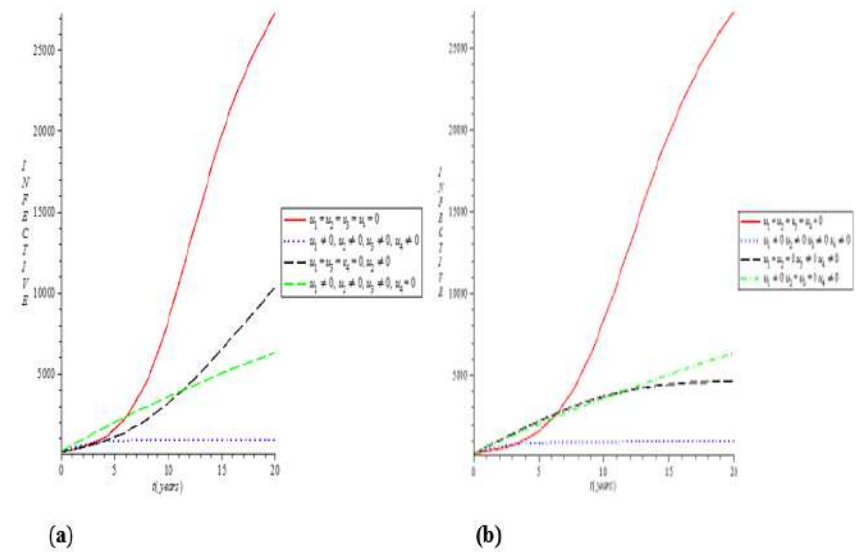

Figure 9(a, b). Plots showing the different control strategies (1,2,3,4,5)

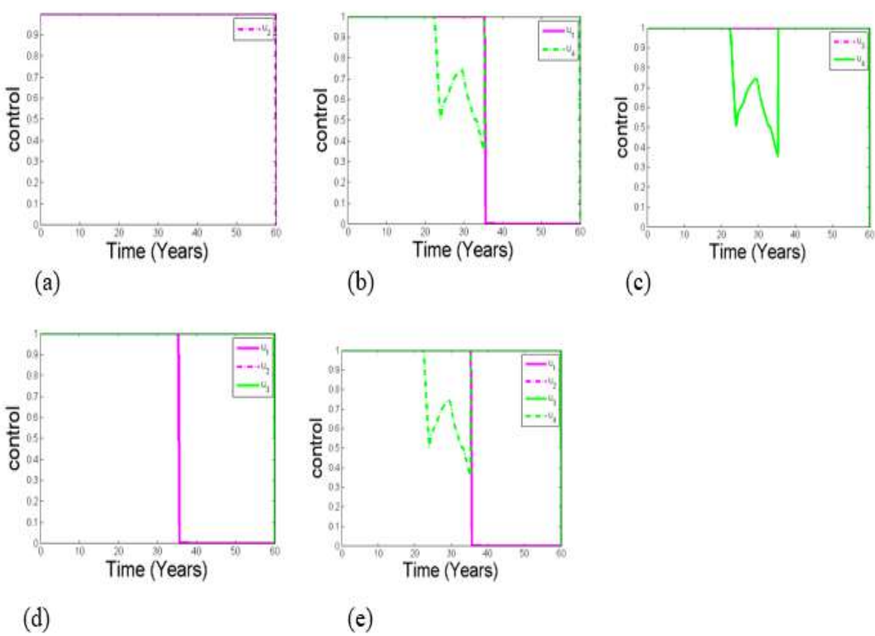

Figure 10(a, b, c, d, e). Plots showing the different control profiles of the strategies (1,2,3,4,5)

Policy 4

The optimal implementation of all the four control functions. The optimal use of public sensitization on the use of all HIV prevention tools in the efforts to prevents susceptible from contacting HIV, (PrEP strategy), Screening of new arrivals and Sexual behavioral therapy. (u_1, u_2, u_3, u_4)

