



IntechOpen

IntechOpen Series
Sustainable Development, Volume 44

Sustainable Development Annual Volume 2025

*Edited by Antonella Petrillo, Ann Hemingway,
Ebba Ossiannilsson, Rui Alexandre Castanho
and Luís Loures*



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Published in London, United Kingdom

Sustainable Development Annual Volume 2025

<http://dx.doi.org/10.5772/intechopen.1014288>

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First published in London, United Kingdom, 2026 by IntechOpen

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For EU product safety concerns: IN TECH d.o.o., Prolaz Marije Krucifikse Kozulić 3, 51000 Rijeka, Croatia, info@intechopen.com or visit our website at intechopen.com.

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

Sustainable Development Annual Volume 2025

Edited by Antonella Petrillo, Ann Hemingway, Ebba Ossiannilsson, Rui Alexandre Castanho and Luís Loures
p. cm.

This title is part of the Sustainable Development Book Series, Volume 44
Series Editor: Usha Iyer-Raniga

Print ISBN 978-1-80631-102-6

Online ISBN 978-0-85466-951-6

eBook (PDF) ISBN 978-1-80631-103-3

ISSN 2753-6580

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Meet the Series Editor



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Meet the Topic Editors



Antonella Petrillo is a Professor at the Department of Engineering of the University of Naples “Parthenope”, Italy. She received her Ph.D. in Mechanical Engineering from the University of Cassino. Her research interests include multi-criteria decision analysis, industrial plants, logistics, manufacturing, and safety. She serves as an Associate Editor for the International Journal of the Analytic Hierarchy Process. She is a member of the AHP Academy and several editorial boards. She has over 160 scientific publications in international journals and conferences, and she is the author of 5 books on innovation and decision-making in industrial applications and engineering.



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Ebba Ossiannilsson, with a Ph.D. from the University of Oulu, Finland, is an internationally recognized scholar and consultant in open, online, and flexible education, specializing in quality, inclusion, scalability, sustainability, innovation, precision learning, and digital transformation in higher education. Prof. Ossiannilsson is deeply committed to equity, human rights, planetism, democracy, green sustainability, accessibility, inclusion, and social justice, promoting ethical, resilient, and future-oriented leadership. With more than 20 years of specialization in OFDL and over 40 years of experience in the education sector, she works primarily at the strategic and policy levels to advance SDG4 and the future of education. She is the founder of Ossiannilsson Quality in Open Online Learning Consultancy and serves on the Board of the International Council for Open and Distance Education (ICDE), where she chairs the ICDE Technology Network (TIN) on Leadership through Uncertainty and has been the Chair and an OER Ambassador since the inception of the ICDE OER Advocacy Committee. She is also Associate Professor of Open Education Leadership at the University of Nova Gorica, Slovenia. She has held visiting professorships at several international universities, including an appointment as Professor and Research Fellow at Victoria University of Wellington, New Zealand. Her research and advisory work encompass open education, OER/OEP, AI in education, leadership, ethics, quality assurance, learner-centered pedagogies, and the global dimensions of digital transformation. She has contributed to major international initiatives with the European Commission, UNESCO, and OECD, and serves on numerous global expert groups, advisory boards, and editorial boards. She serves as an expert and reviewer for the European Commission, collaborates with the Joint Research Centre on quality in open education, and works with ITCILO and

ICoBC. She has previously served on the boards of EDEN and EUCEN and is a quality expert for ICDE, EDEN, and EADTU. She is regularly invited as a keynote speaker at international conferences. A prolific author, she has published extensively on open education, digital transformation, AI in higher education, and sustainable, human-centered learning ecosystems. Her contributions have been recognized through numerous distinctions, including EDEN Fellow, EDEN Council of Fellows, Open Education Europe awards, SPARC Europe Champion (2021), the Leadership Excellence Award from Open Education Global (2022), and ICDE Honorary Membership for outstanding service and impact on ICDE's development.



Rui Alexandre Castanho holds an international Ph.D. in Sustainable Planning in Borderlands. He is Vice-Dean for Sustainable Development, WSB University, Poland, and a visiting professor at the University of Johannesburg, South Africa. He is also a European Climate Pact Ambassador. Dr. Castanho completed a postdoctoral research appointment on the GREAT Project at the University of the Azores, Portugal. He is the vice-coordinator of the VALORIZA - Research Centre for Endogenous Resources, Polytechnic Institute of Portalegre (IPP), Portugal, and collaborates with the Centre for Tourism Research, Development and Innovation (CITUR), Portugal, and the AQUAGEO Research Group at the University of Campinas (UNICAMP), Brazil. Dr. Castanho was awarded the title of Doctor Honoris Causa by the Peruvian University of Science and Informatics (UPCI).



Luís Loures, Ph.D., is a landscape architect and agronomic engineer and the president of the Polytechnic Institute of Portalegre, Portugal. He has a Ph.D. in Planning and a postdoctoral degree in Agronomy. He is also a researcher at VALORIZA – Research Centre for Endogenous Resource Valorization at the Polytechnic Institute of Portalegre, and at CinTurs – Research Centre for Tourism, Sustainability, and Well-being. At the latter, Dr. Loures is a researcher on several funded research projects focusing on urban planning, landscape reclamation, and urban redevelopment, and the use of urban planning as a tool for achieving sustainable development.

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Preface

The world is facing a profound challenge: the global ecological footprint is growing at a faster rate than GDP. While this phenomenon has been studied for many years, the need for clear and actionable strategies has never been more urgent. Sustainable development is no longer a distant goal but a critical necessity. Individuals, businesses, public institutions, and governments must all adjust their approaches and take daily actions that balance progress with environmental responsibility.

In an increasingly interconnected and globalized world, the “drive” for sustainability cannot be confined to individual nations or isolated efforts. The challenges at hand are too vast and complex to be addressed by any one entity alone. For meaningful progress to occur, countries, industries, and communities must collaborate across borders, sharing knowledge, resources, and strategies. Global cooperation is not only desirable; it is indispensable. Tackling the underlying causes of overconsumption and resource depletion requires a collective effort.

Sustainable thinking involves managing resources (i.e., natural, financial, human) efficiently and strategically. By doing so, value is created not only through economic growth but also by enhancing the well-being of communities and the stakeholders involved throughout the value chain.

It is required to move away from a society that measures prosperity through production and material consumption, to one that prioritizes living better by consuming less and focusing on sustainability across all dimensions of life. This transition is not about embracing a minimalist approach, but rather about finding ways to reduce the unsustainable patterns of resource consumption that have defined much of modern society.

At the same time, the role of technology cannot be overlooked. New technologies, particularly those driven by artificial intelligence (AI) and digitalization, offer transformative potential to optimize resource use and streamline processes across industries. These tools can become powerful allies in the fight for sustainability. From improving energy efficiency to reducing waste, AI and digital platforms can help manage and monitor resource consumption more precisely than ever before.

However, these technologies must be applied in ways that do not exacerbate the very problems they seek to solve. The challenge lies in ensuring that digitalization and technological innovation contribute to a more sustainable future without leading to the overexploitation of resources or creating new forms of environmental degradation. These technologies must be a driving force for change, enabling smarter, more sustainable decisions, and creating a positive feedback loop for responsible production and consumption.

The path to sustainable development is complex and multifaceted. It demands a rethinking of business models, supply chains, and societal structures, with an

emphasis on long-term goals that ensure both environmental protection and social equity. In this context, global collaboration is key to overcoming the irrational and consumptive practices that have driven resource depletion. By working together across borders, solutions can be developed that address these challenges fairly and effectively.

This “Sustainable Economy and Fair Society” section explores growth models and strategies to achieve intergenerational equity, with a focus on economic, social, and environmental well-being. It examines critical issues such as risk assessment in a sustainable economy, the pursuit of social justice, and the creation of a fair society. The aim is to provide valuable insights into how sustainability can be integrated into business practices, public policies, and community development, thereby supporting the creation of a more resilient and equitable future.

The challenges ahead are significant, but the opportunities to create a better, more sustainable world are vast. Through collective effort, global cooperation, and the responsible application of new technologies, it is possible to build a future where economic, social, and environmental well-being are achieved in harmony.

I would like to express my sincere gratitude to everyone who contributed to making this work possible. Special thanks go to the editorial team at IntechOpen for their support and dedication throughout the preparation of this volume. I also thank the reviewers for their insightful feedback, which greatly enhanced the quality of this work. Lastly, I appreciate all those working in the back office, including the administrative and technical teams, whose efforts were essential to the success of this publication.

Antonella Petrillo

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Topic Editor: Sustainable Economy and Fair Society

Sustainability is no longer a concept confined to environmental stewardship; it is a framework that encompasses health, equity, and resilience across human and ecological systems. The One Health approach emphasizes that human health is inseparable from the health of animals and the environment, reminding us that climate change, biodiversity loss, and zoonotic diseases are not isolated phenomena but interconnected challenges. For instance, rising global temperatures and deforestation increase the risk of zoonotic spillovers, which in turn disrupt economies and workplaces worldwide. These disruptions disproportionately affect women, who are often concentrated in caregiving roles, frontline health services, and informal labor markets.

At the same time, the sustainability of societies depends on the equitable participation of women in the workforce. Climate change and environmental degradation exacerbate

existing inequalities: women in urban settings often juggle precarious employment with caregiving responsibilities intensified by health crises. Without systemic support, such as flexible work policies, childcare infrastructure, and recognition of the need for women's safety at work and during leisure, the workforce risks losing innovators and creators of social stability.

By weaving together ecological responsibility and gender equity, we can build systems that protect planetary health while empowering women, who are disproportionately affected by environmental and health crises, to thrive in the workforce and in their leisure time. This dual perspective underscores that the future of sustainability depends on both safeguarding ecosystems and dismantling barriers to women's full participation in economic and social life.

Ann Hemingway

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Topic Editor: Health and Wellbeing

The contemporary global education landscape is undergoing a profound and rapid transformation. Driven by digital transformation, artificial intelligence, geopolitical instability, and widening social inequities, these developments challenge long-standing assumptions about educational leadership, institutional responsibility, and the pursuit of inclusive and equitable learning environments. This section, "Inclusivity and Social Equity", addresses these challenges by assembling research and perspectives that advance understanding of how education can contribute to more just, resilient, and sustainable societies.

Within this context, the chapter "The Intersections of Leadership, Openness, Ethics and AI: Leading through Uncertainty" offers a theoretically informed and practice-oriented examination of the evolving demands placed on leadership in higher education. It highlights the critical interplay between openness, ethical responsibility, and technological advancement, with particular attention to the opportunities and tensions introduced by artificial intelligence. Rather than presenting new empirical data, the chapter synthesizes existing scholarship, professional practice, and anticipatory analysis to articulate a leadership orientation capable of responding to uncertainty in complex educational systems. A central contribution of the chapter is the articulation of a leadership framework structured around three interrelated dimensions: Care, Curiosity, and Challenge. These principles encapsulate the dispositions and capacities required to cultivate inclusive, adaptive, and ethically grounded institutional cultures. Positioned within global policy agendas, including the Sustainable Development Goals, the framework highlights the need for leadership that is both contextually responsive and globally aligned. By situating AI within broader discourses on equity, ethics, and openness, the chapter underscores the imperative for human-centered leadership amid significant technological

disruption. It calls for deliberate and informed stewardship to ensure that emerging technologies contribute to meaningful educational transformation and support the realization of socially just futures.

Ebba Ossiannilsson

Ossiannilsson Quality in Open Online Learning Consultancy,
Lund Sweden

Topic Editor: Inclusivity and Social Equity

The Sustainable Development Annual Volume 2025 represents a continued commitment to advancing knowledge, dialogue, and innovative practices in the field of sustainability. This “Urban Planning and Environmental Management” section gathers interdisciplinary research exploring pathways to achieve the United Nations Sustainable Development Goals, with a particular focus on territorial cohesion, energy transition, urban regeneration, and community resilience.

In fact, the section offers diverse perspectives that connect environmental science, policy, governance, and education. The contributions provide evidence-based insights, case studies, and methodological reflections aimed at supporting informed decision-making for academia, practitioners, and policymakers alike.

Therefore, it continues the mission of integrating sustainability into all dimensions of development, reinforcing the role of scientific collaboration in bridging local actions with global strategies. We extend our gratitude to all contributing authors, reviewers, and institutions whose dedication has made one more volume possible.

Rui Alexandre Castanho

Vice-Dean for Sustainable Development,
WSB University,
Poland

EU Climate Pact Change Ambassador for Portugal

Luís Loures

Rector of the Polytechnic Institute of Portalegre,
Portugal

Topic Editors: Urban Planning and Environmental Management

Section 1

Sustainable Economy and Fair Society

Chapter 1

Analysis of a Structural Model for Measuring Agro-Ecotourism Development in the Municipality of Jardín, Antioquia

*Diana Guzmán Álvarez, Mario Cerón-Muñoz
and Holmes Rodríguez Espinosa*

Abstract

The identification of factors that evaluate agro-ecotourism development (AD) becomes a necessity to plan tourism in rural areas and strengthen public policy guidelines. Therefore, the purpose of this study was to identify the factors that define agro-ecotourism development in the municipality of Jardín (Antioquia, Colombia) based on the potentialities and constraints evaluated in 149 rural properties and their owners, using a structural equation model. According to the findings, agro-ecotourism development is the reflection of individual capabilities (IC) with a weight of 1 and residents' perception (RP) with a weight of 0.72. However, infrastructural development (weight 0.44) and farm resources (weight 0.51) reflect this to a lesser extent. In conclusion, the AD is mainly determined by IC and RP, and it is necessary to improve infrastructure and diversify resources on the farms for greater prosperity in terms of AD.

Keywords: agro-ecotourism, indicators, structural equation model (SEM), tourism planning, agro-ecotourism potential

1. Introduction

In the new world scenario, rural tourism is presented as an opportunity and a competitive advantage to be developed in areas with low population density, natural spaces and a diversified supply of resources, which can be used to better position, communicate and market tourist sites [1].

Therefore, it is a good time to propose tourism development models that contribute to the quality of life of communities without being detrimental to their natural resources, are more respectful and inclusive of the local residents, allow action planning with the community to better develop tourism in each place, and gather the aspirations of tourism development (TD) from the local stakeholders [2, 3].

The proposed Land Management Scheme for the municipality of Jardín proposes the development of an agro-ecotourism model that integrates the agrarian cultural

landscape with the urban center diversifying the local productive structure so that it is more competitive and inclusive and guarantees the permanence of the peasantry in the territory [4].

Tourism development is related to promoting local community participation in decision making, responding to the characteristics and needs of individual destinations, and knowledge and understanding of the environments [5]. This development refers to the intention of stakeholders to establish relationships in a joint and coordinated manner to improve the conditions of a territory community [6], seeking to obtain benefits that equitably influence the entire community, and ensuring the preservation of the environment [7].

The measurement of TD has been carried out through qualitative indicators, inquiring about the material of tourism facilities, infrastructure, quality of human resources, social commitment, state management capabilities and tourism resources [8]. Therefore, TD requires the identification and analysis of qualitative and quantitative information of the factors that influence the development model's implementation [9].

Different studies have proposed models for the measurement of TD, as is the case of Mai et al. [8] who proposed a set of factors to measure it, such as: infrastructural development, equipment of tourist facilities, tourist resources, among others; or the study of Afthanorhan et al. [10] whose model included factors concerning the perception of tourism impacts and their influence on TD. Also, the analysis of Kim et al. [11] presented a model based on residents' attitudes toward community TD, concluding a positive relationship between these two variables. Moreover, Marzo [12] concluded in their model that support from local residents positively affects TD. Additionally, the doctoral research of Cañero [13] makes a significant contribution with a model based on latent variables related to positive and negative impacts, direct and indirect, at a social, economic, cultural and environmental level, on support for sustainable TD, while researchers such as Tien et al. [14] analyzed how farmers' skills influence TD.

Previous studies show in their findings that factors such as infrastructure, individual skills or capabilities, available resources, and the perception of residents, have a relationship with the TD. Hence, this study addressed the measurement of agro-ecotourism development (AD) as a modality of rural tourism, which serves as an articulating axis to strengthen the endogenous development of local communities, contributing to environmental conservation, income diversification in rural areas [15] and to strengthening public policies for tourism planning [9].

Now, the structural equation modeling (SEM) approach has been used to validate tourism models in order to test reliability, validity and to establish relationships between variables [8, 14, 16–18], because a better understanding of these relationships can help destination providers to better plan and design tourism sites, as well as assist governments and organizations in terms of sustainability [19]. Researchers such as Li et al. [20] demonstrated that SEM is ideal for assessing the relationship between the perceived positive impacts of rural tourism and the willingness to participate in its development. Studies such as that of Coelho and Gosling [21] found that through these models it was possible to determine factors related to attractiveness, like ease of access, infrastructure, resources, cultural attributes, among others, which are important for the development of tourism in rural areas.

Based on the components above, this study intends to identify the factors that define agro-ecotourism development (AD) in the municipality of Jardín, based on the potential of the farms and their owners, contributing to tourism planning in rural areas and strengthening public policy guidelines for the sector.

In the rest of the manuscript, the authors initially present the methodology with the design, variables, and data analysis; subsequently, the results focus on explaining the structural equation model; following is the discussion where the authors explain the relationship between agro-ecotourism development (AD) with the latent factors, finally highlighting the factors that define AD to a greater extent.

2. Materials and methods

This study was conducted in the municipality of Jardín, Antioquia, located in the southwestern subregion of Antioquia (5°35'58" N to 5°30'29.73" N and 75°50'05" W to 75°53'33.9" W) in the villages of San Bartolo, La Casiana, Morro Amarillo, El Tapado, La Linda, La Selva, La Salada, La Herrera, Serranías, Verdún, Gibraltar, La Arboleda, Río Claro, Alto del Indio, Santa Gertrudis, Macanas and La Mesenia. This territory has altitudes ranging from 1500 to 3000 meters above sea level, with a broken topography and steep slopes. Temperatures average between 19 and 25.8°C.

The population of this study consisted of 149 farms and their owners, corresponding to the total number of members of the Organization Campesinos Construyendo Futuro (OCCF), in the municipality of Jardín, Antioquia. Inclusion criteria consisted of being owners of their farms and willing to participate voluntarily in this research.

A structured questionnaire composed of five latent factors and 33 indicator variables was applied as follows: (1) Infrastructure Development (ID) measured through six indicators adapted from studies conducted by López [22]; (National Administrative Department of Statistics (DANE) [23]; and Mai et al. [8]. (2) Individual Capabilities (IC) measured through 12 indicators, which were adapted from the study conducted by Tien et al. [14]. (3) Farm Resources (FR) measured through seven indicators, adapted from the study conducted by López [22]. (4) Resident perception (RP) measured through eight indicators, adapted from studies conducted by Cañero [13] and Hateftabar and Michel [24]. (5) Agro-ecotourism Development (AD), adapted from the study by Mai et al. [8].

The factors were measured by the following indicators: ID by means of access to the farm (ID1), condition of the access road to the farm (ID2), public services of the dwelling (ID3), construction material of the house (ID4), floor material of the dwelling (ID5), and type of bathroom of the dwelling (ID6). IC by community organization (IC1), community leadership (IC2), community empowerment (IC3), marketing of agricultural and livestock products (IC4), good agricultural practices (IC5), innovation of agricultural and livestock products (IC6), community agro-ecotourism development (IC7), agro-ecotourism businesses management (IC8), family finances (IC9), innovation in non-agricultural and livestock products (IC10), environmental management and conservation (IC11), IT tools (IC12). FR by resources of tree and shrub species (FR1), ornamental species resources (FR2), wildlife resources (FR3), agricultural resources (FR4), aromatic species resources (FR5), livestock resources (FR6), gastronomic resources (FR7). (4) RP by tourism employment opportunity for residents (RP1), tourism provides more business for the local population (RP2), tourism improving the economic situation of the region (RP3), preservation of local culture (RP4), tourism facilitates the development of cultural activities for the local residents (RP5), tourism has a positive impact on local identity (RP6), tourism creates an environment conducive to cultural maintenance (RP7) and tourism encourages the protection of natural resources (RP8). The model is shown in **Figure 1** nearby, with the following hypotheses: The AD is the reflection of ID (H1), IC (H2), FR (H3) and RP (H4).

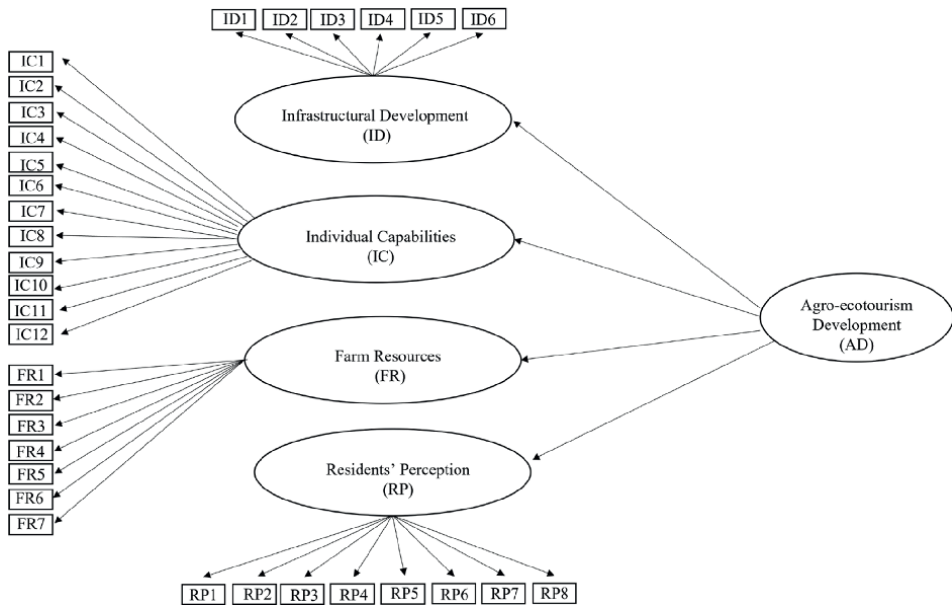


Figure 1.
Theoretical model for agro-ecotourism development in the Municipality of Jardín, Antioquia, Colombia.

The study was based on the structural equation modeling (SEM) methodology proposed by Hair et al. [29]. The Mardia's Kurtosis test was used to verify whether the data followed a normal distribution. The reliability of the scales was validated through Cronbach's Alpha and composite reliability statistics, for which satisfactory values greater than 0.7 were considered [25–28]. To determine the model's goodness of fit, the ratio between the Chi-square and the degrees of freedom was taken into account, being considered an acceptable fit if the values are from 2 to 3 and with limits up to 5 [29, 30]. Other indices, such as the root mean square error of approximation (RMSEA) with a value below 0.08 [31], the comparative fit index (CFI) with values above 0.90 [32], the Tucker-Lewis index (TLI) with values greater than 0.90 [33] and the standardized root mean square residual (SRMR) with a value less than 0.08 [32], were taken into account as criteria to define a good model fit. For SEM analysis, the lavaan [34, 35] library from the R-Project [36] software was used.