From Figure 9a, $u_1 = u_2 = u_3 = u_4 = 0$ indicated by the red line a case where none of the optimal control strategies are implemented. $u_1 = u_3 = u_4 = 0, u_2 \neq 0$ indicated by the black dash line a case where only a single control u_2 is implemented. This implies that when the PrEP strategy u_2 is implemented there is indeed a remarkable reduction in the number of infection but not sufficient to give the optimal reduction need. $u_1 \neq 0, u_2 \neq 0, u_3 \neq 0, u_4 = 0$ indicated by the green dash line a case where triple optimal control measures u_1, u_2 and u_3 are implemented. This shows that a noticeable reduction is achieved which is much better than implementing only u_2. $u_1 \neq 0, u_2 \neq 0, u_3 \neq 0, u_4 \neq 0$ indicated by the blue dotted line a case where all of the four optimal control measures u_1, u_2, u_3 and u_4 are implemented. Result shows that the implementing the four u_1, u_2, u_3 and u_4 could lead to an optimal decrease in the spread of HIV/AIDS. Hence, it is better to implement all the four strategies u_1, u_2, u_3 and u_4 to reduce infection and minimize cost. Thus, sensitization of the public will create an awareness to educate the populace on the new and existing prevention measures particularly that PrEP is an additional preventive measure, all new arrivals must be screened and responsible sexual behavior should be practice.

From Figure 9b $u_1 = u_2 = u_3 = u_4 = 0$ This is indicated by the red line a case where none of the optimal control strategies are implemented. $u_1 \neq 0, u_2 = u_3 = 0, u_4 \neq 0$ indicated by the green dash dot line a case where double optimal control measures, u_1 and u_4 are implemented.

It can be seen visibly that there is a measure of control in implementing u_1 alongside u_4, public sensitization and sexual behavioral therapy play a major role in the reducing infection. Reduction in the number of sexual partners by way of sexual behavioral therapy is beneficial in lowering transmission rate and can greatly slow down the spread of the infection. $u_1 = u_2 = 0, u_3 \neq 0, u_4 \neq 0$ This is indicated by the black dash line a case where double optimal control measures, u_3 and u_4 are implemented. This has more effect on the control of the disease than the earlier combination, screening of new arrivals u_3 and the sexual behavioral therapy u_4 combined has more reducing effect. $u_1 \neq 0, u_2 \neq 0, u_3 \neq 0, u_4 \neq 0$ indicated by the blue dot line a case where all the four optimal control strategies are implemented. The plot shows clearly that the implementation of the four strategies $u_1, u_2, u_3,$ and u_4 can achieve an optimal reduction in the prevalence and incidence of the disease despite the presence of infective immigrants. However, intervention strategies that would be most effective in reducing HIV incidence would aim to reduce infectiousness of people living with HIV and to prevent transmission of susceptible individuals. Therefore, targeting both the susceptible and the infective in the population and among the immigrants can lead to decrease in the new cases of infection, ultimately to a substantial decline in prevalence of infection.

Figure 10(a,b,c,d,e) at the control profiles of the different combinations of control intervention, showing when the controls are at maximum and minimum.

4.1 Efficiency Analysis

Efficiency analysis was carried out to determine the effectiveness of each control combination in reducing the spread of the disease. The efficiency index, as defined by Olaniyi *et al.* (2023), served as the basis for assessing each strategy.

$$\text{E.I} = \frac{\text{Total infection averted by the control intervention}}{\text{Total infection without any control intervention}} \times 100$$

The results presented in Table 2 reveal that Policy 4 (strategy 4) exhibited the highest efficiency, achieving an impressive index of 97%. Strategies 2b followed closely, with efficiency index of 84%. Conversely, Strategies 2a and 3 demonstrated relatively closer efficiency, with indices of 77% and 78%, respectively. Strategies 1 showed a lower efficiency, with indices of 62%.

4.2 Cost-effectiveness Analysis

A detailed cost-effectiveness analysis was carried out to ascertain the most economically viable approach. This entails evaluating two unique intervention strategies aimed at addressing the issues of HIV/AIDS.

4.2.1 Average cost effectiveness ratio (ACER)

The Average Cost-Effectiveness Ratio (ACER) is a measure of quantity used to assess the financial performance metric (efficiency) of different control strategies. It provides a thorough assessment of the cost-effectiveness of each intervention. It is calculated by dividing the total cost of implementing a control measure by the total number of infection cases prevented by that implementation. Mathematically, ACER is represented as

$$\text{ACER} = \frac{\text{Total implementation costs of control intervention}}{\text{Total averted infection by implementation}}$$

The total cost of intervention, which serves as the numerator in the ACER expression, is estimated using the objective functional. The computed ACER values are summarized in Table 2. Notably, Strategy 4 emerges as the most cost-effective approach, consistent with the findings from the Efficiency analysis (EI) analysis. Table 2 provides a comprehensive overview of the results for each strategy arranged in increasing order of infection averted by policies.

Table 2. Total infection averted, total cost, Efficiency indexes and ACER for all strategies considered in order of averted infections

Policy	Intervention strategies	Total infections averted	Total Cost ($)	Efficiency Analysis	ACER
1	1	17 000	137 900	62%	8.111764706
2	2a	21 300	138 922.5	77%	6.522183099
	2b	23 000	139 439.3	84%	6.062578261
3	3	21 500	139 983.2	78%	6.510846512
4	4	26 700	140 622.5	97%	5,266760302

4.3.3 Incremental cost effectiveness ratio (ICER)

To investigate the cost-benefit comparison between the various policies, the Incremental Cost-Effectiveness Ratio (ICER) is utilized. ICER measures the all cost incurred to achieve one extra unit of health outcome, facilitating comparisons between various control strategies. The ICER formula is employed to assess the cost-effectiveness of each strategy, informing the selection of the most efficient approach. Mathematically, ICER is expressed as:

$$\text{ICER} = \frac{\text{Difference in cost between strategies}}{\text{Difference in health effects between strategies}}$$

We compute the ICER for policy 2 with two options for double combinations of controls as follows:

$$\text{ICER(2a)} = \frac{138922.5}{21\,300} = 6.522183099$$

$$\text{ICER(2b)} = \frac{139439.3 - 138922.5}{23000 - 21300} = 0.304$$

ICER(2a)>ICER(2b), clearly strategy 2a strongly dominates strategy 2b, so it is better to exclude strategy 2a since strategy 2b is the most cost effective in Policy 2 (double controls) as shown in Table 3

Table 3. Total infection averted, total cost and ICER for double control interventions

Intervention strategies	Total infections averted	Total Cost	ICER
2a	21 300	138 922.5	6.522183099
2b	23 000	139439.3	0.304

We compare the ICER for Policy 1 of single control with the outcome of policy 2 (double control) which is strategy 2b, it is computed as follows:

$$ICER(1)=\frac{137900}{17000}=8.111764706$$

$$ICER(2b)=\frac{139439.3-137900}{23000-21300}=0.255655$$

ICER(1)>ICER(2b), we discard strategy 1 since strategy 2b is the most cost effective. The most cost-effective strategy 2b is compared with policy 3 (triple control combination) which is strategy 3, it is computed as

$$ICER(2b)=\frac{139439.3}{23000}=6.062578261$$

$$ICER(3)=\frac{139983.2-139439.3}{21500-23000}=-0.3626$$

ICER(2b)>ICER (3), we discard strategy 2b since strategy 3 is the most cost effective of the two 2 as shown in Table 4

Table 4. Total infection averted, total cost and ICER for strategies 2b and 3

Intervention strategies	Total infections averted	Total Cost	ICER
2b	23 000	139 439.3	6.062578261
3	21 500	139 983.2	-0.3626

The most cost-effective strategy of strategies 3 and strategy 4 is computed as

$$\text{ICER}(3)=\frac{139983.2}{21500}=6.510846512$$

$$\text{ICER}(4)=\frac{140622.5-139983.2}{26700-21500}=0.12294$$

Table 5. Total infection averted, total cost, ACER and ICER for strategies 3 and 4.