3. Results

The result of the first proposed model, in **Figure 1**, presented a barely acceptable fit according to the results of the fit indices: RMSEA equal to 0.072, CFI equal to 0.80, TLI equal to 0.79, and the SRMR presenting a value of 0.08. In addition, the ratio between the chi-square and the degrees of freedom ($X^2/g.l$) was 4.62 m approximately equal to 5. Therefore, this ratio was used as a modification index; variables were eliminated to improve the model fit considering the theoretical support of researchers such as López [22], DANE [23], Tien et al. [14], Cañero [13], Hateftabar and Michel [24] and Mai et al. [8].

The original model was re-specified, resulting in a model based on five latent factors, as follows: ID measured by only three indicators, IC measured by only six

indicators, FR measured by only two indicators, RP measured by only four indicators; and AD is the reflection of the four factors mentioned above. The SEM model is Type 1: reflective–reflective [37], also called the hierarchical common factor model, Lohmöller [38] shown in **Figure 2**, with the following hypotheses: The AD is the reflection of ID (H1), IC (H2), FR (H3), and RP (H4).

The data set did not follow a multivariate normal distribution since a p-value of less than 0.05 was obtained. Cronbach's Alpha and composite reliability statistics presented satisfactory coefficients for all the factors, greater than or equal to 0.7 (see **Table 1** nearby), which means that the indicators used to measure the ID, IC, FR, and RP factors in agro-ecotourism development are reliable. To accept the hypotheses of the latent variables, the significance level of the p-value was considered, which was less than 0.05; the ratio between the Chi-Square and the degrees of freedom presented a value of 1.60, indicating that the model has an acceptable fit. The SEM presented an RMSEA of 0.064, a CFI of 0.93, a TLI was 0.91, and the SRMR presented a value of 0.07, indicating a good model fit.

Performance of the variables related to infrastructure was between good and very good, which means that, in general, the infrastructure of each property was in good condition. Regarding the residents' perception, it was possible to note positive appreciations on the impacts caused by tourism. However, in variables such as agricultural product trading and innovation skills, family finances, environmental management and conservation, these are all to be improved and strengthened. Regarding the diversification of resources of agricultural and aromatic species, they both should be diversified (see **Table 2** nearby).

The results obtained in the estimation of the proposed structural model and the acceptability of the global fit, according to **Figure 2**, provide the basis for affirming that the relationship between agro-ecotourism development (AD) with the latent factors: infrastructural development (factor loading of 0.44), individual capabilities (loading of 1.00), farm resources (loading of 0.51), and residents' perception (loading of 0.72) is significant and positive, where the effects of IC and RP are those of greater weight in

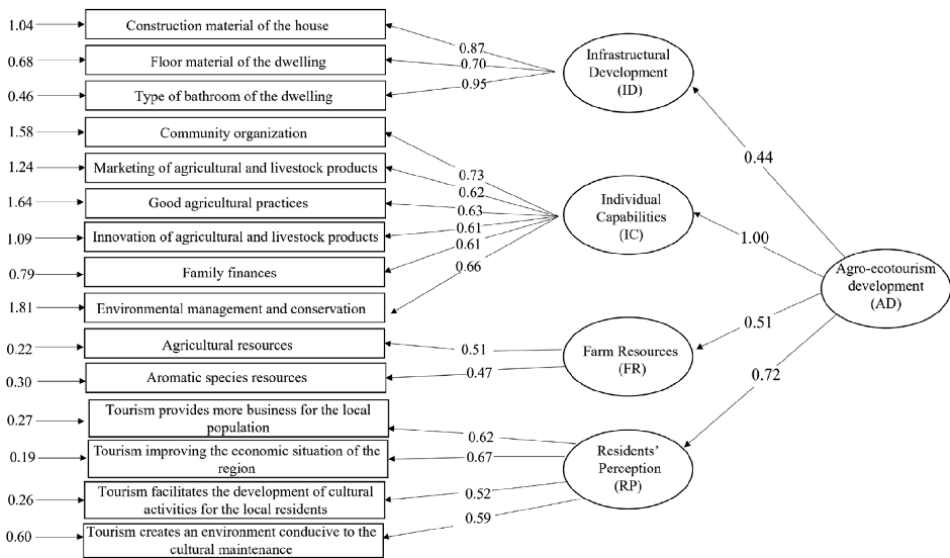


Figure 2.
Factors that define agro-ecotourism development in the municipality of Jardín, Antioquia, Colombia.

Latent factor	Indicator variable	Mean	Median	CR
Infrastructure development (ID) scale from 1 “very poor” to 5 “very good”	Construction material of the house (ID4)	3.99 ± 1.4	5	0.78
	Floor material of the dwelling (ID5)	3.91 ± 1.24	4	
	Type of bathroom of the dwelling (ID6)	4.22 ± 1.13	5	
Individual Capabilities (IC) scale from 1 “none” to 5 “a lot”	Community organization (IC1)	3.38 ± 1.63	4	0.79
	Marketing of agricultural and livestock products (IC4)	2.01 ± 1.42	1	
	Good agricultural practices (IC5)	2.85 ± 1.56	3	
	Innovation of agricultural and livestock products (IC6)	1.81 ± 1.36	1	
	Family finances (IC9)	1.75 ± 1.25	1	
	Environmental management and conservation (IC11)	2.63 ± 1.65	3	
Farm Resources (FR) scale from 1 “none” to 5 “a lot”	Agricultural resources (FR4)	1.75 ± 0.74	2	0.70
	Aromatic species resources (FR5)	1.55 ± 0.77	1	
Residents’ Perception (RP) scale from 1 “none” to 5 “a lot”	Tourism provides more business for the local population (RP2)	4.22 ± 0.93	4	0.87
	Tourism improving the economic situation of the region (RP3)	4.20 ± 0.94	4	
	Tourism facilitates the development of cultural activities for the local residents (RP5)	4.46 ± 0.83	5	
	Tourism creates an environment conducive to cultural maintenance (RP7)	4.08 ± 1.07	4	

Note: CR: Composite reliability.

Table 1.
Latent factors and measures of central tendency of the variables observed for the measurement of agro-ecotourism development in the municipality of Jardín, Antioquia.

n = 149			
Factor	Indicator variables	%	Performance
Infrastructure development (ID) scale from 1 “very poor” to 5 “very good”	Construction material of the house	58	Very good
	Floor material of the dwelling	42	Good
	Type of bathroom of the dwelling	54	Very good
Individual Capabilities (IC) scale from 1 “none” to 5 “a lot”	Community organization	36	Very good
	Marketing of agricultural and livestock products	60	None
	Good agricultural practices	34	A lot
	Innovation of agricultural and livestock products	70	None
	Family finances	68	None
	Environmental management and conservation	45	None

n = 149			
Factor	Indicator variables	%	Performance
Farm Resources (FR) scale from 1 “none” to 5 “a lot”	Agricultural species resources	45	Very few
	Aromatic species resources	58	None
Residents’ Perception (RP) scale from 1 “none” to 5 “a lot”	Tourism provides more business for the local population	46	A lot
	Tourism improving the economic situation of the region	46	A lot
	Tourism facilitates the development of cultural activities for the local residents	60	A lot
	Tourism creates an environment conducive to cultural maintenance	44	A lot

Table 2.
Performance of the variables observed for the measurement of agro-ecotourism development in the municipality of Jardín, Antioquia.

comparison with the ID and FR factors. Therefore, the four hypotheses, which establish that infrastructural development, individual capabilities, farm resources and residents’ perception define agro-ecotourism development are accepted.

4. Discussion

Individual capabilities were more relevant to local agro-ecotourism development, which is consistent with the results of Morozov and Morozova [39] and Tien et al. [14] who found that the development of people’s skills allow improving tourism management, competitiveness and tourist satisfaction. Likewise, it goes hand in hand with the findings of Ariefianto and Hilmi [40] who reported that, when people master their skills through training processes, they become empowered when it comes to agro-ecotourism development.

The results of this study indicate that, in order to strengthen community-based agro-ecotourism, the development of individual capabilities of rural inhabitants is a fundamental aspect from which arises the importance of generating knowledge on issues related to community organization, trading of agricultural products, good agricultural practices, innovation of agricultural products, family finances and environmental management and conservation. This result matches the findings of Moreno de Souza et al. [41]; Policarpio and Martins [42]; Surmeier [43]; and Jamal and Higham [44], who found that individual capacity building through knowledge transfer is important for the development of skills and competencies that enable communities to thrive, alleviate poverty, and be fairly and equitably included in local tourism development systems.

Other studies such as those by Chaskin et al. [45]; Ritchie and Crouch [46]; Moscardo [47]; Mohamad et al. [48]; and Ghaderi et al. [49] agreed with this result, noting that the success of tourism destinations depends on the capabilities or specific abilities that the community has to do things, solve problems and meet proposed objectives, as well as accessing and managing their resources efficiently with greater empowerment for planning, evaluation and decision making, thus further improving the community’s collective knowledge of tourism.

Residents' perception also had a strong and direct impact on agro-ecotourism development, since the perception of the inhabitants revolved around the fact that tourism provides more business for the locality, improves the region's economic standing, facilitates the development of cultural activities and creates an environment conducive to the maintenance of endogenous culture, thus reflecting a positive disposition to participate in the development of rural tourism. This result was highlighted in the studies by Ko and Stewart [50]; Choi and Murray [51]; Rasoolimanesh and Jaafar [52]; Cañero et al. [53]; Gannon et al. [54]; Hateftabar and Michel [24]; Kanwal et al. [55]; Li et al. [20]; Kim et al. [56]; Nematpour and Khodadadi [57]; and Lee [58], who pointed out the fundamental role played by residents' perceptions on tourism development at the local level, due to the fact that having the community's support, sentiments and conscious acceptance of tourism carried out in their territory, with all the positive and negative impacts it entails, contributes to the progress of agro-ecotourism, as long as it is carried out in a planned manner, respecting the culture and ways of life.

According to the results of this study, infrastructure development had a lesser influence on agro-ecotourism development. However, it is no less important, since this study showed that the construction material of the house, floor material of the dwelling and type of bathroom of the dwelling are necessary conditions for tourism progress. This result coincides with the research conducted by Reyes [59]; Seetanah et al. [60]; Campesino et al. [61]; Trukhachev [62]; Jovanović and Ilić [63]; Catudan [64]; de Freitas y de Sevilha [65]; Mai et al. [8]; Durán et al. [66]; Ruiz et al. [67]; and Zeng et al. [68] who defined infrastructure development as a key factor that has a positive effect on tourism development, because it contributes to the competitiveness of destinations and the attraction of tourists.

Dalimunthe et al. [69] proposed that tourism development depends on the infrastructure available in the destinations due to the growing interest of the urban population in visiting natural spaces found in rural areas to have experiences with agricultural activities. Therefore, researchers such as Schaerer and Dirven [70] pointed out that potentially attractive places should improve their infrastructure, such as access, public services and lodging, among others, to guarantee such development.

The farm's agricultural resources had less influence on agro-ecotourism development. However, it was decided to leave this factor because the aromatic species resources and agricultural resources present on the farm contribute to agro-ecotourism development to some extent. This result matches the findings of Henri et al. [71]; Evgrafova et al. [72]; Riveros [73]; Masiero et al. [74]; Forje et al. [75]; Puška et al. [76]; and Ren et al. [77] who stated that fauna and flora biodiversity, as well as the natural landscape, are attributes for ecotourism development, generating economic surpluses for the inhabitants, and contributing to the conservation of the environment and local culture.

Ecotourism resources are key attractions to attract visitors, because people are looking for experiences with nature and its landscapes. This is in agreement with the study by Gültekin et al. [78] who took into account resources and the degree of their attractiveness as key factors for ecotourism development.

5. Conclusions

The results of this study allow us to conclude, through the analysis of the structural model, that agro-ecotourism development in Jardín is defined by four latent

factors such as infrastructural development (ID), individual capacities (IC), resident's perceptions (RP), and farm resources (FR). The IC and RP factors define the AD to a greater extent and the ID and FR factors determine the AD to a lesser extent. According to the results, the variables that presented the lowest performance capacities in the commercialization of agricultural products and family finances, product innovation, environmental management and conservation, and diversification of traditional agriculture.

The theoretical implication of this study is that the capacities individual and resident perception factors determined agro-ecotourism development; producers do not have sufficient capacities to convert agro-ecotourism into a rural development initiative that does not compete with or supplant the agricultural vocation, but quite the contrary, that fulfills the complementary role to farm work. Similarly, it is essential to take into account the resident's perceptions since their wishes are important agro-ecotourism development.

As for the practical implications, this study serves as a tool for tourism planning and provides input for strengthening the public policy of the sector, however, the success or failure in the implementation of the above depends on the participation of the community and the management of the local government.

For future studies, it is suggested to determine SEM models that include aspects that measure the human impact, at the level of disturbance and erosion, in rural agro-ecological systems that serve for the efficient management of installed capacities and the sustainable uses of the resources of the territory. Likewise, it is recommended to attempt to construct models that include factors that measure the impact of the sectoral policies in tourism and the impact of the associative schemes with a territorial focus in rural development, since they can serve as a tool to verify the effectiveness of both in the social, economic, environmental, and the political improvement of a territory.

Acknowledgements

Banco Universitario de Programas y Proyectos de Extensión (BUPPE), project 19899 of 2018. Funding by the Aurelio Llano Posada Foundation (FALLP) and Organización Campesinos Construyendo Futuro de Jardín, Antioquia (OCCF). We would also like to thank the research group on Agro-sciences, Sustainability and Territory GAMMA of the University of Antioquia.

Disclosure statement

The authors report that there are no competing interests to declare.

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Chapter 2

Research of Sustainable Development and Green Growth Industry

Sang Soo Chae

Abstract

We are conducting many industrial considerations for continued growth. In this process, the necessary industries can be regarded as green growth, which can be seen as essential industries that can coexist. A paradigm shift to a low-carbon society is inevitable for survival and strengthening international efforts to actively respond to climate change while aiming for energy independence, such as transition to a low-energy consumption economic and social structure and increasing the penetration of new and renewable energy. Discuss the current status and necessity of green growth, focusing on Korea, and review plans for sustainable growth. Businesses, along with the government, must promptly identify changes in domestic and foreign environmental regulations and policy directions, and make active and proactive efforts to develop new industries and preoccupy the market based on existing accumulated capital and similar technology. The change to a green business model, after all, green growth is not limited to new businesses, but fundamental changes that can lead to changes in corporate competition methods, changes in corporate structures, and changes in industrial structures. It is a manufacturing company or a service company.

Keywords: sustainable development, green growth industry, natural resources, energy resource, low-carbon

1. Introduction

1.1 Concept and importance of green growth industry

A month's worth of fossil fuels used today is close to a year's worth compared to the 1950s. A year's supply of oil in the 1950s is equivalent to six weeks' supply today. Excessive use of these conventional energy resources can be seen as a result of the increase in efficiency due to industrialization and urbanization as economic growth takes place. The UN says drinkable water will decline by 30% in about 25 years, and 30% of Asia's agricultural land is likely to dry out within 20 years. The main reason for this is that mankind overuses natural resources.

The emergence of the green industry and its first claim was about 180 years ago Environmental, in 1827, when the famous French mathematician Fourier, JB pointed out the possibility of global warming caused by carbon dioxide, which is a natural

anomaly along with the earth's abnormal climate phenomenon, resulting in a drastic change unlike before. Earth continues to warn of the seriousness of environmental dangers due to the occurrence of unexpected situations. On April 22, 1970, Senator Gaylord Nelson of Wisconsin, USA declared Earth Day for the first time to arouse national interest in environmental issues. In the largest organized protest in US history, more than 20 million people attended the Earth Day event, heard speeches, held debates, and took action to clean the environment [1].

Since then, environmental pollution has been regarded as a secondary problem due to economic growth. Evidence of this is also revealed in the fact that for 20 years after 1970, events that would arouse environmental crises, such as Earth Day, were stopped. In 1990, Earth Day was held at the center of the US headquarters, and 500 organizations from 100 countries around the world participated (CERES).

Green growth is based on the low-carbon policy to reduce GHG emissions, and in the growth model focusing on the input of existing factors, the use of natural resources increases as the economy grows, in which economic growth and environmental damage such as GHG emissions are coupled. In the process of production and consumption, the emission of pollutants such as carbon dioxide also increases. Green growth is a low-carbon economic development paradigm that reduces greenhouse gases and is based on eco-efficiency that seeks decoupling between economic growth and environmental damage, maximizes the efficiency of resource use and minimizes environmental pollution [2].

Energy A paradigm shift to a low-carbon society is inevitable for survival and strengthening international efforts to actively respond to climate change while aiming for energy independence, such as transition to a low-consumption economic and social structure and increasing the penetration of new and renewable energy [3].

Thus Green Growth,¹ the word is a concept that encompasses both the values of environment and growth. The two concepts are already being realized as a new growth paradigm in developed countries. Discovering promising items and new technologies in the energy and environment-related technologies and industries derived from the process of shifting the existing economic growth paradigm to an environmentally friendly one, and attempting mutual convergence with existing industries to create new growth engines and new jobs [4].

There will be our common future, which was reported to the UN in 1987 by WCED,² environmental preservation and development are not opposing concepts, but under the basic concept that long-term sustainable development is possible only based on environmental preservation, the central sustainable development can be presented as an ideology and support from around the world can be obtained.

The presented concept of sustainable development emphasizes that the active management of environmental assets is a very important issue in the continuous socio-economic development that transcends generations.

The sustainability revolution unfolded in response to the Industrial Revolution, which deteriorated the environment and our well-being. If the growth method so far

¹ It was first mentioned in *The Economist* (January 27, 2000) and began to be widely used through the Davos Forum. The Seoul Initiative for Green Growth (SI) was adopted at the Ministerial Meeting on Environment and Development in Asia and the Pacific ('05), As discussions by the Economic and Social Commission for the Pacific (UNESCAP) and the international community began in earnest, green growth-related content began to be included in the OECD Ministerial Council Declaration.

² World Commission on Environment and Development: The World Commission on Environment and Development was established in 1984.

is adhered to, the natural environment system that supports life on earth will collapse due to global warming, environmental pollution, health and poverty problems, etc.

It is necessary to accurately grasp the reality of global warming. Global warming tends to absorb the infrared long-wave radiation energy emitted from the earth to the outside, while the original greenhouse effect passes the ultraviolet short-wave radiation coming from the sun well. Because of this, some of the heat emitted from the earth is blocked and re-radiated back to the earth's surface, but without this greenhouse effect, the earth's average temperature drops to -18°C , making life impossible. Scientists believe that carbon dioxide plays the biggest role in causing the excessive greenhouse effect. The global average temperature change, sea level rise, and polar area decrease are due to the rapid increase in the amount of carbon dioxide generated artificially through human activities.

Why the world is now facing both a resource crisis represented by high oil prices and an environmental crisis symbolized by climate change is that the world population continues to increase from 6 billion in 2000 to 8.2 billion in 2030, progress in trade liberalization, and economic growth in developing countries. The problem of energy and resource shortage is expected to accelerate due to rapid growth etc., and the years of use of energy sources are 43 years for oil and 62 years for natural gas [5].

The necessity of the green industry can be explained in four ways. First, there is a need to join the international community's efforts to resolve fundamental changes (Greenforall).

The 250 years since the Industrial Revolution, atmospheric CO_2 concentration has soared by more than 35%, and global average temperature has soared by 0.80°C . In 2008, international oil price crises approaching \$ 150 per barrel coincided with the financial and food crises that hit the world. Recognizing these risks, as the response of each country began, a group of financial, energy and environmental experts in the UK proposed a Green New Deal to the British government, inspired by the New Deal policy that overcame the Great Depression in the 1930s.

The United Nations Environment Program (UNEP) proposed Green Economy, and the US Center for American Progress (CAP), a think tank of the Obama administration, presented Green Recovery. Green growth is a concept of converting the pattern of economic growth into an environment-friendly one while pursuing economic growth that is abstract or complementary in terms of the possibility of realizing a wide range of policies for sustainable development (integration of economic development, social equity, and environmental protection) means possible economic growth [6].

Countries around the world are introducing various environmental regulations and systems. The EU has already begun to strengthen environmental standards such as the New Chemical Substances Control System (REACH) and EuP (Energy-using Products) standby power regulation, and China also introduced the New Chemicals Environmental Management Act, which can be called the Chinese version of REACH in May 2009 legislative announcement.

The US Clean Energy and Protection Act, recently passed by the US House of Representatives, includes a border tax provision that would impose regulatory measures or tariffs on products exported from countries that are not committed to reducing greenhouse gases. If this happens, companies that emit a lot of greenhouse gases, energy-efficient products, and products that are harmful to the environment will no longer be able to survive in the global market. Environmental regulations are emerging as new trade barriers.

In most country, where exports account for about large amount of the country's gross domestic product (GDP), prompt response to global environmental regulations

is directly linked to the survival of the country and businesses. So far, in a situation where developed countries, which are the cause of environmental pollution and enormous economic benefits in the process of industrialization, have to take responsibility, the current status of international environmental agreements on environmental regulations made by advanced countries, centered on the EU, will be summarized [7].

1.1.1 Climate change convention

As the greenhouse effect of the earth intensified due to the increase of CO₂, the agreement made by EU countries came to fruition in the Convention on Climate Change adopted at the Rio Conference in June 1992, and Korea It joined in December 1993 and currently has 176 countries. And in December 1997, at the 3rd Conference of the Parties to the Climate Change Convention held in Kyoto, Japan, the Kyoto Protocol on the Climate Change Convention was adopted and specific guidelines were announced.

1.1.2 Kyoto protocol

As an obligation for developed countries, greenhouse gas emissions were reduced by an average of 5.2% from the 1990 level from 2008 to 2012, and Kyoto mechanisms such as the emission trading system, joint implementation system, and clean development system were introduced.

Korea is classified as a developing country (Annex 2 country) rather than a country (Annex 1 country) that fulfills its reduction obligations during the first implementation period, 2008–2012. Movements for reduction are taking place all over the place, and it seems that they will deal a considerable blow to the Korean export industry in the near future.

1.1.3 Basel convention

1983, Greenpeace found 41 barrels of waste from a dioxin spill in Soveso, Italy, in a French village. It has emerged as an international problem. After that, another waste spill occurred, and in June 1987 the Guidelines and Principles on Hazardous Waste were adopted in Cairo.

Based on the Cairo Guidelines in March 1989, the Basel Convention was adopted in Basel, Switzerland, in the presence of representatives of 116 countries, and entered into force in 1992.

The main content is that sound management must be ensured in the disposal of hazardous waste and other waste, and export of hazardous waste. The point is that entry must be notified in advance.