Intervention strategies	Total infections averted	Total Cost	Efficiency Analysis	ACER	ICER
3	21 500	139 983.2	97.5%	6.510846512	6.520846512
4	26 700	140 622.5	99.8%	5.266760300	0.12294

from table 5 we observe that strategy 3 dominate 4 this implies that strategy 3 is more costly and less effective compared to strategy 4. Thus, we exclude strategy 3 from consideration.

Hence, from the above analysis, we conclude that strategy 4 which is the combination of all the four control functions (u_1, u_2, u_3, u_4) which is the use of public sensitization on the comprehensive prevention tools in the efforts to prevents susceptible from contacting HIV, PrEP strategy, Screening of new arrivals and Sexual behavioral therapy respectively. Strategy 4 is the most cost effective and should be considered for implementation particularly in limited resource communities.

Public sensitization on comprehensive HIV prevention tools yields substantial epidemiological benefits by improving awareness, risk perception, and uptake of protective behaviors, thereby reducing the effective contact rate among susceptible individuals. Increased awareness promotes the acceptance and adherence to pre-exposure prophylaxis (PrEP), which significantly lowers susceptibility to infection and contributes to a reduction in transmission potential at the population level. Screening of new arrivals enables early identification and management of infected individuals, limiting the introduction of new infections into the population and reducing external sources of transmission. In addition, sexual behavioral therapy helps modify high-risk behaviors such as multiple partnerships and inconsistent condom use, thereby decreasing exposure probability and interrupting transmission pathways.

Collectively, these interventions act synergistically to reduce the basic and control reproduction numbers, ultimately contributing to sustained epidemic control and potential disease elimination.

CONCLUSION

This study developed and analysed a nonlinear deterministic model of HIV/AIDS transmission that incorporates a variable influx of infected immigrants, alongside pre-exposure prophylaxis (PrEP) and treatment at different stages of infection, to examine endemic dynamics and bifurcation behaviour of the model due to immigration of infective. Building on earlier frameworks by Oladejo and Oluyo (2022) and Oladejo and Lawal (2025), the study further integrates efficiency and cost-effectiveness analyses to identify optimal intervention strategies that minimize HIV transmission. The optimal control framework, comprising public sensitization to reduce effective contact u_1, PrEP implementation u_2, screening of new arrivals u_3, and sexual behavioural therapy u_4. The optimal control quadruple was classified into five policies namely the single control function, u_2; double control implementation comprising of two strategies u_1, u_4 and u_3, u_4; policy 3 the triple consisting of u_1, u_2, u_3 and lastly policy 4 which is the combination of all four control function u_1, u_2, u_3, u_4. to evaluate their combined and individual impacts to know which intervention policies best prevent the infection in the population. Analytical results established the global asymptotic stability of the endemic equilibrium using Lyapunov methods and LaSalle's invariance principle, while bifurcation analysis indicated the presence of forward bifurcation. Numerical simulations showed that expanded PrEP coverage among high-risk HIV-negative individuals substantially reduces new infections, whereas the influx of infected immigrants can significantly amplify disease spread in the absence of adequate control measures. Efficiency and cost-effective analysis reveal that policy 4 which is the combination of all four-control function averted the greatest number of cases of HIV/AIDS in this study making it the most cost effective and efficient policy

The findings of this study support a set of coordinated recommendations aimed at strengthening HIV prevention and control efforts. Public health policies should prioritize integrated intervention strategies that combine public sensitization, PrEP implementation, screening of new arrivals, and sexual behavioural therapy, as these measures act synergistically to reduce transmission more effectively than isolated approaches. Scaling up PrEP programs among high-risk HIV-negative populations is essential, with emphasis on adherence support and targeted education to maximize its preventive benefits. Routine screening and testing of incoming populations should be strengthened to minimize the introduction of new infections into susceptible communities. In addition, sustained behavioural change interventions, including sexual health education and risk-reduction counselling, should be reinforced to lower high-risk practices that drive transmission dynamics. Policymakers are also encouraged to incorporate cost-effectiveness considerations into decision-making to ensure optimal allocation of limited healthcare resources.

Despite these insights, the study is subject to certain limitations, notably the reliance on hypothetical parameter values, which may affect the precision and generalizability of the findings; incorporation of real-world data would enhance the robustness of the results.

Future research should focus on incorporating real-world epidemiological and behavioural data to improve model calibration, validation, and predictive accuracy. Extending the model to explicitly account for risk compensation among PrEP users is crucial, as behavioural changes may influence the overall effectiveness of prevention strategies. Further studies should explore the role of adherence dynamics, including discontinuation and inconsistent use of PrEP and treatment, in shaping long-term outcomes. Additionally, integrating more complex population structures such as age stratification, heterogeneous sexual networks, and spatial mobility patterns would provide deeper insights into transmission pathways and improve the realism of model predictions. Exploring stochastic modeling approaches and data-driven parameter estimation techniques could further enhance the robustness of future analyses.

Overall, the findings underscore that a combination of integrated control measures is markedly more effective than isolated strategies, highlighting the importance of coordinated public health interventions in reducing HIV transmission and prevalence.

REFERENCES

Abbas, U. L., Anderson, R. M., & Mellors, J. W. (2007). Potential impact of antiretroviral chemoprophylaxis on HIV-1 transmission in resource-limited settings. PloS one, 2(9), e875. doi:10 1371/journal. Pone.0000875

Brauer, F., & Van den Driessche, P. (2001). Models for transmission of disease with immigration of infectives. Mathematical Bioscience and Engineering, 171, 143-154. doi:10.1016/S0025-5564(01)00057-8.

Castillo-Chavez, C., & Song, B. (2004). Dynamical models of tuberculosis and their applications. Mathematical. Bioscience and Engineering, 1(2), 361-404, doi:10.3934/mbe.2004.1.361

Chazuka, Z., Mudimu, E., & Mathebula, D. (2024). Stability and bifurcation analysis of an HIV model with pre-exposure prophylaxis and treatment interventions. Scientific African, 1(23), e01979. doi:10.1016/j.sciaf.2023.e01979.

Cohen, M. S., Chen, Y. Q., McCauley, M., Gamble, T., Hosseinipour, M. C., Kumarasamy, N., Hakim, J. G., Kumwenda, J., et al. (2016). Antiretroviral PrEP therapy for the Prevention of HIV-1infection transmission. New. England Medical Journal, 375(9), 830-839. doi:10.1056/NEJMoa1600693

Cohen, M. S., McCauley, M., & Sugarman, J. (2012). Establishing HIV treatment as Prevention in HIV Prevention Trial Network (HPTN): 2011 HPTN 052 randomized trial: an ethical odyssey. Clinical Trials, 9, 340-347. doi:10.1177/1740774512443594

Dabbo, M. I., Seidu, B., & Makinde. O. D. (2013). Modeling the Combine Effect of Careless Susceptible and Infective Immigrants on the Dynamics of HIV/AIDS. Journal of public Health and epidemiology, 3(1), 362-369. https://doi.org/10.5897/JPHE12.092

Diekmann, O., Heesterbeek, J. A. P., & Metz, A. P. (1990). On the definition and computation of the basic ratio Ro in the model of infectious disease in heterogeneous population. Mathematical Biology, 2(1), 265-382, doi:10.1007/BF00178324

Drabo, E. F., Hay, J. W., Vardavas, R., Wagner, Z. R., & Sood, N. (2016). A cost-effectiveness analysis of preexposure prophylaxis for the prevention of HIV among Los Angeles County men who have sex with men. Clinical Infectious Diseases, 63(11), 1495-504. doi:10.1093/cid/ciw578.