However, there were many difficulties in adopting the definition of hazardous waste because each country may define it differently, and Korea joined the Basel Convention in March 1994. As for the related domestic law, there is the 'Act on the Transboundary Movement of Waste and its Treatment, 'which is particularly burdensome in the waste-related fields such as the automobile and electronic industries.

1.1.4 Ramsar convention

Environmental convention adopted in Ramsar, Iran on February 2, 1971 for the conservation and wise use of wetlands, the official name is the Convention on

Wetlands of International Importance as Waterfowl Habitats. The main content is to conserve wetlands, which have great ecological value, and to systematically protect the natural ecosystem.

1.1.5 Montreal protocol

It is a treaty mutually regulating ozone emissions by countries around the world. The purpose is to prevent damage to the global ecosystem and animals and plants caused by ozone layer destruction by protecting the ozone layer by suppressing the emission of substances that destroy the ozone layer.

The Republic of Korea acceded to the Vienna Convention and the Montreal Protocol in February 1992, at the first amendment in December 1992, and at the second amendment in December 1994. The most core fuel mainly dealt with in the Montreal Protocol is CFC (freon), but regulations are separately regulated for developing countries.

The reason is that CFC is a widely used material in industry. Fortunately, South Korea was allowed to use regulated substances such as CFCs by 2010 in the location of developing countries.

1.1.6 Convention on biological diversity

Decrease in species. It is a convention adopted by the Rio Conference in June 1992 for the prevention and rational use of biological resources. It was created out of concerns about the extinction of biodiversity due to global environmental problems that are being polluted and destroyed.

In this agreement, there is also a provision to make good use of genetic resources using biotechnology, and currently, developing countries are requesting the transfer of genetic engineering technology from developed countries instead of providing their own genetic resources. But Developed countries such as the US, Australia, and Japan, which have excellent biotechnology, are only taking the position of exporting biotechnology products without technology transfer.

1.1.7 Current status of environmental regulations in the EU

Based on various international environmental agreements, the EU has made specific regulations on these environmental issues. The EU's environmental regulation policy is strictly applied not only to member states within the region but also to member states outside the region without exception of even 1%.

The EU has consistently come up with a number of policies, the most important of which is regulation that can exert a rather large influence on our industry. Through WEEE, the EU can reuse, recycle, and recycle at their own discretion. Determine the rate of recovery, and Only companies complying with this ratio can sell electrical and electronic products to the EU.

1.2 Necessity of green growth industry

The necessity of green growth industry is first, the deepening environmental crisis caused by global warming, and global warming is now acting as a threat to human survival. Second, the global energy and resource depletion crisis is deepening. The imbalance between energy supply and demand is deepening due to global economic growth and increased demand in emerging economies, and the fossil fuel-centered

energy consumption structure is accelerating resource depletion as China's oil consumption has soared more than twice. 85% of the world's energy sources depend on fossil fuels. Greenhouse gas emissions are also rapidly increasing due to the excessive use of fossil fuels.

Third, there is a global trend of increasing movement to utilize green markets and green industries, such as the carbon credits market and new renewable energy, as new national growth engines. So far, major developed countries have achieved high economic growth by intensively fostering key industries such as heavy chemicals and electronics.

Fourth, as a new opportunity for national development, a new paradigm that promotes economic growth and environmental protection simultaneously through Green Conversion has emerged. A new paradigm is needed to secure a competitive edge and create new markets by converting the entire value chain for each industry into an eco-friendly, low-carbon type. Factor input based on domestic price competitiveness, reduced suitability of manufacturing export-oriented industrial development strategy Considering the environment and carbon regulations, economic, social and environmental constraints occurred simply by relying on fossil fuels.

The core of green growth lies in a virtuous cycle structure in which economic growth is pursued while resource use and environmental pollution are minimized, and then used as a driving force for economic growth. After all, green growth is maximizing the synergy between the environment and economic growth. The point is that balanced development and just development at the global village level are linked to sustainable development, and the existing concept of development is reinterpreted from a social and integrated perspective by linking the solution of poverty in poor countries to environmental problems.

Rejuvenative production can be also separated by economic and non-economic sector. Passive restorative has the effect of reservation by nothing performance in economic revenue. This is natural effect because nothing is going on natural and ecosystems entirely. And active restorative has reality performance of detail policy for revenue, therefore it has been related with economic effect in green industry.

In vital technologies, circular vital has effect of technology that is related with protection of environment can affect the human health. This is very important thing which has condition for wellbeing life for life and is indirectly effect in phases of transmission, then this may be indirect effect by courses of non-economic sector. Lifelike vital has the effect which use the real resource remaining like ultra-low energy, carbon etc. then this can be effect on direct performance of economic sector. We can set the field of economic and non-economic sector that is also detailed separated 4 sector again (**Table 1**).

The concept of sustainable development is based on the concept that human beings are the center of solving all problems and that future generations are considered. Meaning, recent politics. Economy. It is becoming a basic concept that should be considered first when establishing policies in all fields, including society. Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

According to the announcement of the Global Footprint Network, which surveys the Earth's environmental capacity every year, the world's ecological capacity has decreased by 8–10 times compared to 1960. In this way, we must make efforts to eliminate the ecological footprint created by pursuing only the convenience of life.

The conclusion of the necessity of the green growth industry is that the vicious cycle of resource depletion risk and environmental damage due to rapid consumption

Restorative activities	Vital technologies
Passive restorative	Circular vital
Activities utilizing the strong natural growth and recovery capabilities of ecosystems. Value creation strategies that protect ecosystems and leave them sufficiently undisturbed to allow natural recovery – protecting and building value by doing nothing	Technologies that utilize scarce resources or have potentially harmful implications for ecosystems and human health use closed loop systems such as total stewardship, circular materials handling & management and cradle-to-cradle industrial principles
Active restorative	Lifelike vital
Harnessing natural production with verified positive benefits in terms of the diversity, resilience and health of Natural Capital, e.g. sustainable biological production in sectors such as timber, agriculture, pharmaceuticals and industrial materials.	Biological and lifelike production technologies borrow from and harness natural production techniques, including: ultra-low energy growth, abundant degradable production, waste to feedstock processes, room temperature materials production.

Source: Terrafiniti, J. Tantram and Tantram [8].

Table 1.
Rejuvenative production.

of fossil energy must now be revived with a virtuous cycle structure that preserves, protects or restores the environment with renewable energy and green industries to revive the depressed global economy.

It is the only option to develop the environment and the economy together in the new economic paradigm shift, and green growth suitable for the present generation to satisfy the needs of future generations who prioritize society, integration and the environment in the existing development concept, and to prevent a decline in ability. Sustainable development of the industry is necessary.

2. Economic and non-economic effects of green growth industries

2.1 Economic effect

The impact of green growth on industry and economy goes beyond new business opportunities in the environment and energy dimension, and the suspension of all companies can affect competitiveness. It is an industry with potential to emerge. Green growth is attracting attention as a solid global trend. Green growth is defined as sustainable growth that reduces greenhouse gas emissions and environmental pollution which means economic growth to generates revenue.

In the market, despite the economic downturn, solar power, green car, LED, wind power, nuclear power, fuel cell, biofuel, geothermal, power IT, and carbon market-related companies are attracting investors' attention, and now green growth is environmental energy-related companies. It provides numerous new business opportunities. Green growth is not just limited to new business opportunities in the environment and energy dimension, but if it is used well, all companies regardless of industry can have new opportunities to strengthen their competitiveness in the short to medium term. Specifically, green growth is to secure cost leadership through carbon emission trading and monetization of surplus electricity, commercialize carbon reduction technologies and processes, and provide marketing differentiation opportunities through appeal of green quality management capabilities.

It can show the table result (**Table 2**). This is resultant of GHG emission energy. These are consisted with CO₂ and CO₄ which take an emission. It can see the world GHG emission result, from 23,642 in 1991–1995 average to 36,839 in 2016–2021. But result is showing a further decline as of late.

In result of world emission level, it shows the 11,888.7 during 1991–1995, and 12,038.3 during 2016–2021. This has gap of Non-OECD group of from 11,066.1 during 1991–1995 to 23,694.7 during 2016–2021.

These means that OECD group have controlled in emission from energy. And advanced countries like OECD have lower rate emission energy versus non-OECD country. Rather non-OECD countries have more opportunity for using from any more advanced countries. These are non-economic effect of GHG emission entirely [10].

Even representative chimney companies are actively running for green growth while suffering immediate losses. Many predict that green growth will pose a major threat to traditional businesses. However, in the course of the investigation, it is paradoxically disproved that companies that have emitted large amounts of greenhouse gases so far have rather secured vested interests, which also means that they have secured a lot of rights to emit. In addition, it was found in the course of the research that if production does not reduce emissions, it can turn into a serious problem if greater profits are generated even without industrial activities.

The move to strengthen cost leadership through green growth is already becoming a reality. Currently, the economic feasibility of renewable energy is lower than that of fossil energy. However, if fossil energy is gradually depleted over time, the price of fossil energy will inevitably rise. On the other hand, the price of renewable energy will drop rapidly due to technology development and mass production. In fact, some argue that the sale of surplus power is already a reality, as in some parts of Africa electricity costs are higher than the production cost of solar cells. In developed countries, surplus electricity sales are also being attempted.

The point is that green growth can be used as a new opportunity to strengthen competitiveness in the short to medium term for all companies regardless of industry, going beyond the level of new growth businesses related to environment and energy. However, the changes that green growth will bring do not stay at this level. From a long-term perspective, the true revolution that green growth will bring lies in the possibility of changing corporate business paradigms.

Alvin Toffler suggested the agricultural revolution as the first wave, the industrial revolution as the second wave, and the knowledge and information revolution as the third wave. Renewable energy optimists point to the possibility that renewables could be the starting point of a fourth wave comparable to previous power shifts. This is because new and renewable energy has publicity of resources unlike existing fossil

	1991–1995	1996–2000	2001–2005	2006–2010	2011–2015	2016–2021
World	23642.5	25400.9	28351.2	32664.6	35904.0	36839.0
OECD	11888.7	12862.4	13341.7	13213.9	12709.6	12038.3
Non-OECD	11066.1	11731.7	14096.5	18347.2	22043.1	23604.7

Source: IEA [9], GHG Emissions from Energy.
Author calculation.¹GHG emissions from energy presents energy-related GHG emissions, including total GHG emissions from fuel combustion plus CO₂ and CH₄ fugitive emissions from energy.

Table 2.
GHG energy¹ (unit: IPCC source/category 1).

energy. Developing fossil energy entails numerous constraints, such as mining know-how, scale of movement, and mining and refining know-how, so companies without know-how and large-scale capital cannot easily enter.

Existing energy companies have used this characteristic to monopolize and control resources to generate large-scale profits. Even though other Fortune 500 companies have undergone significant changes over the decades, energy companies have maintained their staunch position. Renewable energy provides an opportunity for all companies to become energy producers themselves in the long term. The rule of the game may be who uses resources efficiently rather than who monopolizes and controls resources. The company that wins the game can acquire future power. This is the fourth wave that could be triggered by green growth.

Advanced technologies will lead green growth, but for the time being, companies with solution capabilities that find and apply the optimal combination of commercialized technologies will benefit from the green growth era. In order to save energy, it is possible to develop and apply state-of-the-art new technologies such as solar cell installation, geothermal power generation, and development of energy-efficient building materials.

2.2 Non-economic effect

Change to a green business model after all, green growth is not just limited to new businesses, but can be a fundamental change that can lead to changes in corporate competition methods, corporate structures, and industrial structures. This means that whether a manufacturing company or a service company can take advantage of green growth through new and renewable energy as an opportunity, it can create a completely different competitive edge. Businesses must overcome the traditional stereotype of receiving money from those who give value, and come up with creative green ideas that separate the flow of value and profit by using the new carbon market.

By strategically fostering the cultural content industry, a representative low-carbon, high value-added industry, it is possible to intensively develop and nurture five convergence-type contents such as computer graphics, digital virtual world, distance learning, broadcast communication convergence, and virtual reality.

We can note that recent trend of carbon scale (**Table 3**). These are average of CO₂/GDP in region by each five-year period. In this table, we can note that world index of carbon/GDP was 0.54 at 1991–1995, but it shows the 0.4 during 2016–2021. It notes that decrease of 25.9% in carbon market. It can consider the effect of committee in Climate Change meeting in 1997.

This would be clearly index in OECD countries, it notes the 0.38 in 1991–1995, but it has been changed to 0.22 which is closely 41.6%. On the other side, non-OECD sectors has a little lower result in 35% from 0.98 to 0.64.

	1991–1995	1996–2000	2001–2005	2006–2010	2011–2015	2016–2021
World	0.54	0.49	0.47	0.46	0.44	0.40
OECD	0.38	0.35	0.32	0.29	0.26	0.22
Non-OECD	0.98	0.85	0.82	0.78	0.72	0.63

Source: IEA [9], GHG Emissions from Energy.
Author calculation.

Table 3.
Carbon market of region (unit: CO₂ emissions/GDP (2015)).

Environmentally friendly tax policy create a foundation for creating more jobs while inducing environmental preservation and resource saving through environmentally friendly tax reform, such as the introduction of a carbon tax. It can be an industry in which all economic entities participate by maintaining tax neutrality through tax reduction or exemption.

Enhancement of the country's image through green industry brand marketing that enhances the national brand, response to climate change, and active publicity abroad to promote the image as a global environmental leader, and promotion of international green leadership through vitalization of trade between developed and developing countries in the field of climate change response can be utilized Revitalization of environmental diplomacy, such as international conferences and international organizations in the field of environment and MOUs for various environmental cooperation agreements, is an opportunity for green leadership.

Also, as realizing green technology as a next-generation growth engine, it is possible to preoccupy the global market through rapid growth of the country's domestic market and increased exports. In addition, the effect of expanding the country's domestic consumption and exports will continue to increase, and the effect of creating added value in the way of driving the industry based on green technology is also continuously possible.

In terms of job creation effect, the use of green technology and the introduction of eco-friendly and low-carbon processes in terms of groundbreaking CO₂ reduction and environmental preservation have shown significant CO₂ reduction effects among greenhouse gases over the past 10 years.

To summarize the effects of green growth, the change to a green business model, after all, green growth is not limited to new businesses, but fundamental changes that can lead to changes in corporate competition methods, changes in corporate structures, and changes in industrial structures. It is a manufacturing company or a service company.

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Policy Suggestions for Increasing the Attraction of Investment Capital for Sustainable Development: A Case Study in Vietnam

Lu Phi Nga and Phan Thanh Tam

Abstract

Sustainable development is a prevailing and aspirational objective pursued by numerous nations, including Vietnam. These policies have led to notable accomplishments in the Vietnamese economy, which has experienced significant growth, increased competitiveness, and shifting toward industrialization and modernization. Objective: The study aims to determine the key factors influencing investment capital attraction and sustainable development in Vietnam. Besides, the authors proposed policy recommendations to enhance investment capital attraction. Methodology: The authors conducted a descriptive survey based on the quantitative method and primary data collected directly from 800 managers related to enterprises with investment capital from three provinces and 01 City interviewed via a structured questionnaire and data analysis using SPSS version 20.0 and Amos software. Result: The five critical factors influencing investment capital attraction and sustainable development in Vietnam are based on a five percent significance and eleventh accepted hypothesis. Unique contribution: The financial and technological factor exhibits the highest standardized estimate coefficient and exert the most influence on attracting investment capital. It plays a crucial role in developing the digital and green economy by facilitating the adoption of clean technology and green finance, contributing significantly to sustainable development.

Keywords: policy recommendations, investment capital, sustainable development, technology, green finance

1. Introduction

In recent years, Vietnam has increasingly prioritized sustainable development as a vital aspect of its operations. This is not merely an aspect but a fundamental

value that plays a crucial role in shaping Vietnam's vision and strategy. To facilitate thorough, effective, and swift sustainable development during the Fourth Industrial Revolution, digital transformation across the economy, society, management, and environment is essential. To integrate and improve upon the goals set by the state, the environmental, social, and governance (ESG) principles provide a framework for the digitization process [1, 2]. Companies may fulfill expanding public and consumer expectations, uncover new opportunities, and boost their worldwide position by incorporating ESG concepts into corporate operations. The following are some ways capital attraction supports sustainable development:

Green projects like sustainable infrastructure, renewable energy, and technology development need finance. For example, local and foreign investors can provide capital through preferential loans, green bonds, and sustainable investment funds [3]. Investment capital for enterprises and governments improves industrial technology, resource consumption, and environmental impact. This boosts innovation and technology, which is essential for a sustainable economy and long-term development that does not deplete natural resources [4].

Furthermore, these variables establish a framework for sustainable development by balancing economic growth, environmental stewardship, and social responsibility, as follows: (1) Economic factors based on economic stability and growth promote sustainable development by providing a solid platform for investment and industrial expansion, thereby improving long-term economic health and social well-being. (2) Political Factors based on Political stability and a strong legal framework are critical for attracting long-term investments because they provide predictability, protect business interests, and support long-term policy consistency, which is required for sustainable growth. (3) Technological Factors: Technological innovation fosters sustainable development by enabling efficient resource usage, decreasing environmental impact, and facilitating green infrastructure projects, making it critical for current economic policies that prioritize sustainability. (4) Environmental Factors: Adherence to environmental standards and sustainable resource management methods is crucial for establishing a green economy and attracting investments that are in line with global sustainability goals. (5) Social factors focused on social development, such as education, workforce quality, and healthcare, contribute to a stable investment environment by promoting an inclusive society that adheres to the ideals of sustainable and fair growth.

Capital attraction allows businesses and governments to invest in public transit, clean energy, and resource management. This preserves the environment, enhances quality of life, and provides jobs. Sustainable development prioritizes environmental conservation, social equity, and meeting social expectations [5]. We must invest in social issues like reducing poverty and enhancing education and healthcare to ensure progress benefits everyone.

Advocating ethical and sustainable corporate practices and socially and environmentally conscious businesses are more likely to attract investors in today's market. If companies can secure long-term investment capital, they can boost their credibility, increase their wealth, and open the door to potential new strategic alliances. Companies and projects receiving funding from green funds and sustainable investors are expected to adhere to transparency requirements and disclose their societal and environmental implications. This is done to promote openness and accountability [6, 7]. As a result, businesses are more likely to answer questions about their resource management practices and their impact on local communities and the natural environment.

Investment in sustainable development can help alleviate risks connected to climate change, environmental degradation, and resource depletion. This is because sustainable development can help mitigate risks related to both the environment and the economy. Nations and enterprises can enhance their resistance to future economic and environmental shocks by channeling capital into initiatives and activities that are environmentally sustainable. Furthermore, capital investment inflows into Vietnam have seen positive trends in both quantity and quality. Investment initiatives are increasingly conforming to Vietnam's green and sustainable development goals. This study seeks to identify the determinants of investment capital attraction and sustainable development while offering policy recommendations for managers and the Vietnamese government to enhance investment capital attraction and sustainable development in Vietnam.

2. Literature review and hypothesis development

2.1 Sustainable development (SD)

The term “sustainability” describes a state of affairs in which human activities are maintained at a level that allows them to continue indefinitely without causing harm to future generations, the environment, or scarce resources. Planets are the three fundamental principles on which sustainability is based. These principles encompass economic, social, and ecological considerations [7–9]. Furthermore, economic sustainability refers to preserving economic growth and development without exhausting the economy's resources. As part of its mission to enhance the quality of life for all, social sustainability prioritizes safeguarding the rights and well-being of communities and individuals. Ecosystem protection and natural resource conservation are critical to environmental sustainability [10–12]. A holistic approach to sustainable development must incorporate economic, social, and ecological interdependencies. To meet present and future generations' needs without compromising the former, “sustainable development” is essential.

Sustainable development promotes social, economic, and ecological well-being without sacrificing future generations' ability to do so. A balance between these three requirements is the goal: Sustainable development seeks long-term economic growth without harming ecosystems or depleting resources. This includes resource efficiency for a sustainable economy. Second, social sustainable development requires social fairness, which raises living standards, eliminates poverty, improves health-care and education, and ensures that all members of society benefit from growth. Thirdly, environmental concerns: One goal of sustainable development is to lessen the impact of pollution, climate change, and soil erosion on ecosystems and the environment. The protected natural resources will be helpful to generations to come [13, 14]. A shared framework for talks on sustainable development, the 17 Sustainable Development Goals (SDGs) are put out by the United Nations. Their declared objective is to guarantee everyone a better and more stable future.

2.2 Investment capital attraction (ICA)

Attracting investment capital, which requires the strategic deployment and mobilization of financial resources, is essential for meeting the capital needs of economic development. Attracting investors to fund R&D, production, and marketing to reach

specific objectives requires a mix of policies and processes that consider the legal and technological framework and social, resource, and environmental factors [15–17]. A company's "investment capital attraction" is its total expenditure on investment operations, primarily financed by domestic and foreign capital. By integrating science and technology, developing human resources to elevate labor productivity, reorganizing ownership to capitalize on the strengths of various economic sectors while safeguarding the environment and natural resources, and undergoing economic restructuring to leverage the unique advantages of each nation, investment capital fosters comprehensive economic growth and substantial quality enhancement and also bolsters competitiveness [18–21].

The goal of recruiting investment capital is to raise funds from various sources, such as individuals, companies, or even countries, to fund initiatives that support economic development, infrastructure improvement, or expanding the operational scale of existing enterprises, organizations, or nations [17, 19]. From a strategic standpoint, this process boosts competitive capacities, financial resources, and long-term economic growth. There are various ways to entice investment funds, including (1) Foreign direct investment occurs when individuals or organizations from outside the host country inject capital into the local economy. This can happen in several forms, such as forming new businesses, partnerships, or acquiring current shares. Foreign direct investment (FDI) is a boon to international integration, technology transfer, and manufacturing capacity. (2) Foreign portfolio investment allows non-resident investors to purchase shares, bonds, and other financial instruments without having a hand in controlling or operating the company. The liquidity and adaptability of this investment kind make it ideal for attracting capital, but it also carries the risk of causing market fluctuations. (3) Mobilizing investment capital is necessary for financing initiatives that can generate social and environmental value and have the potential for long-term development [16, 20, 22]. Funds for sustainable development, pensions, and hedge funds are all in this category. (4) Funds provided by global banks and other lending organizations: The World Bank, the Asian Development Bank, and the International Monetary Fund are where businesses and governments can get loans. These donations often come with conditions, such as promises to improve the economy or protect the environment. (5) Bonds and stocks are two common ways companies can access the capital markets. Bonds let you borrow money at a fixed interest rate and repay it later. On the other hand, stocks allow you to raise equity without taking on debt.

Technology transfer, improved managerial capabilities, and expanded consumer markets are all significantly aided by attracting investment capital, which also supplies financial resources. To fully capitalize on capital attraction, firms, and governments must have policies that are easy to understand and follow. They should also work to create an appealing atmosphere for investors and mitigate risks associated with market swings and strict lending requirements.

2.3 Economic factors (EF) affecting investment capital attraction (ICA) and sustainable development (SD)

An appealing investment climate results from a confluence of economic factors, one of which is sustained economic growth. If GDP is increasing at a steady rate, it shows that the economy has room to grow in the long run, which makes investors feel better. Vietnam is becoming more appealing to investors at home and abroad due to its burgeoning economy, opening up numerous opportunities in new sectors and

increasing household income and consumption. The business climate in Vietnam is stable and appealing to investors because of the country's consistently strong GDP growth rate. An opportunity for sustainable development initiatives arises, and investment returns are guaranteed by a strong GDP growth rate [8, 21, 23]. The actual worth of investments is better protected when inflation is stable. Inflation stability is essential for sustainable projects to guarantee long-term investment efficiency, as these projects often have cycles that last several years.

Regarding economic structure, sustainable development-minded investors are flocking to the green and digital economy as it transitions from the old industrial economy [9, 24]. Investors are more likely to invest their money in a country with a steady economic growth track record. To entice investors, it is essential to have stable economic statistics, such as GDP growth. Stable tax, interest, and exchange rate policies lead to macroeconomic stability, reducing investor risk [25]. Capital attraction is further enhanced by investment incentives like tax breaks and financial support. Retaining investment value and guaranteeing the feasibility of sustainable initiatives are two ways low inflation and price stability inspire confidence among investors. Therefore, H1 and H2 are proposed in **Figure 1**.

2.4 Political and legal factors (PLF) affecting investment capital attraction (ICA) and sustainable development (SD)

Political stability is crucial to inspiring trust among investors and having more faith in projects' security and longevity in a politically stable country. However, investors may be wary of asset risks, policy shifts, and business interruptions in an unstable political climate [11, 26]. Sustainable development initiatives, particularly those involving renewable energy, green infrastructure, and development, attract investors prepared to put money into the long haul when they believe in a country's stability and advance environmentally friendly technological practices. Because of

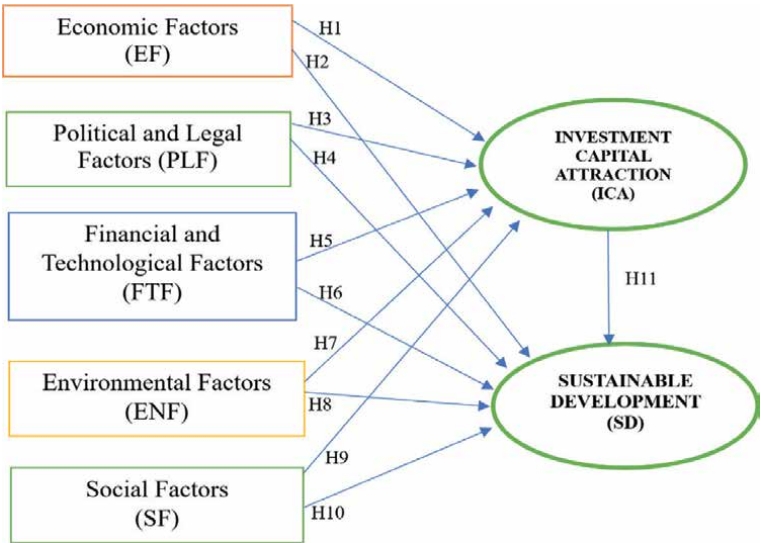


Figure 1.
The framework for five factors affecting investment capital attraction and sustainable development. Source: The authors suggested.

the time it takes for these projects to turn a profit, political stability is essential to ensuring that they will not be halted due to power shifts. Peace of mind for investors is created by a legal framework that is clear, transparent, and reliable. Investors can better plan for potential legal risks when rules are applied fairly and transparently [22, 24, 26]. The legal framework must prevent rapid changes or conflicts in essential areas like taxes, land use, and intellectual property rights. Sustainable project investors need a sound legal framework to avoid environmental and technical violations. These programs may develop renewable energy or sustainable technologies for sudden change. Straightforward and dependable legislation encourages businesses to adopt sustainable development and environmental protection rules [16, 17].

Issues of politics and law by policy on investment incentives by the government offer tax breaks and other incentives to businesses that invest in green and sustainable development projects. More laws require environmentally responsible development and preservation. These policies require corporations to meet emissions, resource, and waste management standards to support green investment projects. Government commitments to international accords: Vietnam has signed the Paris Agreement and pledged net-zero emissions. These pledges increase international investors' confidence in Vietnam's steady growth. Therefore, H3 and H4 are proposed in **Figure 1**.

2.5 Financial and technological factors (FTF) affecting investment capital attraction (ICA) and sustainable development (SD)

Fiscal policy, green finance accessibility, capital costs, and public-private financial channels affect Vietnam's ability to attract investment capital and promote sustainable development. To ensure long-term, environmentally friendly programs succeed, the government must sustain its financial support policies and establish new, more resilient financial instruments. Aspects related to finances based on obtaining green capital through sustainable development projects are attracting the attention of green investment funds worldwide [17, 21, 27]. Solar power, wind power, and organic farming are examples of sustainable enterprises and commercial bank projects offering preferential financing. Like many banks, green credit policies have established green credit products to support sustainable development projects. Preferential loan conditions regarding interest rates and long-term repayment periods help businesses access sustainable capital sources while minimizing financial costs [26, 28].

Technological factors by investing in green technology: Advanced technology, especially technology related to energy saving, renewable energy, and waste treatment technology, is an inevitable trend. Businesses that innovate in technology and apply green solutions will have a significant advantage in attracting investment capital because this reduces costs and helps protect the environment, creating a competitive advantage in long-term competition [5, 27, 29]. The application of digital technology by the development of financial technology (Fintech) helps businesses access capital sources faster, easier, and more transparently while supporting sustainable development projects through effective capital management. To attract investment capital and ensure sustainable development, businesses in Vietnam need to focus on balancing economic profit, social responsibility, and environmental protection. Supportive policies from the government, combined with the global green investment trend, are opening up many opportunities for sustainability-oriented businesses. Thus, H5 and H6 are proposed in **Figure 1**.

2.6 Environmental factors (ENF) affecting investment capital attraction (ICA) and sustainable development (SD)

Environmental factors have an essential influence on attracting investment capital and sustainable development, especially in the international context of increasing emphasis on environmental protection standards and green development [7, 21, 23, 26]. The importance of environmental protection rules and regulations in luring investment capital, particularly from overseas investors, is growing. Environmental protection, waste management, and greenhouse gas emission standards are all possible components of these rules. Foreign investors, particularly those from industrialized nations, are increasingly demanding high environmental requirements and feel more comfortable putting money into renewable energy, green industry, and clean technology development if the country's environmental protection laws are explicit, clear, and stringent. In addition to reducing the environmental toll of economic activity, environmental protection rules provide a way for companies to fund environmentally friendly initiatives [19, 23, 24, 26].

The objective of comprehensive sustainable development is advanced, and national competitiveness is bolstered. Establishing green and adaptation projects to climate change is more critical than ever. More money is usually put into projects that do their part to keep the planet habitable and use resources sustainably [19, 25, 26]. Utilization of natural resources: Investors are drawn to renewable energy and clean resource projects due to the limited availability of these resources and the strict rules that govern their usage. Attracting investment capital and encouraging sustainable development are both impacted by environmental considerations. Environmental regulations and actions will make the country a more attractive business destination and prevent long-term environmental damage from sustainable development. Thus, H7 and H8 are proposed in **Figure 1**.

2.7 Social factors (SF) affecting investment capital attraction (ICA) and sustainable development (SD)

Social factors affect sustainable development and investment capital, creating an investment climate and sustainable economic growth that prioritizes social well-being. Service, manufacturing, and technology investors seek places with a young, skilled workforce. With the fast-growing middle class, demographics affect consumer demand and economic growth [8, 24, 29]. A young, active, educated population boosts investment confidence in long-term development. Technology, services, and manufacturing companies worldwide are investing in Vietnam due to its inexpensive labor and quickly growing educational system. High-quality workers may use green technologies and clean production, boosting sustainable development. Workforce development boosts long-term economic growth without damaging the environment. Investors in the high-tech and service sectors will evaluate local labor education and trainability [18, 29, 30].

Improving education quality and providing specialized training programs help attract more investors into high-value-added sectors. A qualified workforce will quickly absorb and apply advanced technologies to production, including environmentally friendly solutions. This helps promote sustainable development and enhance economic competitiveness. Social factors have a profound impact on attracting investment capital and sustainable development. Social policies must ensure the workforce is well-trained, society is stable, public health is taken care of, and businesses

adhere to social responsibility. These factors help create an attractive investment environment and ensure sustainable economic development and harmony between economic, social, and environmental benefits. Therefore, hypotheses H9 and H10 are proposed in **Figure 1**.

2.8 Investment capital attraction (ICA) affecting sustainable development (SD)

Many crises and variations characterize the global trend. Not to mention that market standards are getting higher, supply chain regulations are getting tighter, and businesses have a social obligation to care for the environment, the government, and society. Business expansion is linked to greater social responsibility and increased economic value [8, 16, 31]. Companies must invest in production to meet sustainable development demands while ethically luring investment capital from local and international sources. They must also employ cutting-edge technology that is both clean and environmentally friendly, and they must produce goods with high added value. Many important investment projects have been attracted to Vietnam, contributing to sustainable growth due to the country's proactive approach to inviting and working with investors, intensifying administrative reform, and enhancing the investment environment [24, 30].

One of the main factors that propel sustainable development is investment capital attraction, which includes economic resilience, environmental preservation, and societal well-being, all aided by ICA's practice of allocating funds to sustainable industries and initiatives. If we want to see economic growth that does not harm the environment or leave anyone out in its wake, we need governments, banks, and companies to collaborate on sustainable development programs. Therefore, hypothesis H11 is proposed in **Figure 1**.

In light of the literature mentioned above, the authors formulated a research model based on five factors influencing Vietnam's ability to attract investment capital and achieve sustainable development. The authors suggest a structural equation model, as shown in **Figure 1**.

Figure 1 illustrates five factors affecting Vietnam's investment capital attraction and sustainable development with five factors including: (1) Economic factors (EF), (2) Political and legal factors (PLF), (3) Financial and technological factors (FTF), (4) Environmental factors (ENF), (5) Social factors (SF). There are two independent: (1) Investment capital attraction (ICA) and (2) Sustainable development (SD).

3. Research methods and data

The authors included two primary quantitative steps in the study's design. These stages are necessary for investigating, evaluating, and analyzing the relationship between variables in a theoretical model and detailed contents, and they are followed by a total of 12 steps [32].

Step 1: Objective formulation and theoretical framework refinement: The authors commence the research by clearly defining the study's objectives, focusing on the examination, evaluation, and analysis of the relationships between variables within the theoretical model. They refine and enhance previously established scales from related literature, adapting them to the Vietnamese context. This process involves accounting for cultural, linguistic, and developmental distinctions to ensure the model's relevance and applicability [32].

Step 2: In-depth qualitative exploration and model calibration: To ensure the first model is accurate, a qualitative phase is carried out that includes thorough interviews. Using a convenience sample technique, the authors interview 15 seasoned investors and 15 managers from the investment capital attraction and sustainable development departments. These phone conversations aim to reach theoretical saturation by collecting expert insights. The study scales are validated for use in the quantitative phase after the feedback helps calibrate them.

Third, create research tools and conduct pilot tests: The writers fine-tune the research tools based on the insights gained from the qualitative interviews. A thorough pilot test ensures the survey questions are clear, relevant, and reliable. Feedback from the pilot test is considered to further improve the scales and ensure they are suitable for the target demographic in terms of culture and context.

Step 4: Quantitative phase design and sampling strategy: The formulation of a sample plan initiates the quantitative stage. The authors utilize convenience sampling because managers and investors are a distinct demographic. The sample size was decided based on theoretical and empirical recommendations for robust statistical analysis, and the population consisted of 10,000 managers.

Fifth Step: Analytical methodology and sample size determination: The authors compute sample size using many statistical methods. These approaches include Structural Equation Modeling (SEM), EFA, and Cronbach's alpha (threshold >0.7). SEM model fit indices are configured as follows: $RMSEA \leq 0.1$, $GFI \geq 0.900$, $TLI \geq 0.900$, $CFI \geq 0.900$. These standards assure the outcome's validity and trustworthiness [32].

Step 6: Empirical sample size calculation: The empirical requirement of five respondents per observed variable determines the sample size. The model has 27 observed variables; hence, EFA and multiple regression analysis require 125 and 98 samples, respectively. The authors distribute 800 surveys over four Vietnamese areas to boost sample size and precision.

Step 7: Data collection using Likert scale questionnaire: A five-point Likert scale assesses respondents' opinions, with one denoting strong disagreement and five strong agreements. The authors circulated 800 surveys, receiving 763 valid replies. The data collection process was developed for maximum response and quality, and SPSS was used to process and validate data.

Step 8: Geographical distribution and demographic representation of the sample: The survey was conducted from March to July 2024 in four regions of Vietnam: Ho Chi Minh City, Dong Nai Province, Binh Duong Province, and Ba Ria-Vung Tau Province. Each region contributed 200 manager respondents, ensuring geographical and industrial diversity in the sample.

Step 9: Reliability and internal consistency assessment: Using Cronbach's alpha, the authors checked that each scale's reliability coefficient was higher than the 0.7 cutoff. The veracity of the data was confirmed by verifying the scales' internal consistency. This ensures the scales are robust from a statistical perspective and can reliably produce results.

Phase 10: Validation of scales and confirmatory factor analysis: The authors used Amos software for confirmatory factor analysis (CFA) after the reliability analysis to validate the scales. The CFA results and model fit indices ($RMSEA$, GFI , TLI , and CFI) validated that the model suited the data well. In light of these findings, we fine-tuned the scales for the final analysis by making any required modifications to the model [32].

Eleventh step: Constructing a model to test a theory: The authors tested the study assumptions and overall efficacy of the theoretical model using Structural Equation Modeling (SEM). With this technique, the authors could assess the direction and intensity of correlations between variables, illuminating the full scope of each component's role in achieving the study's aims. EFA and CFA analyses were used to back up the results.

Step 12: Summarizing demographic data and descriptive statistics: Descriptive statistics were employed to give a synopsis of the sample's overall trends and summarize the respondents' demographic data. The writers concisely provided these facts, including the managers' ages, genders, educational backgrounds, and experience levels.

Phase 13: Research instrument finalization and model validation: After the model was confirmed by SEM, the study instruments were prepared, and all scales were standardized and could be used in future investigations. A systematic presentation of the study methodology, findings, and analysis procedure was made to provide clarity and transparency.

Step 14: Drawing conclusions and making policy recommendations for attracting investment and enduring development. Last, the writers drew inferences from the study's empirical data. They proposed policy suggestions to improve Vietnam's capacity to entice investment capital and foster sustainable development. The research has uncovered particular demands and issues, and these suggestions are based on data analysis to solve those problems.

4. Study results

4.1 Analysis of descriptive statistics and Cronbach's alpha for factors affecting investment capital attraction and sustainable development

The survey was conducted from March to July 2024 in four regions of Vietnam: Ho Chi Minh City, Dong Nai Province, Binh Duong Province, and Ba Ria-Vung Tau Province. Each region contributed 200 manager respondents, ensuring geographical and industrial diversity in the sample. The authors distributed 800 questionnaires, collecting 763 valid responses. The research findings show that five factors affect investment capital attraction and that investment capital attraction affects sustainable development, as shown in the results below **Table 1**.

Table 1 presents the reliability analysis results by Cronbach's alpha, mean scores, and standard deviations for five critical factors influencing investment capital attraction (ICA) and sustainable development (SD). These factors include economic factors (EF), political and legal factors (PLF), financial and technological factors (FTF), environmental factors (ENF), and social factors (SF). The results are summarized: (1) Economic factors (EF) with Cronbach's alpha of 0.871, indicating a high internal consistency and reliability level for scale measuring economic factors. The mean is 3.082, suggesting that respondents perceive economic factors as moderately influential in attracting investment capital. The standard deviation (SD) is 0.960, reflecting a relatively moderate response variability. (2) Political and legal factors (PLF) with Cronbach's alpha is 0.943, demonstrating excellent reliability, implying that the items used to measure PLF are highly consistent. The mean is 3.057, indicating that political and legal factors are also perceived as moderately influential. SD is 0.981, showing moderate variability in respondent perceptions. (3) Financial and technological

Code	Items	Cronbach's alpha	Mean	Std. Deviation
Economic factors (EF)		0.871	3.082	0.960
EF1	The country's stable GDP growth creates favorable conditions for investment	0.844	3.065	0.961
EF2	Vietnam has an attractive GDP growth rate for foreign investors	0.808	3.075	0.986
EF3	Stable inflation helps protect the real value of investments	0.866	3.130	0.930
EF4	Investors realize that green industries in Vietnam have the potential to attract investment	0.817	3.058	0.961
Political and legal factors (PLF)		0.943	3.057	0.981
PLF1	The Vietnamese government has many preferential policies for sustainable investment projects	0.920	3.018	0.992
PLF2	The government's economic stimulus packages play an important role in promoting investment	0.930	3.049	0.993
PLF3	The environmental legal system in Vietnam is strict enough to ensure sustainable development	0.932	3.094	0.948
PLF4	The Vietnamese government is strongly committed to implementing international agreements on climate change	0.921	3.067	0.992
Financial and technological factors (FTF)		0.956	3.089	0.992
FTF1	Businesses in Vietnam can easily access green capital sources	0.940	3.079	0.993
FTF2	Commercial banks have many preferential credit programs for sustainable projects	0.954	3.062	1.016
FTF3	Enterprises with strategies to apply green technology will have an advantage in attracting investment capital	0.945	3.111	0.969
FTF4	Applying digital technology helps improve capital management efficiency and attract investment	0.931	3.105	0.989
Environmental factors (ENF)		0.855	2.392	0.672
ENF1	Businesses that can adapt well to climate change will attract more investment capital	0.804	2.333	0.658
ENF2	Adaptation to climate change is an important factor in investment decisions	0.814	2.436	0.675
ENF3	Projects that use resources sustainably have great potential to attract investment capital	0.846	2.381	0.658
ENF4	Sustainable natural resources are a key factor in sustainable development	0.800	2.418	0.695
Social factors (SF)		0.957	3.070	0.987
SF1	Investors are increasingly interested in socially responsible businesses	0.941	3.050	0.991
SF2	The rise of funds investing in businesses with a commitment to protecting the environment and the community	0.954	3.058	0.998
SF3	A highly qualified and environmentally friendly labor force is a factor in attracting investment	0.946	3.093	0.963

Code	Items	Cronbach's alpha	Mean	Std. Deviation
SF4	Investors tend to choose businesses with sustainable human resource development strategies	0.933	3.079	0.994
Investment capital attraction (ICA)		0.940	3.341	0.971
ICA1	Economic, political, financial, technological, environmental and social factors	0.926	3.409	0.955
ICA2	The government's current investment incentive policy is attractive enough to attract investors	0.884	3.326	0.975
ICA3	Postal infrastructure, electricity, roads, schools, and medical stations, the quality of public services	0.927	3.287	0.984
Sustainable development (SD)		0.870	2.381	0.671
SD1	Political and legal stability, financial and technological factors	0.854	2.324	0.655
SD2	Economic growth	0.803	2.423	0.676
SD3	Environmental protection	0.860	2.371	0.658
SD4	Social equity	0.814	2.406	0.695

Source: Calculations by the authors.

Table 1.
Testing Cronbach's alpha, mean, and standard deviation value for five factors.

factors (FTF) with Cronbach's alpha is 0.956, also signifying excellent internal consistency for this factor. The mean is 3.089, slightly higher than PLF and EF, indicating a higher perceived importance of financial and technological factors. SD is 0.992, suggesting moderate variability in the responses regarding the influence of FTF. (4) Environmental factors (ENF) with Cronbach's alpha is 0.855, indicating a solid level of reliability, though slightly lower than other factors. The meaning is 2.392, revealing that respondents perceive environmental factors as less influential in attracting investment capital. SD is 0.672, suggesting lower variability and indicating a more consistent perception among respondents regarding environmental factors' less importance. (5) Social factors (SF) with Cronbach's alpha of 0.957 indicates excellent internal consistency for the social factors scale. The mean is 3.070, suggesting that social factors are perceived as having a moderate influence, similar to EF and PLF. SD is 0.987, reflecting moderate variability in the respondents' views. (6) Investment capital attraction (ICA) with Cronbach's alpha of 0.940 indicates excellent reliability for the items measuring ICA. The mean is 3.341, the highest among all factors, indicating that respondents perceive ICA as a crucial element in sustainable development. SD is 0.971, indicating a moderate level of variability in the perception of its importance. (7) Sustainable development (SD) with Cronbach's alpha of 0.870, demonstrating strong reliability for the SD scale. The mean is 2.381, the lowest among all factors, suggesting that respondents perceive sustainable development as relatively less influential. SD is 0.671, showing low variability, indicating more consistent perceptions of SD across respondents.

4.2 Testing key five factors of the investment capital attraction and sustainable development

Figure 2 presents the analysis that confirms that all five factors: economic, social, environmental, political and legal, and financial and technological significantly

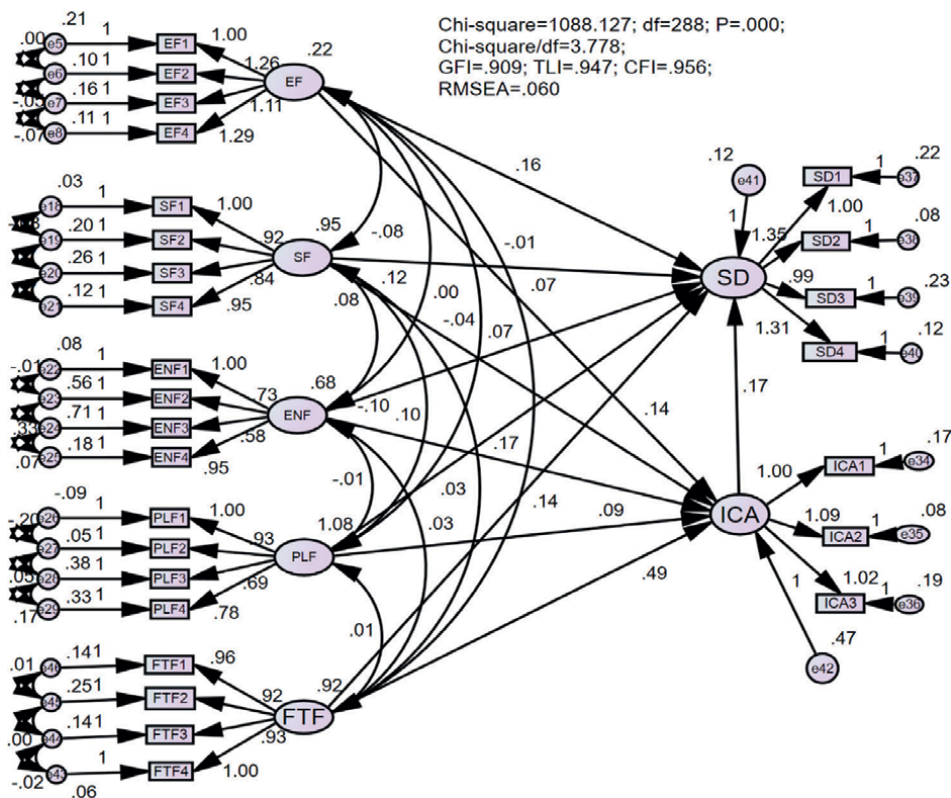


Figure 2.
The five elements affect the attractiveness of investment capital and sustainable development in Vietnam. Source: The results from SPSS 20.0 and Amos.

influence investment capital attraction and sustainable development. Notably, Financial and technological factors demonstrate the most substantial effect on investment capital and sustainable development, reflecting the central role of technological innovation and financial systems in promoting investment and sustainable development [8, 21, 23]. Moreover, investment capital attraction is a crucial driver of sustainable development, suggesting that effective capital mobilization is critical for sustainable growth. From these findings, policymakers and stakeholders can learn about the relevance of permitting investment capital flows and sustainable development. Finally, the analysis demonstrates that all the measured factors exhibit strong reliability, as evidenced by the high Cronbach's alpha values above 0.7. The means suggest a variation in the perceived importance of these factors, with investment capital attraction receiving the highest average score and environmental factors and sustainable development being perceived as relatively less necessary by respondents. This provides valuable insights into prioritizing factors that impact investment capital attraction and sustainable development in the study context.