Fleming WH, Rischel RW. Determinstic and Stochastic optimal control. Springer, New York. 1975.

International Organization for Migration (IOM), The world migration report 2020. Accessed 6th March 2024. worldmigrationreport.iom.int

Issa, S., Massawe, E. S., & Makinde, O. D. (2011). Modelling the effect of screening on the spread of HIV infection in a population with variable flow of infective immigrants. Scientific Research and Essays, 20, 4397-4405, doi:10.5897/SRE11.385.

Joint United Nations Programme on HIV/AIDS (UNAIDS). (2023). Global Report 2023. Accessed 16th February 2024. https://thepath.unaids.org

Kemnic, T. R., & Gulick, P. G. (2024). HIV Antiretrviral Therapy, StatPearls Publishing. https://www.Ncbi.nlm.nih.gov/books/NBK513308

Keno, T. D., & Etana, H. D. (2023). Control strategies for COVID-19 model. Journal of Mathematics. Hindawi, 2023(1) Article ID 2050684. doi:10.1155/2023/2050684

Kim, S. B., Yoon, M., Ku, N. S., Kim, M. H., Song, J. E., Ahn, J. Y., et al. (2014). Mathematical modeling of HIV prevention measures including pre-exposure prophylaxis on HIV incidence in South Korea. PLoS ONE 9(3), 1–9. http://doi.org/10.1371/journal.pone.0090080

Lasalle, J.P. (1976). The stability of dynamical systems, Society for Industrial and Applied Mathematics. http://dx.doi.org/10.1137/1021079

Lenhart S, Workman. Optimal control applied to biological models. CRC press, New York. 2007.

https://doi.org/10.1201/9781420011418

Coffee, M.. Lurie, M. N., & Garnett, G. P. (2007). Modeling the impact of migration on the HIV epidemic in south Africa. AIDS, 21(3), 343-350. DOI: 10.1097/QAD.0b013e328011dac9

Mahato, B. Mishra, B. K., Jayswal, A., & Mishra, B. K. (2015). Mathematical model of malaria for co-infection of plasmodium vivax and plasmodium falciparium in India. British Microbiology Research Journal, (BMRJ), 5(36), 285-299. doi:10.9734/BMRJ/2015/10267

McCullom, R. (2020). An African Pope Won't Change the Vatican's Views Condoms and AIDS previous next An African Pope Won't Change the Vatican's Views on Condoms and AIDS, The Atlantic. http://www.theatlantic.com/sexes/archive/2013/02/an-african-pope-won't-change-the vatican's-views-on-condoms-and-aids/273535.

Mohammed, I. D., & Baba, S. (2012). Modelling the Effect of Irresponsible Infective Immigrants on the Transmission Dynamics of HIV/AIDS. Advances in Applied Mathematical Biosciences, International Research Publication House, 20, 31-40. http://www.irphouse.com

Moya, E. M., Rodrigues, D. S., Pietrus, A., & Severo, A. M. (2022). A mathematical model for HIV/AIDS under pre-exposure and post-exposure prophylaxis. Biomathematics. 11(2), 14, 2208319. doi:10.55630/j.biomath.2022.08.319

Murray, J. D (2001). Mathematical Biology: I. An introduction, Third Edition. Springer. doi:10.2307/40378655.

Odebiyi, O. A., Oladejo, J. K., Elijah, E. O., Olajide, E., Taiwo, A. A., & Taiwo, A. J., (2024). Mathematical Modeling on Accessing the impact of screening on HIV/AIDS Transmission dynamics. Journal of Applied Science and Environmental Management 28(8), 2347-2347. https://www.ajol/index.php/jasem

Odebiyi, O. A., Salahu, W.O., Oladejo, J. K., Adepoju, O.A., Adeboye, A.O., Olajide, O.A., Elijah, E.O. and Ayanrinola A. (2025). Analysis of Mathematical Modeling and Optimal Control of HIV/AIDS Dynamics. Asian Journal of Pure and Applied Mathematics Volume 7, Issue 1, Page 808-826, 2025; Article no. AJPAM.2244. https://doi.org/10.56557/ajpam/2025/v7i1244

Oladejo J. K., & Oluyo, T. O. (2022). Effects of PrEP on the HIV/AIDS dynamics with immigration of infectives. International Journal of Mathematical Analysis and Modelling. 5(2), 36-54. https://tnsmb.org/journal/index.php/ijmam/article/view/54

Oladejo, J. K and Lawal, W. O. (2025). Optimal Control Strategy of HIV/AIDS Model with Pre-Exposure Prophylaxis and Behavioral Change. Journal of Nigerian Mathematical Society, 44(1), 99-113. https://ojs.ictp.it/jnms/index.php.

Olaniyi S, Falowo KO, Okosun KO, Mukamuri M, Obabiyi OS, Adepoju OA. Effects of saturated treatment on malaria spresd with optimal intervention. Alexandria Enginering Journal 65. 2023. 443. https://doi.org/10.1016/j.aej.2022.09024

Pontryagin LS, Boltyanskii VG, Gamkrelidze RV, Mishchenko EF. The Mathematical theory of optimal control processes. John Wiley & Sons, New York. 1962. https:/doi.org/10.1002/zamm.19630431023.

Pontryagin LS. The Mathematical theory of optimal control processes, Routledge. London. 2018. https:/doi.org/10.1201/9780203749319.

Ram, N., Agraj, T., & Dileep, S. (2009). Modeling and analysis of the spread of AIDS epidemic with immigration of HIV infectives. Mathematics and Computer, 49(3). 880-892. doi.org/10.1016/j.mcm.2008.09.013.

Rector CR, Chandra S, Dutta J. Principles of optimization theory. Narosa Publishing House, New Delhi. 2005.

Ross, J., Cunningham, C. O., & Hanna, D. B. (2020). HIV outcomes among migrants from low-income and middle-income countries living in high-income countries; a review of recent evidences. Current Opinion Infectious Disease 31(1), 25-32. doi:10.1097/QCO.0000000000000415.PMID:29095720

Sharp, P. M., & Hahn, B. H. (2011). Origins of HIV and the AIDS Pandemic. Cold Spring Harbor perspectives in medicine, 1, a006841. doi:10.1101/cshperspect. a006841.

Siegfried, N., Muller, M., Deeks, J. J., & Volmink, J. (2009). Male circumcision for prevention of heterosexual acquisition of HIV in men. Cochrane Database System Reviews. (2), CD003362. [PubMed:19370585]. https://pubmed.ncbi.nlm.nih.gov

Silva, C. J., & Torres, D. F. (2017). Modeling and optimal control of HIV/AIDS prevention through PrEP. arXiv preprint arXiv, 1703.06446. doi:10.3934/dcdss.2018008

Van den Driessche, P., & Watmough, J. (2002). Reproduction numbers and sub-threshold endemic equilibria for compartmental models of disease transmission. Mathematical. Bioscience and Engineering. 180, 29-48, doi:10.1016/S0025-5564(02)00108-6

Walensky. R. P., Park, J. E., & Wood, R (2012). The cost –effectiveness of Pre-exposure prophylaxis for HIV infection in South African women. Clinical infectious disease 2012(54), 1504-1513.Writing Group HIV Treatment as Prevention: Models, Data,

Wang, X. (2004). A Simple Proof of Descartes's Rule of Signs. The American Mathematical Monthly, ISSN 0002-9890, 111(6), 525. doi:10.2307/4145072

World Health Organization Policy Brief, WHO Expands its Recommendation on the use of oral PrEP on HIV infection. November 2015. Geneva. Accessed 5th January 2024

ISBN: 978-625-91915-0-8

9 786259 191508 >