Table 2 displays the hypothesis testing results on the five components and how they affect sustainable development and investment capital attractiveness. The results include standard errors, standardized and unstandardized estimates, critical ratios, p-values, and whether the hypotheses were accepted at 0.05 [11, 19, 21, 26]. Five critical criteria and their effects on investment capital attraction and sustainable development are shown in **Table 2**. Economic, political, legal, financial,

Relationships			Standardized estimate	Unstandardized estimate	SE	CR	P	Result
ICA	<---	EF	0.079	0.144	0.058	2.485	0.013	Accepted H1
ICA	<---	SF	0.091	0.080	0.028	2.865	0.004	Accepted H9
ICA	<---	ENF	0.160	0.167	0.035	4.798	***	Accepted H7
ICA	<---	PLF	0.111	0.092	0.027	3.472	***	Accepted H3
ICA	<---	FTF	0.543	0.486	0.030	16.225	***	Accepted H5
SD	<---	ICA	0.329	0.175	0.022	7.798	***	Accepted H11
SD	<---	EF	0.167	0.162	0.032	5.002	***	Accepted H2
SD	<---	SF	0.158	0.074	0.015	4.791	***	Accepted H10
SD	<---	ENF	0.123	0.068	0.019	3.624	***	Accepted H8
SD	<---	PLF	0.078	0.034	0.013	2.554	0.011	Accepted H4
SD	<---	FTF	0.288	0.137	0.019	7.168	***	Accepted H6

*The data was processed by SPSS 20.0, Amos, and the significance level was ***, equal to 0.01.*

Table 2.
Testing key five factors of the investment capital attraction and sustainable development.

technological, environmental, and social factors are involved. To test hypotheses, the study employed Amos and SPSS to calculate critical ratios, p-values, standardized and unstandardized estimates, standard errors, and critical ratios. The findings are detailed below.

Table 3 shows the high composite reliability of all constructs, indicating excellent internal consistency across examined items. All components have Average variance extracted values over 0.50, suggesting that each construct captures variable variation. The low maximum shared variance values imply excellent discriminant validity since the constructs are sufficiently distinct. These results confirm the robustness of the measuring approach across all factors affecting investment capital attraction and sustainable development.

According to **Table 4**, the findings of the bootstrap analysis show that, across 30.000 samples, the correlations between the factors impacting investment capital

Code	CR	AVE	MSV	Results
ICA	0.925	0.806	0.345	Very good
EF	0.892	0.675	0.027	Very good
SF	0.955	0.841	0.040	Very good
ENF	0.835	0.573	0.029	Very good
PLF	0.944	0.809	0.017	Very good
FTF	0.958	0.852	0.345	Very good
SD	0.877	0.644	0.307	Very good

The data was analyzed using SPSS 20.0, Amos.

Table 3.
Composite reliability for attracting investment capital and sustainable development.

Parameter			SE	SE-SE	Mean	Bias	SE Bias	CR	Results
ICA	<---	EF	0.080	0.002	0.133	0.002	0.003	0.67	Good
ICA	<---	SF	0.027	0.001	0.079	0.001	0.001	1.00	Good
ICA	<---	ENF	0.043	0.001	0.159	0.003	0.002	1.50	Good
ICA	<---	PLF	0.029	0.001	0.080	0.002	0.003	0.67	Good
ICA	<---	FTF	0.041	0.001	0.485	0.001	0.001	1.00	Good
SD	<---	ICA	0.025	0.001	0.178	0.003	0.001	3.00	Good
SD	<---	EF	0.047	0.001	0.149	0.003	0.002	1.50	Good
SD	<---	SF	0.017	0.000	0.069	0.005	0.004	1.25	Good
SD	<---	ENF	0.020	0.000	0.061	0.002	0.003	0.67	Good
SD	<---	PLF	0.020	0.000	0.036	0.002	0.003	0.67	Good
SD	<---	FTF	0.021	0.000	0.134	0.003	0.002	1.50	Good

Data processed by SPSS 20.0, Amos.

Table 4.
Results of Bootstrap using 30,000 samples for capita attracting investment and sustainable development.

attraction and sustainable development are consistent and statistically significant [1, 5, 17, 19, 21, 27]. With critical ratios ranging from 0.67 to 3.00, we can see that the model is entirely consistent and reliable. Further supporting the findings' robustness is slight bias and SE bias across all parameters. These findings support the structural model and provide more evidence that technological, political, legal, social, and economic aspects all play a part in determining the attractiveness of investment capital and the rate of sustainable development.

4.3 Discussion of findings

Researching factors influencing both dimensions reveals several essential insights into the links between sustainable development and investment capital attraction. An in-depth analysis of the statistical data is presented in this section, along with a discussion of their theoretical and practical consequences.

1. A normalized estimate of 0.079 and a substantial p-value (0.013) highlight the crucial importance of economic stability in attracting investment [9, 19, 24, 33]. Economic factors are based on the positive link between economic factors and investment capital attraction. Economic factors, including growth rates, inflation, and fiscal policies, affect capital inflows, directly impacting investor confidence. Additionally, bootstrap analysis confirms the association's robustness with minimal bias and a decent critical ratio (CR = 0.67), providing further evidence for the link. Just like a healthy economy promotes sustainable growth, economic considerations notably impact sustainable development ($p < 0.01$). Capital inflows should support infrastructure, employment, and environmental sustainability; thus, economic policies must align with sustainability goals in the long run.
2. A normalized estimate of 0.091 for investment capital attraction and a significant p-value (0.004) indicate that social factors moderately impact investment

capital attraction. Societal conditions include workforce quality, education, and healthcare [5, 12, 22, 24, 26]. Despite a reduced effect size compared to financial and economic considerations, the beneficial impact is essential, particularly for nations striving to build social infrastructure and human capital. Additionally, the p-value for the effect of social determinants on sustainable development is under 0.01. Based on these results, spending money on social infrastructure like schools, hospitals, and community centers pays off in the long run, for social capital and stability are needed for long-term investment.

3. Environmental sustainability factors are essential for investment capital and sustainable growth. The significant p-value ($p < 0.01$) and standardized estimate of 0.160 for ICA suggest that investors increasingly consider environmental factors in their decision-making [5, 17, 21, 27, 34]. This study supports the global trend of investing in environmental, social, and governance aspects. Bootstrapping confirms the stability and significance of a CR of 1.50. Environmental sustainability is vital for long-term economic growth, as evidenced by the positive impact of environmental factors on sustainable development ($p < 0.01$). Environmentally friendly economic development attracts investors and protects the environment. Governments and corporations should prioritize environmental sustainability policies if they want investment and sustainable growth.
4. Political stability and legal frameworks significantly impact capital inflows, as shown by the positive correlation between PLF and investment capital attractiveness ($p < 0.01$). Investors value transparent legal systems and stable governance, according to the standardized estimate of 0.111 [7, 13, 21, 23, 26, 33]. To attract investors, evaluate how the political and legal context may affect their risk and security perceptions. PLF also promotes sustainable development ($p = 0.011$), demonstrating the need for governance. Effective legal frameworks and management are needed to ensure investments support long-term development goals like social equity, environmental conservation, and economic resilience.
5. A normalized estimate of 0.543 and a significant p-value ($p < 0.01$) indicate that financial and technology factors have the most significant impact on investment capital attractiveness. This discovery highlights the importance of financial markets and technical infrastructure for investment capital [8, 12–14, 24, 29, 34, 35]. Investor trust in a digitalizing economy depends on efficient financial institutions and cutting-edge technologies. Bootstrapping analysis shows no bias and a CR of 1.00, proving the relationship's stability. Financial and technological factors significantly impact sustainable development (standardized estimate is 0.288, $p < 0.01$), indicating that developments in these areas significantly contribute to sustainability. Innovation, digital infrastructure, and fintech investments attract capital and promote long-term growth. Policymakers should prioritize financial and technological infrastructure to attract investors and assure long-term success.
6. The positive and robust association between investment capital attraction and sustainable development shows that capital mobilization is essential for sustainable development. The standardized estimate for this connection is 0.329, with a significant p-value < 0.01 [9, 13, 14, 24, 30, 34, 35]. Capital must enter

the economy to invest in infrastructure, technology, and social welfare, which is essential to sustainability. Bootstrap analysis of CR is 3.00, which confirms the robust results, emphasizing the importance of capital attraction in long-term development.

Research has significant ramifications for politicians and corporate leaders. Governments should improve economic stability, legal and governance, and environmental sustainability to attract investment capital. Investing in social infrastructure and technical innovation attracts capital and ensures long-term sustainability. Businesses must grasp the growing importance of ESG factors to acquire financing, especially in global markets where investors value sustainability. Adopting financial and operational efficiency technology will boost investor interest.

The financial-technical element emerges as the most influential because of its ability to promote both economic growth and sustainability through green finance and technology innovation. This component improves capital attractiveness by enabling efficient funding channels such as green bonds and sustainable investment funds, which provide critical finance for renewable energy, infrastructure, and other environmentally friendly initiatives. Furthermore, technology improvements enable firms to embrace environmentally responsible practices, such as energy-saving and waste-reduction technologies, which are increasingly valued by investors.

Furthermore, the advancement of financial technologies (Fintech) increases capital market accessibility and transparency, allowing investors to engage with sustainable initiatives more swiftly while incurring lower transaction costs. Fintech solutions promote efficient capital management, boost investor confidence through improved financial monitoring, and allow for speedier project growth. Together, these aspects establish the financial-technological factor as a cornerstone for long-term, significant projects that are aligned with global environmental goals.

5. Conclusions

Based on the quantitative method and primary data collected directly from 800 managers related to enterprises with investment capital from three provinces and 01 City interviewed via a structured questionnaire and data analysis using SPSS version 20.0 and Amos software. The research results showed that the five critical factors influencing investment capital attraction and sustainable development in Vietnam are based on a five percent significance and eleventh accepted hypothesis. This study demonstrates the multifaceted nature of factors influencing investment capital attraction and sustainable development. While financial and technological factors exert the most substantial influence, environmental, political, social, and economic factors also play critical roles in determining investment attractiveness and sustainability outcomes. These findings highlight the need for an integrated approach that aligns economic policies with sustainability goals to attract capital and foster long-term development.

6. Policy recommendations

Based on the findings, the authors proposed improving Vietnam's investment capital attraction and sustainable development simultaneously.

1. Improve the financial and technological factors: it has the most substantial positive influence on ICA with the highest standardized estimate of 0.543. This suggests that financial infrastructure, technological advancements, and innovation significantly attract investment capital. Investors prioritize efficient financial systems and cutting-edge technology, making this factor the most important in influencing capital inflows. To further stimulate investment, the government should work with the State Bank of Vietnam to keep interest rates steady and suitable. Capital expenses for sustainable projects, particularly those involving renewable energy and green infrastructure, should be kept reasonable by implementing flexible monetary policies. By constructing and extending green finance mechanisms, such as assisting in creating green investment funds, urging banks to take part in green finance initiatives, and growing the green bond market, Vietnam continues to develop and expand its green financial sources. Promoting green infrastructure, renewable energy, and environmental rehabilitation initiatives are examples of sustainable sectors that might benefit from public-private partnerships. Finally, The government should strengthen green finance systems by promoting the growth of green bonds, sustainable investment funds, and green loans. Collaborate with the State Bank and commercial banks to offer low-interest loans and special financial terms for environmentally friendly initiatives, particularly renewable energy and sustainable infrastructure. Invest in fintech growth by supporting financial technology (Fintech) to expedite capital flows and improve transparency in sustainable investments. This could involve assisting digital platforms in facilitating green project investments, improving investor access to information, and shortening transaction times. Promote technical innovation and green technology through funded research and development of energy-saving technologies, waste management systems, and other green advancements. By subsidizing sophisticated green technologies, the government may assist firms in cutting costs, improving environmental performance, and gaining a competitive advantage.
2. The standardized estimate of 0.160 shows that improving environmental issues substantially influences attracting investment. Investors now prioritize environmental considerations due to the increasing worldwide focus on sustainability and environmental responsibility, but it is still vital, mainly because environmental, social, and governance factors are becoming more critical to investors. Greenhouse gas emissions, waste management, and the preservation of natural resources are just a few areas where the government should implement stricter laws. Legal norms should be explicit, easily understood, and backed by solid enforcement procedures to gain investors' trust. The government must implement national measures to address climate change, lessen the likelihood of disasters, and cut emissions. Some examples of this include funding disaster-proof infrastructure and advocating for environmentally friendly technology to reduce the effects of climate change. Finally, the government should implement tighter environmental rules to meet international sustainability goals, including more significant emissions, waste management, and resource conservation criteria. These policies should be implemented consistently to establish a level playing field and attract environmentally concerned investment. Encourage resource efficiency projects by providing grants or tax breaks for initiatives focusing on sustainable resource utilization, such as renewable energy production, water conservation, and sustainable agriculture methods. This will make the country more appealing to investors seeking to fund environmentally beneficial projects.

Invest in climate adaptation projects such as flood defenses, drought-resistant agriculture, and sustainable urban planning to help climate resilience efforts succeed. Policies encouraging climate resilience help to protect assets from environmental threats, making climate investment safer.

3. Improve the political and legal factors: statistically significant, with a standardized estimate of 0.111. Stable political conditions and transparent legal frameworks provide investors with security and predictability, thereby enhancing capital attraction, a factor in shaping investment decisions. Moreover, the government must maintain political stability to build trust among domestic and foreign investors. Any changes in economic or legal policies should be communicated in advance and implemented in an orderly manner to avoid sudden decisions that could affect business plans. Transparent governance practices will enhance predictability and reduce investment risks. The government must continue reforming the legal framework to ensure transparency and consistency in investment, land, intellectual property rights, and environmental protection regulations. This includes enacting and enforcing clear legal rules to minimize investor legal risks. The government should simplify and digitalize administrative procedures, particularly in investment licensing and business registration processes, making it easier for investors to start projects quickly. Finally, the government should guarantee transparent governance, which improves transparency in the legal frameworks that govern investments, particularly in land use, intellectual property rights, and environmental rules. Clear and stable laws eliminate investor uncertainty and promote a trustworthy business climate. Strengthen ecological law enforcement and provide companies with clear standards for compliance. This will attract investors who value sustainability by ensuring a predictable legal environment. Create investment-friendly policies by implementing specific incentives, such as tax reductions, expedited licensing processes, and safeguards against unexpected policy changes, particularly for sustainable development initiatives. This might involve fast-tracking approvals for environmentally friendly and high-impact projects.
4. Starting with the standardized estimation of the social components at 0.091 is an intelligent spot. Social stability, education, and human capital help to draw investment capital. Economic and investment strategies should consider this in the long run, even though its impact is small compared to other variables. Moreover, the government should invest heavily in education and training to improve the quality of the workforce, especially in technical, technological, and service sectors. Building a highly educated workforce will enhance Vietnam's appeal as an investment destination for emerging and complex industries. Encouraging corporate social responsibility (CSR) by enabling businesses to develop and implement CSR policies by providing tax incentives and financial support to businesses undertaking sustainable and environmentally friendly initiatives. Finally, the government should focus on education and skill-building programs in green and technical domains to provide a skilled workforce for sustainable enterprises. Provide scholarly and practical training in renewable energy, environmental management, and digital finance. Encourage corporate social responsibility (CSR) by offering tax breaks or certifications to companies that implement CSR initiatives, particularly those addressing environmental sustainability and social equality. Encouraging CSR will boost corporate reputations and attract socially

conscious investors. Improve public health and social services by investing in healthcare, education, and public services to raise the overall level of living. A steady and healthy workforce attracts investors who value a consistent labor pool and contribute to long-term sustainable development.

5. Improve the economic factors: it has the most negligible but statistically significant effect on ICA, with a standardized estimate of 0.079. Economic stability, including GDP growth and inflation, is essential for fostering a conducive investment environment. Although its influence is lower than other factors, economic factors still contribute to attracting capital by providing a stable foundation for investment activities. Moreover, the government should continue to ensure macroeconomic stability through flexible fiscal and monetary policies to control inflation and maintain steady growth. This includes controlling public debt and maintaining reasonable interest and exchange rates to foster a stable economy conducive to domestic and foreign investment. Investment in infrastructure, especially in transportation, telecommunications, energy, and industrial zones, should be bolstered. The government can develop public-private partnership projects to mobilize private capital for critical infrastructure projects, improving connectivity and stimulating investment. Finally, the government should preserve macroeconomic stability by enacting flexible fiscal and monetary policies that manage inflation and assure steady GDP growth. This stability reassures investors and creates an ideal climate for long-term investments. Increase infrastructure development by allocating public funds and fostering public-private partnerships for vital infrastructure projects such as transportation, electricity, and communications. Improved infrastructure will attract investors by lowering operating costs and increasing connectivity. Increase incentives for green investments: Provide tax breaks, low-interest loans, or grants for initiatives that promote renewable energy and sustainable infrastructure. This can accelerate the shift to a green economy by making eco-friendly investments more financially appealing.

7. Limitations and future research

This study provides valuable insights into sustainable development and investment capital attractiveness; however, it has several limitations: The study only examined one area, and thus, the results may not apply to a broader population. Regional, national, and international economic, political, and social issues may affect capital attraction and sustainable development. (2) A cross-sectional technique collects data instantly. The design ignores that sustainable development and investment capital attractiveness fluctuate over time. The findings could be improved by longitudinal data showing how these associations change over time, especially in response to social or economic changes. We propose many research areas to expand the current findings: (1) Longitudinal studies could follow the relationship between sustainable development and investment capital attractiveness across time. This research would illuminate how technological advances, natural disasters, economic crises, and other external shocks affect capital attraction and sustainability. (2) Cultural, geopolitical, and investor behavioral characteristics will expand future research. We can learn how to attract investment capital and create sustainable growth by studying digital transformation, CSR, and global supply chain disruptions. (3) This study is primarily concerned with Vietnam, which may limit the applicability of findings to other regions with different

economic or political environments. Future research should look at these factors in different geographic contexts, such as rapidly developing areas in Sub-Saharan Africa or politically stable economies in Western Europe, to see if similar influences on investment attraction and sustainable development apply across the board. Furthermore, this study is cross-sectional, with data collected at a particular point, which may not reflect changes in factors impacting sustainable investment over time. Longitudinal research over numerous economic cycles environmental or political transition periods may demonstrate how these aspects evolve. Future studies should investigate economies affected by political transitions or ecological catastrophes; a longitudinal approach could provide more significant insights into how investor motivations and determinants influence transformation in response to external shocks.

Acknowledgements

The authors thank all lecturers and managers of Lac Hong University (LHU). This study is supported and funded by LHU, Vietnam.

Author contributions

Lu Phi Nga and Phan Thanh Tam did everything equally, such as the conception and design, data analysis, critical revision of intellectual content, and final approval of the version to be published.

Disclosure statement

No potential conflict of interest was reported by the authors.

JEL classification

F63, G38, O10, O38, Q01.

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Optimizing Coffee Logistics *via* Physical Internet and Multi-Agent PILAR Framework

Mizna Rehman, Antonella Petrillo, Antonio Forcina and Fabio De Felice

Abstract

This study introduces the PILAR framework (Physical Integration, Intermodal Transport, Logic & Control, Adaptive Service, Responsive Interface), a multi-layered logistics architecture grounded in the Physical Internet (PI) to enhance multimodal supply chains through decentralized, data-driven coordination. The framework integrates agent-based modeling (ABM), IoT-enabled π -containers, autonomous π -movers, and intelligent π -nodes within a Geographic Information System (GIS)-based simulation environment that models both forward and reverse coffee logistics flows. Using Q-learning, Monte Carlo analysis, and mixed-integer linear programming (MILP), the system dynamically optimizes routing, disruption recovery, and Pareto-efficient decision-making. Quantitative outcomes—derived from 10,000 Monte Carlo simulation runs calibrated with empirical transport data and optimization parameters—show a 30% reduction in logistics costs through improved routing and vehicle utilization, and a 50% improvement in spent coffee grounds (SCG) recovery efficiency enabled by IoT-based collection and decentralized processing hubs. The model further incorporates kanban-based flow control, stochastic demand forecasting, and adaptive energy-aware scheduling. Its technical implementation leverages RESTful APIs, TLS-encrypted MQTT communication, and edge computing for secure, real-time coordination. Results confirm the PILAR model's ability to achieve high asset utilization (82.4%), lower CO₂ emissions by up to 25%, and enable scalable, resilient logistics systems aligned with circular economy goals.

Keywords: physical internet, agent-based modeling, circular economy, supply chain resilience, multimodal transport, kanban control, smart contracts, coffee waste recovery

1. Introduction

The Physical Internet (PI) is a transformative logistics model aimed at improving efficiency, sustainability, and connectivity in transportation networks. It integrates multimodal, intermodal, and co-modal transport systems. Multimodal transport involves at least two transportation modes using various units like containers or

vehicles [1], while intermodal transport ensures goods remain in a single unit across modes, reducing handling and delays. Co-modal transport enhances resource efficiency by promoting collaboration among shippers [2]. Synchromodal transport advances these concepts with real-time adaptability *via* digital technologies. Defined as the flexible, coordinated use of transport modes enabled by data sharing, synchromodality includes key principles such as real-time switching, integrated planning, horizontal collaboration, and mode-free booking [3, 4]. Despite innovations, logistics systems face disruptions, such as unforeseen events that hinder supply chains [5]. These include facility-related and transportation disruptions. Robustness refers to a system's ability to maintain function during minor issues, while resilience is its capacity to recover from major disruptions like strikes or infrastructure failures [6].

PI is structured around three core elements: π -containers, π -movers, and π -nodes [7]. π -containers are modular, trackable transport units with embedded smart technologies, mirroring data packets in the Digital Internet. They are moved by π -movers; vehicles, carriers, or conveyors, within and between π -nodes. π -hubs, a type of π -node, are essential for routing and optimizing freight flow. Developing this infrastructure is central to scaling PI. Ultimately, PI seeks to establish a modular, standardized logistics network that enhances interoperability, optimizes resource use, and reduces the environmental impact. However, existing literature on the Physical Internet has largely focused on generic freight or industrial goods, with limited attention to agri-food commodities such as coffee, where fragmented production networks, perishability constraints, and reverse logistics of by-products create unique coordination challenges. This research addresses this gap by positioning the coffee supply chain as a critical use case for demonstrating how PI principles can enhance traceability, resource efficiency, and circular recovery.

1.1 Transformation of logistics through the Physical Internet

Growing freight demand, road congestion, and concerns over sustainability and reliability have exposed limitations in traditional logistics systems. While intermodal transport offers efficiency by combining different transport modes, its static structure and lack of real-time responsiveness limit its ability to manage disruptions [8]. Many shippers also view it as slow and inflexible, favoring unimodal road transport despite congestion issues [9]. To overcome these constraints, synchromodal transport introduces real-time adaptability, allowing dynamic decisions about routes and modes based on operational conditions, improving cost and delivery performance [2, 10].

At the core of this evolution is the PI, which enhances synchromodality by leveraging modular π -containers, decentralized routing, and a globally open logistics network to increase interoperability and reduce inefficiencies [11]. A key advantage of PI is improved resilience, the ability to recover post-disruption, achieved through adaptive routing, predictive analytics, and autonomous logistics decisions [6]. Agent-based modeling (ABM) supports this resilience by simulating disruption scenarios and logistics flow reconfiguration [12], while AI-driven analytics anticipate bottlenecks, enabling proactive interventions. While traditional logistics innovations have primarily focused on the digitalization of documentation and standardization of containers, the Physical Internet takes these steps further by introducing new business models [13].

PI goes beyond digitizing logistics by introducing new business models, such as dynamic auction-based pricing, where logistics providers bid for shipments in real time [14], and subscription-based logistics, offering customizable delivery tiers

through Logistics Access Providers, similar to Internet Service Providers (ISPs) [15]. This system allows customers to choose delivery options based on speed, location, and cost, which in turn incentivizes competition among LAPs to improve service offerings.

Logistics challenges like the Vehicle Routing Problem (VRP), Shortest Path Problem (SPP), and Facility Location Problem (FLP) are central to PI and synchromodal systems. VRP involves designing optimal routes under multiple constraints [16], while Single Shipment Problem (SSP) focuses on the best route for individual shipments [17]. These problems have evolved from exact methods to scalable metaheuristic solutions. Synchromodality emphasizes shared resources and centralized optimization, whereas PI advances this by decentralizing data flow and standardizing unit design, using autonomous nodes like digital routers to manage freight.

Empirical studies show that PI and synchromodal models can significantly boost modal shift potential, from 26.5 to 58.4% under ideal conditions [8], while also cutting costs and emissions [18]. However, realizing the full potential of PI requires overcoming challenges in data sharing, stakeholder cooperation, and governance. Addressing these will depend on continued research into decentralized algorithms and global logistics integration. Existing literature on the Physical Internet has largely focused on generic freight, manufacturing, and containerized transport systems, with limited attention to agri-food commodities. In particular, the coffee supply chain presents distinctive features—high fragmentation among smallholders, perishability, multimodal transport dependencies, and complex reverse flows of organic waste—that remain underexplored within PI research. This study addresses this gap by positioning coffee logistics as a critical testbed to evaluate how PI principles can enhance transparency, efficiency, and circularity in bio-based supply chains. The proposed PILAR framework extends current PI models by coupling agent-based simulation, Q-learning, and mixed-integer optimization within a data-driven, circular economy context, thereby bridging the methodological and application-level frontiers of Physical Internet research [19].

1.2 Systemic challenges in the coffee supply chain and the role of PI

The global coffee supply chain, from cultivation to retail, faces significant inefficiencies that impact sustainability, cost, and responsiveness. At the farm level, smallholder farmers (responsible for 60% of global production) often lack access to real-time market data and climate-resilient practices, limiting informed decision-making and exacerbating inefficiencies [20]. Fragmented operations hinder yield aggregation, resulting in underutilized transport and higher costs [21]. PI-based digital platforms can address these issues by enabling data sharing and collaborative logistics planning, integrating farmers into a transparent, connected network. In the processing and export stages, manual, paper-based documentation delays customs clearance by 48–72 hours, increasing holding costs [22]. Inconsistent bean quality sorting causes up to 12% processing waste [23]. Implementing digital documentation, AI-driven sorting, and blockchain-backed smart contracts under the PI framework can streamline operations, enhance traceability, and reduce waste and delays.

Transportation inefficiencies further strain the system, with nearly 40% of maritime containers returning empty, adding to fuel consumption and emissions [24]. Static routing fails to account for variables like port congestion and fuel prices. PI's dynamic routing algorithms and real-time forecasting can optimize container repositioning and route planning, reducing costs and environmental impact.

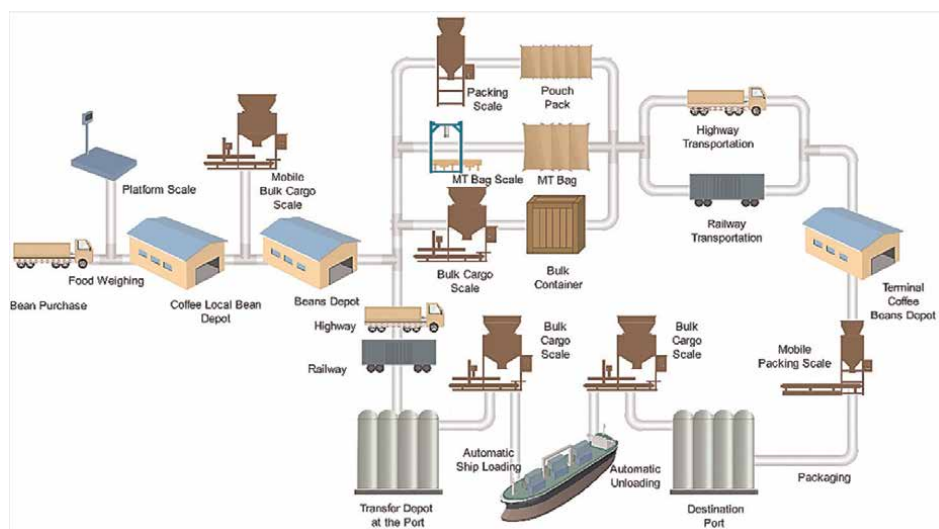


Figure 1.
Flow of modular coffee logistics aligned with Physical Internet principles.

At the warehousing and retail stage, inventory mismatches and traceability gaps lead to ~\$740 million in annual holding costs, while only 34% of retailers offer sourcing transparency [25]. PI-enabled digital twins and AI inventory systems can improve visibility, reduce overstocking, and support traceability from farm to shelf, enhancing consumer trust and ethical sourcing compliance.

Figure 1 illustrates a PI-modeled coffee logistics flow, where beans move through modular layers (e.g., depots, warehouses, packaging centers) encapsulated in standardized units like π -containers. Each stage applies labeling, routing, and modular handling, reflecting PI principles of modularity, interoperability, and synchronization. Movement between nodes (by road or sea) reflects intermodal transfers governed by PI routing logic based on efficiency and availability, analogous to Internet packet routing. Like digital networks, this system ensures shared infrastructure, real-time visibility, and efficient, scalable distribution.

2. Optimizing recovery and reuse of spent coffee grounds (SCGs) with Physical Internet (PI)

Spent coffee grounds (SCGs) hold significant potential for reuse in biofuel, fertilizers, and bioplastics, yet their recovery is hindered by challenges in collection, transportation, and processing. Applying PI principles offers a structured, data-driven approach to streamline SCGs recovery through automation, interconnectivity, and sustainable logistics.

A key barrier is the fragmented nature of SCG generation, originating from cafés, restaurants, and homes, which makes collection inefficient and costly. Traditional methods lead to inefficient routing, raising operational costs by $\sim 20\%$ [26], compounded by poor coordination and lack of data visibility, resulting in inconsistent pickups and processing delays.

A PI-enabled solution uses IoT-based smart bins that monitor SCG levels and transmit real-time data to a decentralized network. This enables automated pickup

Parameter	Conventional methods (baseline)	PI-enabled model
Transportation Cost	\$2 million per year (inefficient routing)	\$1.4 million per year (30% reduction due to optimized routing)
SCG Recovery Rate	20–30% recovery rate	+50% improvement in recovery efficiency
CO ₂ Emissions	1000 tons/year	750 tons/year (25% reduction)
Administrative overhead	\$500,000 per year (manual processing costs)	\$175,000 per year (65% reduction through automation)
Energy recovery potential	~500,000 MWh	Up to 1.5 million MWh

Table 1.
Quantitative assessment of the improvements when transitioning from conventional methods to a PI-enabled model.

scheduling, reducing idle time by 30% [27]. AI-driven dynamic routing further optimizes logistics by factoring in bin fill levels, traffic, and plant capacity [28]. Establishing decentralized PI processing hubs near urban areas cuts transport distances by 36.8% and reduces emissions [29].

Using standardized π -containers ensures compatibility across multimodal logistics, while autonomous electric π -movers reduce energy use by 23% [30]. Blockchain-based tracking adds transparency and traceability, while smart contracts automate verification, reducing administrative overhead by 65% [31, 32].

The quantitative impact of these PI methodologies is significant, with AI-driven logistics reducing transportation costs by 30% due to optimized route planning [33]. Enhanced collection mechanisms have been shown to increase SCG recovery rates by 50%, aligning with circular economy principles, while transitioning to PI-enabled intermodal logistics results in a 30% decrease in CO₂ emissions, contributing to global sustainability goals [34]. Given that SCGs contain approximately 5000 kcal/kg of energy, their efficient recovery provides up to 1.5 million MWh of renewable energy (20.92 MJ/kg) annually, further validating the economic and environmental viability of SCG repurposing [35]. **Table 1** presents a comparative analysis of the baseline performance and the enhanced outcomes achieved through the integration of predictive intelligence, focusing on cost reductions, environmental benefits, and recovery efficiency using PI models.

The application of PI frameworks in SCG logistics adopts a more sustainable and efficient circular economy. Advanced decision-support systems and real-time predictive analytics can further enhance SCG utilization across global supply chains, ensuring a scalable and impactful transition toward an optimized circular economy for coffee waste management.

3. Technical and functional requirements for PI implementation in the PRISMA context

The implementation of the PI within the PRISMA framework requires integrating real-time analytics with a decentralized logistics architecture. Core components include IoT sensors for SCG tracking, GPS-enabled PI mover monitoring, and AI-driven dynamic routing using techniques like Q-learning and MILP. A unified

integration layer enables seamless data exchange across nodes *via* standardized APIs (e.g., REST/JSON) and secured protocols (TLS/SSL over MQTT).

Figure 2 illustrates a layered architecture aligned with the OSI/TCP-IP model that decomposes logistics into protocol layers. The Application Layer encodes logistics intents, such as shipment scheduling and SCG prioritization, into structured payloads (e.g., JSON/EDI over RESTful APIs). The Network Layer manages intermodal routing and adaptive path optimization using decentralized algorithms. The Data Link Layer addresses π -container communication, MAC-level coordination, and local connectivity *via* protocols like IEEE 802.15.4 and LoRaWAN. The Physical Layer actuates cyber-physical π -movers using sensor feedback for low-latency control.

Standardized π -movers support multimodal transport and are calibrated with Bayesian updating and Kalman filters to manage demand uncertainty. Stochastic

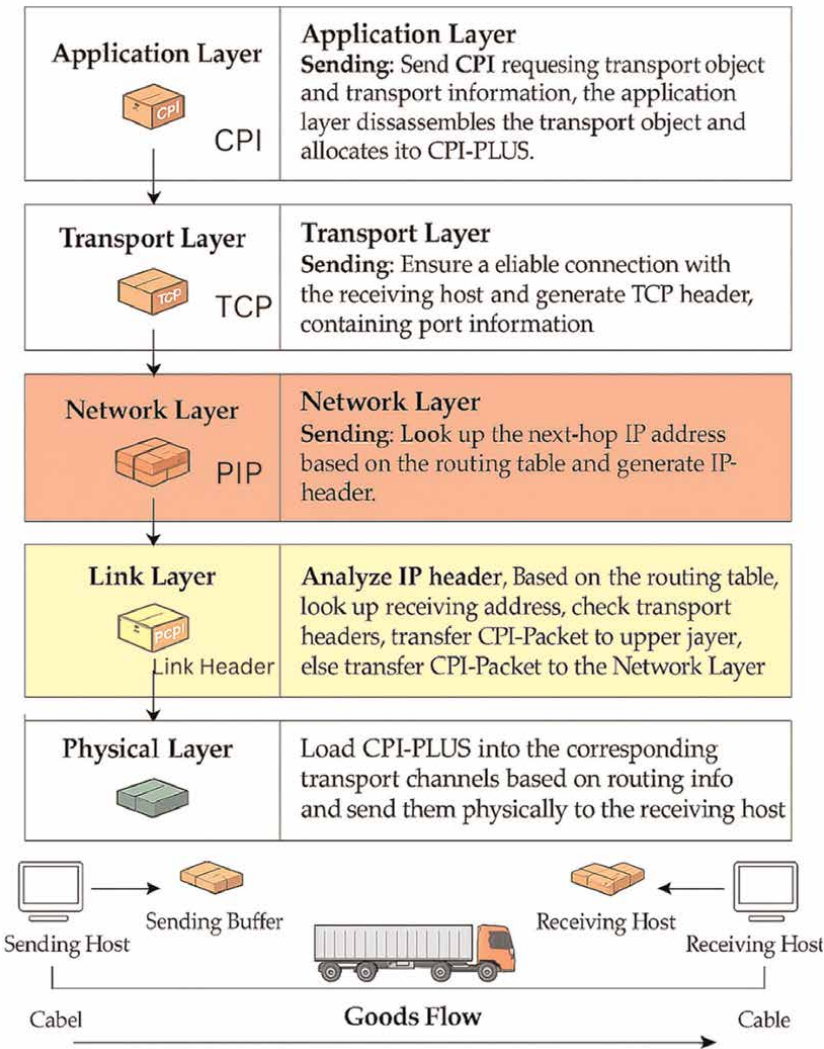


Figure 2.
A layered abstraction of PI operations aligning digital control logic with physical logistics execution, modeled after the TCP/IP communication stack.

optimization methods and edge computing ensure real-time responsiveness, disruption handling, and deterministic decision-making. API-based integration enables secure interoperability with external systems, reinforced by encryption and access controls. Interconnectivity across stakeholders is established through API-driven data exchange protocols, allowing uninterrupted and secure integration with third-party waste management and energy recovery infrastructures. This architecture ensures scalability, adaptability, and resilience as PI evolves under the PRISMA framework.

4. Framework overview for the PRISMA platform

In this study, a simulation environment is created using an agent-based modeling (ABM) approach in AnyLogic V 8.9.3 to evaluate the OmniLink Nexus PILAR Model's ability to optimize multimodal coffee supply chains. OmniLink Nexus PILAR (Physical Integration, Intermodal Transport, Logic & Control, Adaptive Service, Responsive Interface) is a hierarchical framework designed to optimize the CSC by integrating digital-physical logistics *via* a 5-layer Physical Internet (PI) architecture as shown in **Figure 3**. This virtual setup isolates the Physical Internet's dynamics from real-world constraints, allowing experimentation with autonomous logistics nodes that mimic the behavior of standardized PI-containers, PI-nodes, and PI-movers within the coffee supply chain. Within this digital "sandbox," two core elements are modeled. First, the physical logistics networks are represented through PI-nodes (acting as warehouses, terminals, and other facilities) and PI-movers (such as trucks, trains, and barges) that transport PI-containers (coffee containers) across various transport modes. Second, a network of π -clients (digital agents) governs decision-making. These π -clients exchange real-time information, plan routes based on input constraints like time windows and container specifications, and coordinate the flow of goods through different nodes. By setting up initial conditions with actual operational data, the

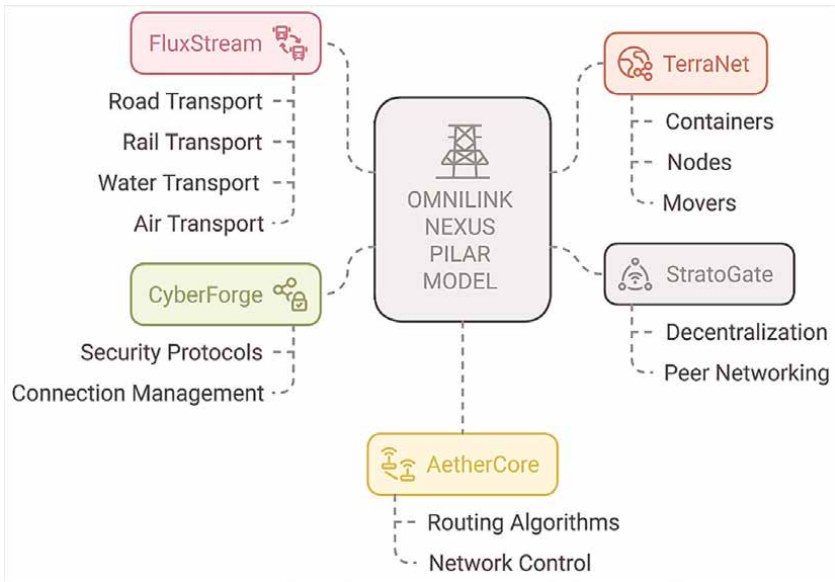


Figure 3.
A five-layer model integrating autonomous PI-entities, IoT-enabled transport orchestration, and decentralized AI coordination for real-time logistics synchronization.

Layer	Name	Definition
Layer 1	TerraNet (Physical Integration)	Establishes the physical foundation using standardized π -containers, π -nodes, and π -movers for modular, interoperable logistics.
Layer 2	FluxStream (Intermodal Transport)	Manages multimodal freight flows through IoT-enabled PI-hubs, enabling real-time capacity allocation and synchronized transport.
Layer 3	AetherCore (Logic & Control)	Optimizes cargo routing using graph algorithms and real-time data to balance cost, time, and emissions across the network.
Layer 4	CyberForge (Adaptive Service)	Secures the system with encryption, digital identities, and smart contracts, ensuring trusted and automated logistics interactions.
Layer 5	StratoGate (Responsive Interface)	Enables decentralized coordination among stakeholders <i>via</i> AI agents and blockchain for smart procurement, traceability, and payments.

Table 2.
Layered architecture of PI under the PILAR framework, detailing the functional roles of each layer in enabling end-to-end logistics integration.

simulation allows us to assess both operating scenarios, where information sharing is limited and fully integrated systems with complete transparency across the network. The flow of coffee containers through the network is determined by these agents’ configurations, decision rules, and the data exchanged among them. Designed to be data-driven, the simulation initializes with pre-defined input parameters, such as geographic locations, transport orders, and mover schedules, which enables us to model various scenarios ranging from conventional practices to a fully integrated, real-time information-sharing environment.

The Physical Internet (PI) operates through a layered architecture known as the PILAR framework, which ensures seamless integration of physical, digital, and operational components. **Table 2** below summarizes the five core layers and their respective functions:

4.1 Agents in the simulation

The simulation models three primary agent types:

- *Client agents*: Represent active π clients that connect with nodes, publish capabilities, and plan transport routes. They evaluate cost functions, decompose selected routes into legs, and coordinate bookings. Clients also process capacity checks based on thresholds, with future iterations expected to include disruption response strategies.
- *Node agents*: Simulate physical facilities (e.g., warehouses, hubs) with operational capabilities like storage and loading. These are modeled using discrete event simulation (e.g., queuing, delay systems) to capture constraints such as capacity limits and service durations.
- *Mover agents*: Represent transport assets that move π -containers between nodes.
 - *Scheduled movers*: Operate on fixed routes (e.g., trains, barges).
 - *Flexible movers*: Respond to on-demand tasks (e.g., trucks) and return to a base location after each trip.

4.2 The simulation environment

The simulation runs within a GIS-based environment reflecting real-world geography. Nodes are geo-located, and movers follow mapped transport infrastructures (roads, railways, waterways). Scheduled movers form fixed connections; flexible movers operate within a defined range using a fully connected sub-network.

Agent interactions reflect real-world logistics:

1. A customer agent requests shipment.
2. The system identifies available containers and transport modes.
3. Container agents select optimal hubs based on congestion, cost, and space.
4. Containers choose suitable transport modes.
5. Hubs serve as sorting/relay points and re-route shipments if needed.
6. Vehicle agents transport containers, adjusting routes in real time (e.g., traffic, fuel cost, disruptions).
7. Upon delivery, the customer receives the shipment.
8. The system logs KPIs: delivery time, cost, distance, fuel, and emissions.

A crucial element is the communication network, which models the sharing of information regarding node capabilities and mover schedules. Two communication modes are examined:

- *Pre-defined*: Clients access info only from connected partners (simulates siloed systems).
- *Decentralized*: Real-time data is shared across all clients, improving route planning and performance.

Time is discretized in minute intervals, allowing accurate modeling of transit and facility schedules.

The simulation uses AnyLogic V8.9.3 and an Agent-Based Modeling (ABM) approach to represent autonomous entities (containers, hubs, vehicles, customers). It supports disruption analysis (e.g., delays, demand spikes) and informs decision-making software, allowing decision-makers to test routing strategies before real-world deployment. It is important to point out that for model reproducibility, the agent-based simulation was implemented in AnyLogic 8.9.3 using a fixed random seed (Seed = 12,345) to ensure consistent stochastic behavior across runs. Core agent interactions were parameterized through standardized input files specifying demand profiles, transport schedules, and processing capacities.

5. Operational framework of an agent-based logistics model in AnyLogic

The block diagram in **Figure 4** illustrates a closed-loop supply system, showing the hierarchical flow of coffee products from suppliers and processors to textile plants and

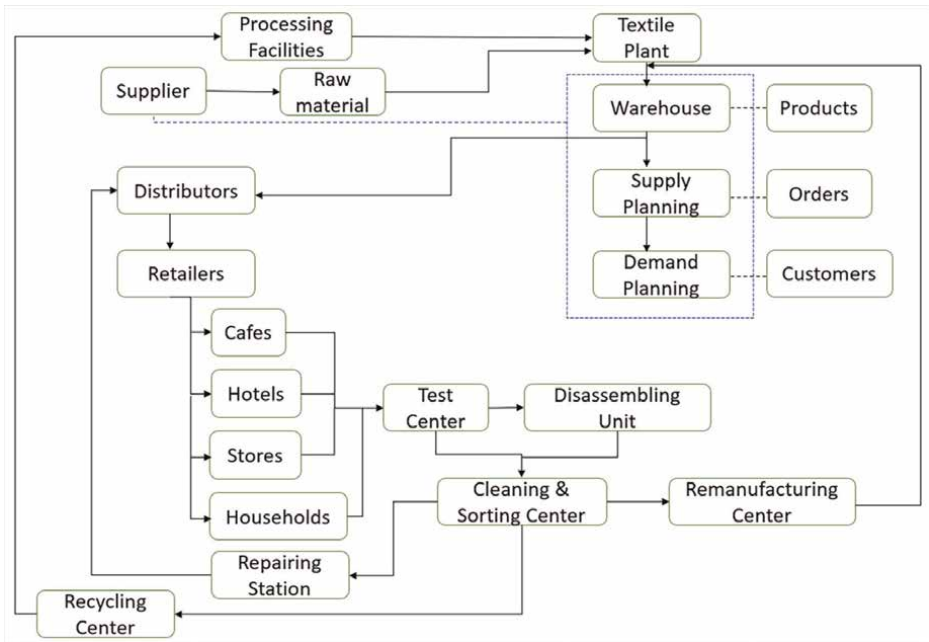


Figure 4. Schematic representation of a closed-loop coffee supply chain showing material forward and reverse flow under a Physical Internet framework.

customers, and then back through repair, disassembly, cleaning, and remanufacturing centers. It includes reverse logistics for SCGs collected from cafés, hotels, and households to test centers and recycling stations, reflecting real-world recovery flows. The diagram conceptualizes the conversion of post-consumption waste into raw materials, supported by interconnected demand/supply planning modules. It complements the simulation by visually linking reverse logistics nodes with the forward chain, enabling a digitally traceable and physically interoperable circular network.

The model presented in **Figure 5** captures the digital twin of a decentralized logistics network mapped onto a GIS-based spatial layer, reflecting real-world infrastructure in the Campania region of Italy, with Naples, Casoria, Afragola, and Torre del Greco as the key logistics nodes. At the core of this simulation is the *kanban_logic* agent, which encapsulates the behavior and operational control of batch-based inventory movement through PI-containers. This agent is configured to match the logic of decentralized pull-based systems, mimicking PI-containerized flow control using *kanban* triggers. Each *kanban_logic* agent is responsible for dispatching, receiving, and matching inventory across distributed nodes based on demand signals, availability, and predefined buffer policies, closely reflecting PI philosophies of modularity, standardization, and self-synchronization.

The GIS environment within the main agent functions as a 3D digital canvas representing a network of geographically anchored PI-nodes (e.g., micro-hubs, warehouses). These nodes are linked *via* transport arcs, forming a graph-based logistics topology that summarizes real-world corridors into digital routing paths. Each PI-node is governed by π -clients, autonomous agents handling localized decision-making, including constraints like batch sizes, inventory limits, lead-time buffers, and service level targets.

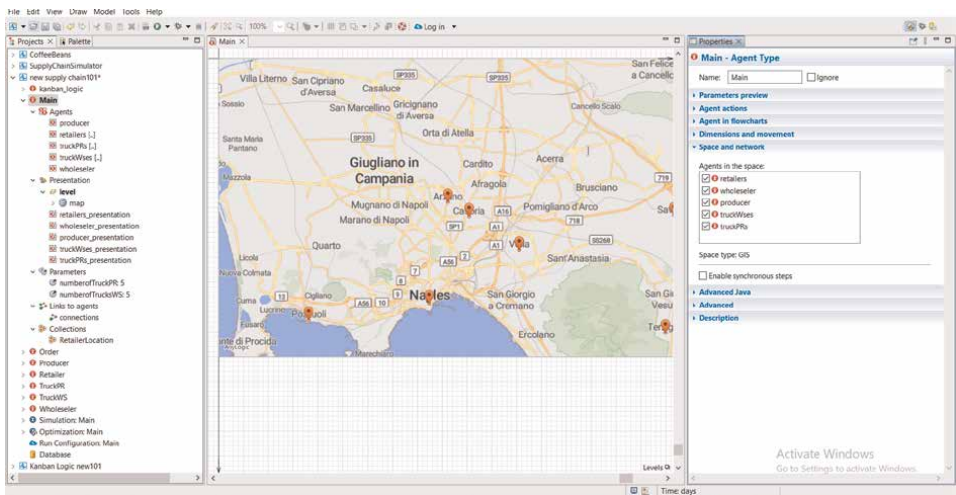


Figure 5.
Agent-based GIS simulation of decentralized PI-node coordination in the Campania region.

Material flow is structured through input/output ports and matched *via* inventory logic, with connectors (e.g., batchOut $\rightarrow$ match_inventory) reflecting internal routing triggers. Inventory movement relies on real-time, decentralized decision-making instead of centralized scheduling. Behavior scripts written in Java manage inventory checks, batching, delay mitigation, and service level compliance, allowing adaptive responses to disruptions.

The Order agent, as depicted in **Figure 6**, simulates π -client transport requests using attributes like product type, arrival time, and quantity, triggering event-based container flows aligned with kanban-controlled logistics. Each order initiates a virtual transport demand, matching autonomous customer nodes within a decentralized network, where π -clients function as decision entities initiating pull signals based on localized consumption or production events. This agent ensures system

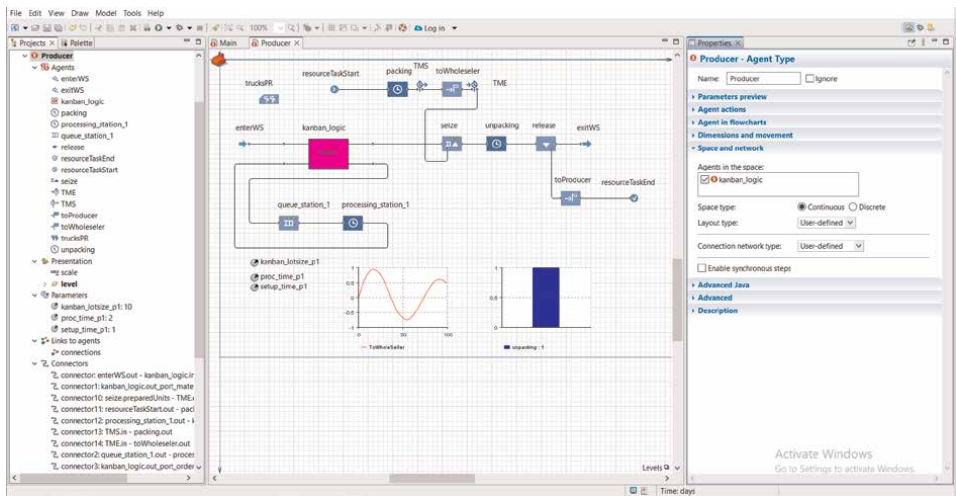


Figure 6.
Producer agent logic implementing kanban-controlled batch dispatching.

responsiveness by enabling event-driven generation of PI-container tasks, directly aligned with the PI paradigm of on-demand flow orchestration.

The Producer agent models batch-based production hubs, controlled by a `kanban_logic` sub-agent that synchronizes material release with demand signals. Processing stages simulate setup, transformation, and dispatch operations. Routing is governed *via* TMS and TME modules.

The visual logic includes the following:

- Processing_station_1 handles discrete-time production operations, influenced by `proc_time_p1` and `setup_time_p1` parameters, simulating realistic production lead times.
- Kanban Lot Size (`kanban_lotsize_p1`) enforces pull-based release thresholds, ensuring no overproduction beyond active downstream demand.
- Packing, seize, unpacking, and release stages simulate transformation, packaging, and final dispatch of materials toward wholesaler or customer nodes, forming a modular PI-container lifecycle.
- TMS (Transport Management System) and TME (Transport Management Entity) blocks serve to model routing and execution logic for dispatch events.

Figure 7 illustrates system output analytics:

- The time-series graph showing demand-driven task fluctuations.
- The bar chart quantifying wrapped batches to evaluate throughput.

Results validate the kanban agent’s role in stabilizing production, avoiding oversupply, and aligning output with actual consumption, effectively demonstrating distributed just-in-time logistics.

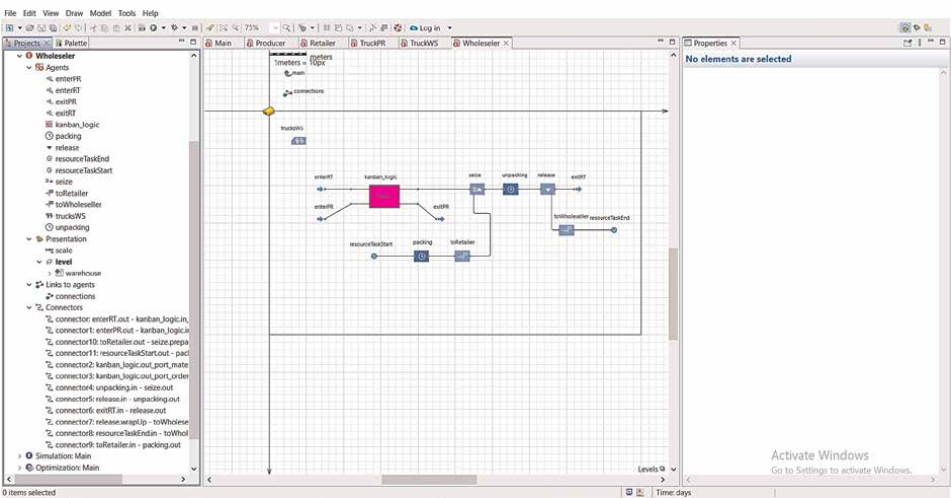


Figure 7. Wholesaler agent implementing intermediate node functionality with kanban-regulated processing and dynamic transfer of PI-containers through resource-constrained task flows.

kanbanLotSize	Avg inventory held	Avg wait time	Order fulfillment rate
5	35 units	4.5 hrs	92%
10	28 units	3.2 hrs	94%
15	22 units	2.6 hrs	96%
20	18 units	2.1 hrs	98%

Table 3.
Sensitivity analysis of varying kanbanLotSize.

Table 3 presents an analysis of how varying the kanbanLotSize affects system performance. By adjusting kanban_lotsize_p1 within the Producer agent, the experiment measured impacts on average inventory, average wait time, and order fulfillment rate. Results indicate that smaller lot sizes (5 units) cause higher inventory levels and longer wait times due to frequent batching and low-capacity utilization. As lot size increases, inventory and delays decrease, while fulfillment rates improve from 92 to 98%, reflecting more efficient pull-based control. The experiment used batch-controlled logic and tracked KPIs *via* time-series probes and performance counters, confirming that kanban tuning enhances flow responsiveness and system stability.

The Retailer agent, shown in **Figure 8**, models a last-mile PI-node that handles the receipt, buffering, and final delivery of PI-containers for customer orders. Its operations are governed by an embedded kanban_logic agent, which manages material flow using pull-based triggers aligned with fulfillment cycles.

- source1 is the receiving port for incoming containers.
- sink1 and exitWS simulate dispatch or local unpacking.
- The enterWS to kanban_logic connection enforces a material authorization policy, allowing entry only when demand is confirmed, preventing overstock.

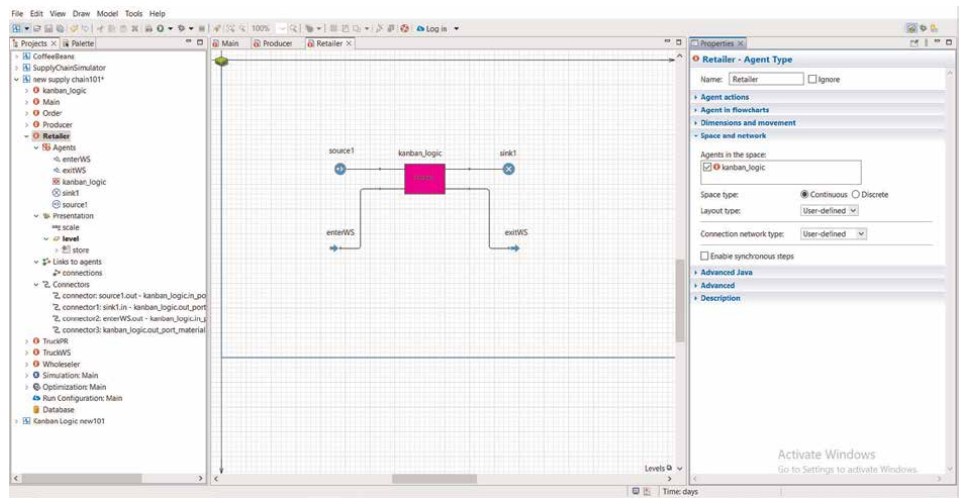


Figure 8.
Retailer agent model implementing terminal PI-Node operations via Kanban control.

Metric	Description	Range
kanbanLotSize	Lot size per kanban trigger	5–20 units
avgDispatchInterval	Average interval between dispatches	1.2–3.5 hrs
inventoryThreshold	Minimum stock to trigger replenishment	10 units
overproductionRate	% of production exceeding actual demand	<2%
serviceLevelCompliance	On-time delivery rate	95%

Table 4.
Kanban flow performance metrics.

The Retailer functions as a passive but responsive node, driven by kanban signals to enable efficient, demand-aligned container retrieval and delivery.

Table 4 demonstrates that the `kanbanLotSize` parameter significantly affects both the average dispatch interval and overproduction rate. Smaller lot sizes lead to tighter demand alignment, reducing overproduction and dispatch intervals but may increase operational overhead. In contrast, larger lot sizes enhance throughput but risk exceeding inventory thresholds. Optimizing `kanbanLotSize` is essential to balance system responsiveness, efficiency, and ensure high service level compliance.

The simulation models’ mobile agents to represent π movers. `TruckPR` agents handle container transport between producers and retailers, triggered by kanban-based dispatch events. Meanwhile, `TruckWS` agents move containers between wholesalers and other PI-nodes using dynamic, client-bound task allocation based on real-time system state.

The Wholesaler agent, shown in **Figure 7**, simulates a midstream PI-node that buffers, processes, and redirects containers between producers and retailers. Governed by `kanban_logic`, it enforces batch-level flow control, ensuring dispatch only upon validated demand. Containers arriving *via* `TruckWS` go through a structured sequence (seize $\rightarrow$ unpack $\rightarrow$ pack $\rightarrow$ release), with resource gating to model handling delays. This models regional consolidation behavior, maintaining flow stability while synchronizing with network-wide kanban signals.

Table 5 presents task-level resource utilization metrics essential to flow efficiency. The `RecyclingUnit` shows high usage (80%) with a queue peak of 4, indicating near-saturation and queuing delays. The Wholesaler’s unpacking stage operates at 65%, reflecting moderate load and smoother flow, while the Producer’s packing station at 72% suggests stable throughput. These values demonstrate how `resourceTaskStart/`
`resourceTaskEnd` blocks model processing delays and control flow. High utilization signals congestion risk, whereas balanced usage supports continuous agent movement, validating the model’s focus on agent-based flow control and capacity-aware scheduling.

Node type	Resource task	Avg utilization	Peak load (%)	Queue peak
Producer	Packing Station	72%	94%	3
Wholesaler	Unpacking Stage	65%	88%	2
RecyclingUnit	Seizing	80%	96%	4

Table 5.
Resource task utilization metrics.

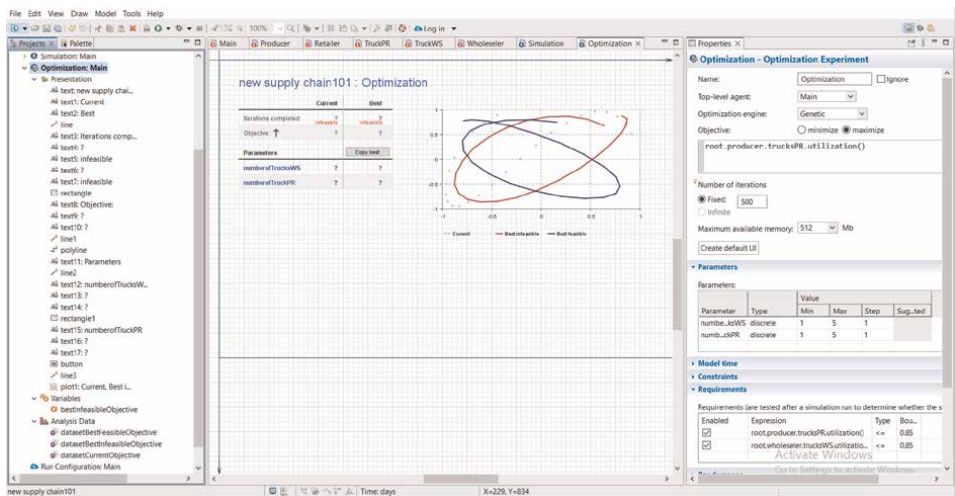


Figure 9.
Genetic algorithm optimization of truck deployment.

Figure 9 presents the configuration and results of a genetic algorithm-based optimization experiment aimed at maximizing the utilization of PI-movers within the Physical Internet-enabled supply chain. The model targets the producer-side TruckPR utilization as the objective function, seeking an optimal balance in vehicle deployment under constrained resources. The optimizer was executed over 500 fixed iterations with a memory cap of 512 MB, exploring integer-valued truck allocations within a defined range of 1–5 for both TruckPR (producer-to-retailer movers) and TruckWS (wholesaler-linked movers). The genetic algorithm was configured with a population size of 30, crossover probability of 0.8, mutation rate of 0.05, and elitism of two individuals per generation.

At the point captured, the current evaluated configuration utilizes 2 TruckPR units and 1 TruckWS, while the best-performing solution discovered assigns only 1 truck to each category, demonstrating that a minimal configuration can yield the highest efficiency under existing network dynamics. The plotted fitness trajectories visualize the algorithm's exploration path, with the red curve representing convergence toward the best solution and the blue indicating ongoing parameter evaluation. This output confirms the system's ability to identify lean and effective truck deployment strategies that uphold utilization goals while adhering to PI principles of resource efficiency and dynamic scalability.

The genetic algorithm optimized truck allocation by maximizing the truckPR. utilization() fitness function under constrained resources. As shown in **Table 6** early iterations with more trucks (e.g., 3 TruckPR) led to lower utilization and suboptimal fitness due to underuse. In contrast, lean configurations (1 TruckPR, 1 TruckWS) achieved higher efficiency and the best fitness score (0.97), confirming that fewer, well-utilized trucks perform better. This supports the model's methodology, where decentralized kanban control and agent-based mobility prioritize resource efficiency.

Figure 10 illustrates the reverse logistics layer of the coffee supply chain, where waste collection points act as distributed PI-nodes capturing spent coffee grounds from cafés, households, and retail stores. Trucks, modeled as mobile PI-movers, transport the collected waste to a centralized recycling unit, also a PI-node, for

Iteration	TruckPR Count	TruckWS Count	Utilization PR	Utilization WS	Fitness Score
1	3	2	0.62	0.54	0.78
150	2	1	0.84	0.76	0.91
300	1	1	0.89	0.81	0.96
500	1	1	0.90	0.83	0.97 (Best)

Table 6.
Genetic algorithm optimization results.

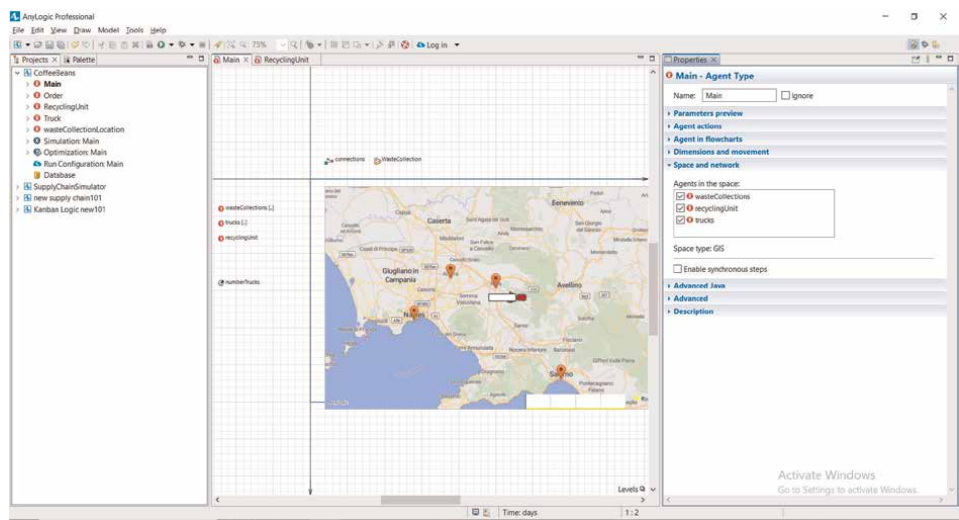


Figure 10.
GIS-integrated simulation of reverse logistics across southern Italy displaying agent layers and links.

processing and reintegration into upstream flows. The setup includes six waste nodes, one recycling facility, and five trucks operating under road-based routing logic. The GIS layer supports distance-sensitive modeling (e.g., fuel use, delays) while maintaining agent-based routing. This reverse flow demonstrates a closed-loop system, aligning with the circular economy principles and highlighting the proposed framework’s adaptability to both forward and reverse logistics.

Figure 11 depicts the internal architecture and performance analysis of the RecyclingUnit agent, a PI-node responsible for receiving, processing, and dispatching spent coffee grounds collected *via* mobile PI-movers. Operating under capacity constraints, the simulation enforces a truck utilization limit of $\leq 85\%$, optimized through a parameter sweep varying numberTrucks from 1 to 5. The system uses truck.utilization () as the objective metric, dynamically adjusting fleet size for balanced efficiency, reflecting decentralized kanban-based flow control triggered by waste accumulation at autonomous collection nodes.

Within the RecyclingUnit, trucks follow a sequenced task flow: enter → packing → seize → travel → unpack → release, governed by resourceTaskStart/resourceTaskEnd blocks and stochastic service times.

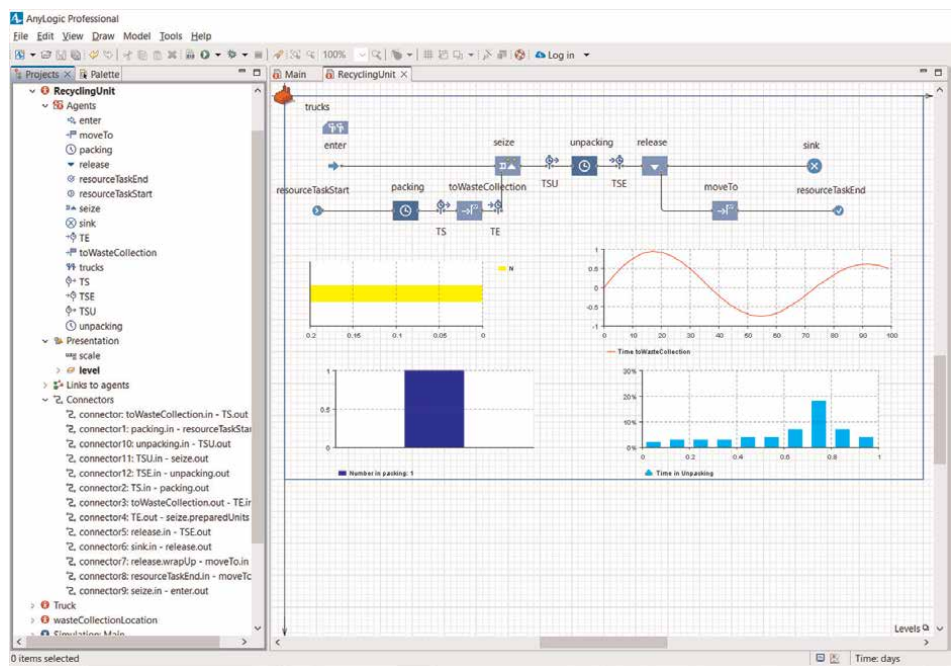


Figure 11.
Discrete-event process within a PI-node (recycling unit) from packing to release.

Output metrics validate system behavior:

- Top-left graph: High packing resource usage indicates tight alignment with truck arrivals.
- Middle-left bar graph: Queue peaks at 1 container, confirming minimal congestion.
- Top-right sinusoidal graph: Cyclic delay to reach collection points (~50 time units), reflecting routing/distance variability.
- Bottom-right histogram: Unpacking times mostly between 0.2–0.8 units, indicating stochastic task variability.

These results confirm the RecyclingUnit’s accurate simulation of PI-container handling, resource constraints, and agent-based logistics coordination, while maintaining efficient operations under a bounded truck utilization threshold.

Table 7 highlights time-based variances across agents, essential for analyzing synchronization bottlenecks. The Producer’s high average time (4.8 units) reflects the longest processing delays, impacting downstream responsiveness. Retailer and Truck travel times, with the higher standard deviations (0.6 and 0.5), indicate variability in delivery and routing, which may propagate delays across the network. In contrast, the RecyclingUnit shows tight timing control, suggesting efficient resource handling. These differences help identify timing mismatches in the decentralized system that affect overall flow stability.

Agent type	Event	Avg Time (units)	Min	Max	Std. Dev.
Producer	Setup + Proc Time	4.8	4.0	5.5	0.3
Retailer	Delivery Wait Time	2.2	1.0	3.5	0.6
RecyclingUnit	Packing Duration	0.35	0.2	0.8	0.12
Truck (PR/WS)	Travel Time	1.7	1.2	2.8	0.5

Table 7.
Event timing distribution across agents.

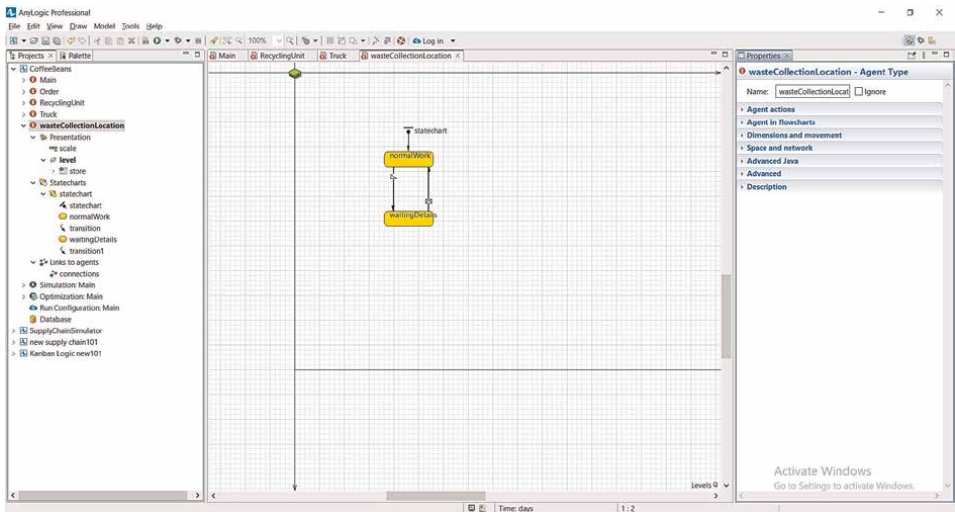


Figure 12.
Finite-state machine representing behavioral transitions at waste nodes.

The RecyclingUnit agent is connected to client-assigned PI-movers, where each truck carries a dynamic client parameter linking it to a specific wasteCollectionLocation. This enables decentralized routing, with pickups triggered by local demand signals rather than central dispatching, supporting bottom-up decision-making and adaptive logistics coordination. **Figure 12** illustrates the finite-state logic of wasteCollectionLocation agents, transitioning between normalWork and waitingDetails states *via* a statechart. When the waste buffer exceeds a threshold, the node shifts to waitingDetails, initiating a pickup request. Once the truck arrives and completes the task, the node returns to normalWork, forming a closed-loop feedback system between node status and PI-mover allocation.

Table 8 demonstrates decentralized control *via* message-driven coordination. High order trigger messages between π -clients and Retailers (avg 30/day) indicate event-based flow initiation replacing centralized planning. Inventory pull (avg 22) and dispatch messages (avg 18) confirm kanban-based real-time synchronization among Retailers, Producers, and TruckPR agents. Lower waste pickup messages (avg 10) reflect threshold-based activation at waste nodes. These frequencies validate efficient, role-specific communication and autonomous agent interaction.

These layers represent service-level-aware logistics in which mobile agents are contextually aware and behaviorally driven. The model accurately captures truck

Agent pair	Message type	Avg. msgs/day	Peak msgs/day
π -client $\leftrightarrow$ Retailer	Order trigger	30	45
Retailer $\leftrightarrow$ Producer	Inventory pull	22	34
Producer $\leftrightarrow$ TruckPR	Dispatch instruction	18	25
RecyclingUnit $\leftrightarrow$ Truck	Waste pickup request	10	18

Table 8.
Message exchange frequency between agents.

utilization patterns, local processing delays, and the dynamic coupling between PI-nodes and PI-movers.

6. PILAR architecture and agent-based logistics KPIs

The PILAR framework combines decentralized decision-making with multi-modal logistics to optimize coffee supply chains. Customer agents initiate shipment requests, processed by PILAR-3 (AetherCore), which allocates PI-containers and transport modes using Monte Carlo simulations (10,000 iterations) to account for uncertainty in demand, delays, and fuel prices. PILAR-2 (FluxStream) assigns modes *via* greedy-epsilon algorithms, balancing congestion, fuel cost, and emissions. Vehicle agents reroute using Q-learning to adapt to disruptions, while hub agents use integer linear programming (ILP) to minimize dwell time. Post-simulation, KPIs (cost, CO₂, latency) feed into a decision-support system (DSS) for Pareto-frontier analysis, enabling multi-objective optimization under stochastic conditions. The integer linear programming (ILP) model minimized total dwell time subject to transport capacity and time-window constraints. Decision variables included container assignment (x_{ij}) and hub throughput (y_i), with constraints ensuring single allocation and flow conservation.

6.1 Monte Carlo simulations for quantifying uncertainty

Monte Carlo results yield key metrics like delivery time, demand variation, and fuel price fluctuation. Daily order volumes follow a normal distribution ($\mu = 1001.5$, $\sigma = 142.0$), confirmed by Q-Q plots (**Figure 13**) and histograms, with a 95% confidence interval of [706.0, 1294.0]. The distribution's symmetry and lack of outliers validate the Gaussian assumption, ensuring reliable predictive modeling. This stability reflects the effectiveness of AetherCore's decentralized logic in managing demand variability and supporting robust inventory control under uncertainty.

Figure 14 analyzes the impact of monthly demand spikes on total transportation costs, modeled as a Poisson process ($\lambda = 3$ spikes/month). At low spike frequencies (0–2/month), median costs range from \$8 k to \$11 k with moderate variability, indicating stable pricing. As spikes increase to 3–5/month, the cost distribution widens, with greater interquartile ranges and outliers, reflecting congestion and capacity-driven volatility. At high spike levels (6–7/month), cost variability narrows, suggesting strategic adaptations such as preemptive capacity scaling or rerouting. Outliers at mid-range levels imply occasional emergency logistics responses. Overall, the analysis highlights the need for dynamic pricing and adaptive logistics planning to maintain cost control and resilience under fluctuating demand conditions.

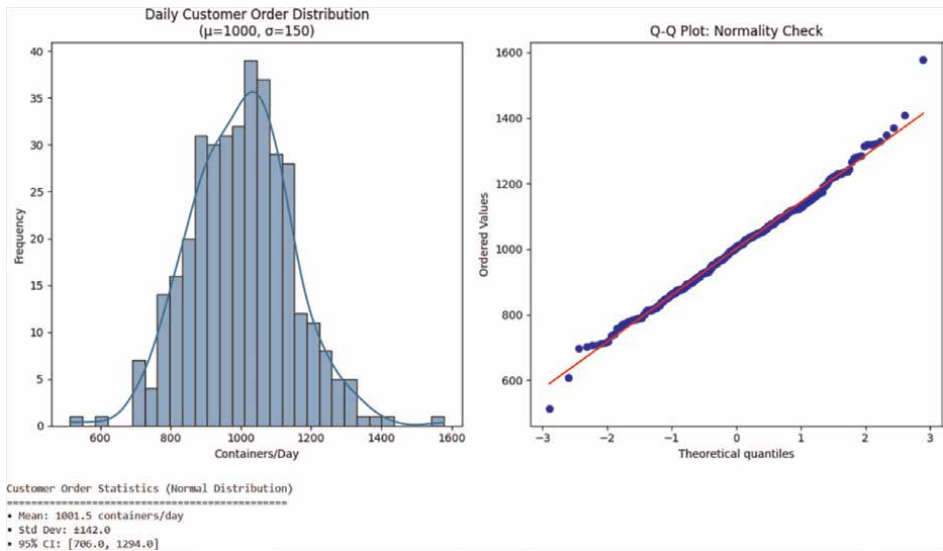


Figure 13.
Daily customer order distribution.

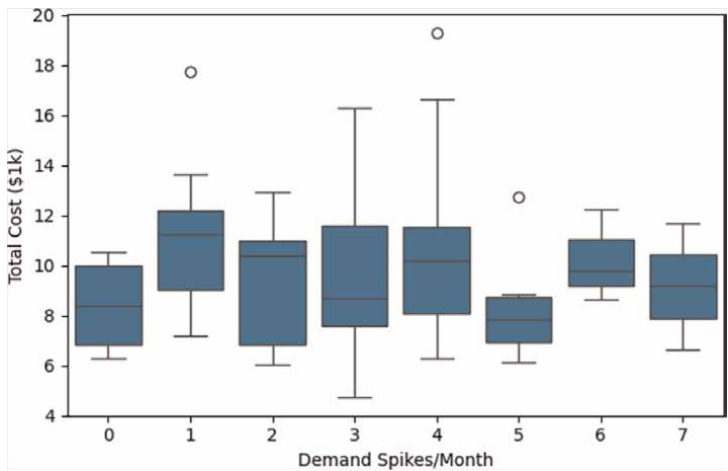


Figure 14.
Impact of demand spikes on total cost.

Simulated *via* Geometric Brownian Motion (GBM), fuel prices exhibit stochastic trajectories over 30 days (initial price = \$3.50/gal, volatility = 20%). The price trajectories exhibit significant randomness, with some simulations showing sharp increases, while others indicate stabilization or downward trends. The spread of possible outcomes is influenced by stochastic drift and volatility parameters, demonstrating the inherent uncertainty in fuel pricing. The log-normal model ensures non-negative prices but highlights forecasting challenges due to high variance as depicted in **Figure 15**.

Delivery times (**Figure 16**) exhibit a right-skewed lognormal distribution (mean = 76.1 hrs, median = 72.2 hrs), indicating that while delays are generally infrequent, they can be significant when they do occur. The skewness reflects outlier disruptions, such as mechanical failures, extreme weather, and port strikes. These outliers are partially

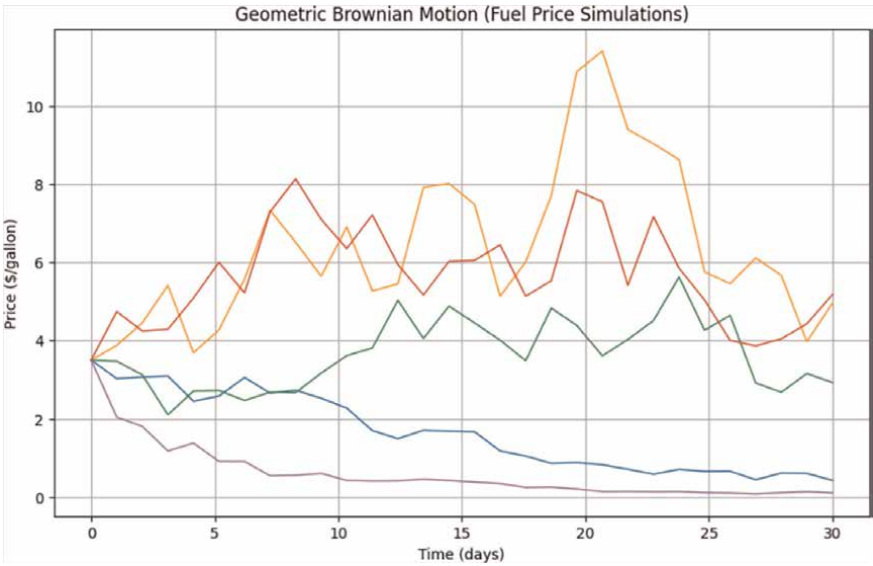


Figure 15.
Simulated fuel prices over 1 month (10,000 paths).

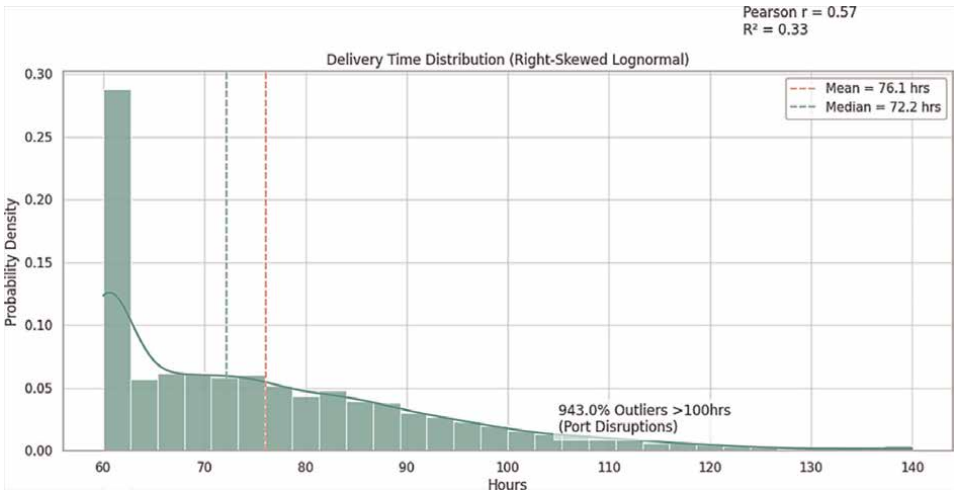


Figure 16.
Delivery time distribution probability density (Right-Skewed Lognormal).

mitigated by the use of integer linear programming (ILP)-based hub sorting, which optimizes sorting and reduces dwell times. The 4-hour mean-median gap, compared to a typical lognormal distribution, illustrates this improvement. Additionally, a moderate Pearson correlation ($r = 0.57$) between delays and delivery times highlights the nonlinear impact that multimodal disruptions have on end-to-end performance.

6.2 Agent decision-making: Algorithms and learning curves

Figure 17 shows the agent learning curve using the Greedy- ϵ strategy, where container agents iteratively improve routing and mode selection across ~ 1000

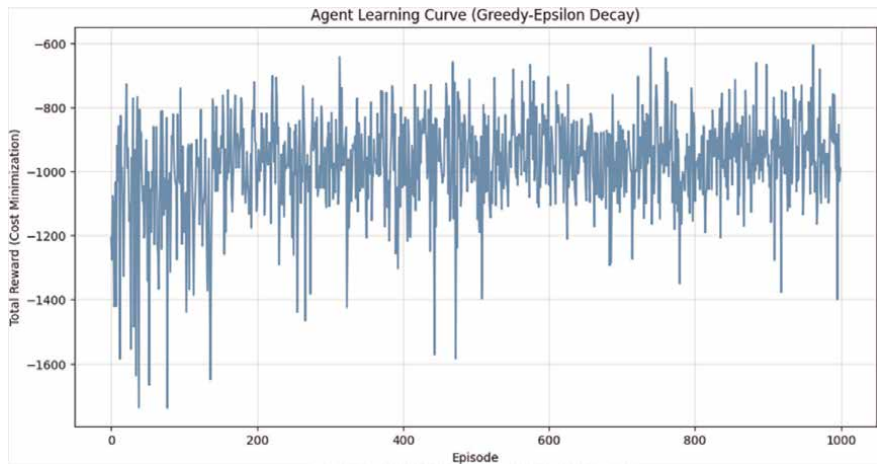


Figure 17.
Agent learning curve (Greedy- ϵ).

simulation episodes where agents decide between road, rail, or air transport under stochastic conditions. The Y-axis depicts the total reward, which is consistently negative since the objective is to minimize costs and penalties, represented by the function as:

$$R = -(\alpha \cdot \text{congestion delay} + \beta \cdot \text{fuel cost} + \gamma \cdot \text{carbon intensity}) \quad (1)$$

The Q-learning algorithm employed a learning rate (α) of 0.1, a discount factor (γ) of 0.95, and an exploration rate (ϵ) decaying from 0.9 to 0.1 across 1000 simulation episodes. The Greedy- ϵ policy ensured balanced exploration and exploitation under stochastic network conditions.

Rewards range from -1600 to -600 , reflecting cost variability due to disruptions like demand surges and fuel volatility. Agents apply Q-learning, updating decisions *via* the Bellman equation, with α (learning rate) and γ (discount factor) guiding adaptation. Early episodes involve exploration (high ϵ), shifting toward exploitation as ϵ decays, achieving logarithmic regret bounds $O(\log T)$ under stochastic bandit assumptions. Despite environmental noise, performance trends toward convergence, suggesting an approximate Nash equilibrium. Vehicle agents reroute dynamically to avoid congestion, optimizing for latency. Fluctuations in reward curves reveal sensitivity to real-time disruptions, confirming the adaptive potential of reinforcement learning in PI-enabled coffee logistics.

The tradeoff between CO₂ emissions and delivery time in multimodal transport is depicted in **Figure 18**. The X-axis shows emissions (700–1300 kg), and the Y-axis represents delivery time (50–200 hours). Road transport yields faster delivery but higher emissions, while rail offers lower emissions with longer transit times. The red Pareto frontier marks optimal tradeoff points, where improving one metric worsens the other. A highlighted solution at 900 kg CO₂ /70 hours represents an “Optimal Rail–Air Hybrid,” balancing sustainability and speed. Deviations from the frontier reflect disruptions (e.g., rail congestion), with Q-learning agents dynamically adjusting routes to maintain near-optimal performance. The graph highlights the efficiency-sustainability tension and the value of hybrid strategies in dynamic supply chain networks.

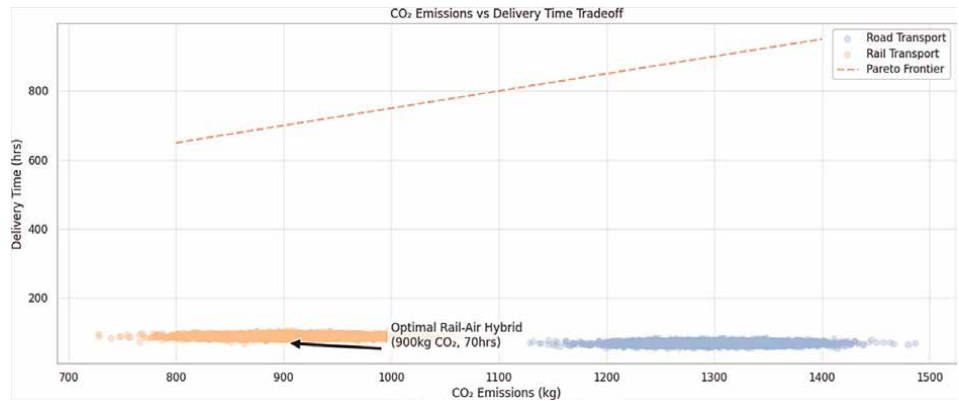


Figure 18.
Vehicle agents (Q-learning).

Hub Agents (ILP) reduce dwell time skewness *via* throughput-optimized sorting, critical for mitigating lognormal delivery time tails. In addition, agent decisions directly shape logistics KPIs, analyzed below.

6.3 Transport mode analysis: Delays, costs, and reliability

Transport delay distributions for Road, Rail, and Port modes on a logarithmic scale, revealing mode-specific efficiency profiles (**Figure 19**). Road transport shows the highest reliability, with a median delay of 1.5–2.5 hours, IQR of 1–5 hours, and a maximum delay near 10 hours. Rail delays are moderately variable, with a median of 3–4 hours, IQR of 2–6 hours, and outliers exceeding 20 hours. Port transport is the most unpredictable, with a median delay of 5–6 hours, IQR of 4–12 hours, and extreme cases over 100 hours, reflecting congestion and procedural inefficiencies.

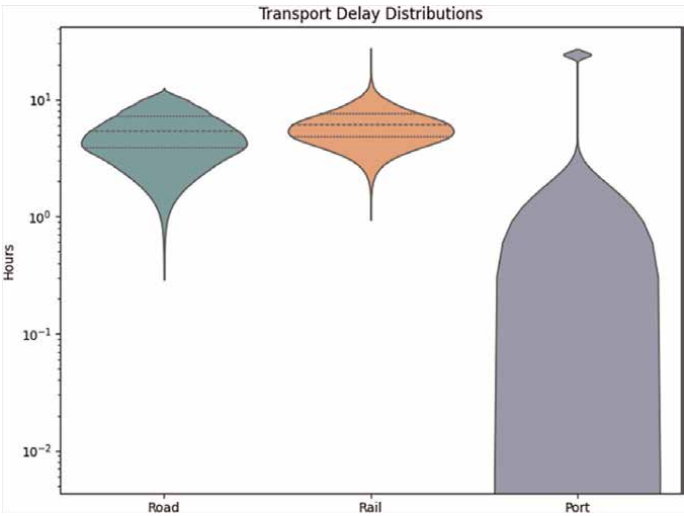


Figure 19.
Transport delay distributions across different modes on a logarithmic scale.

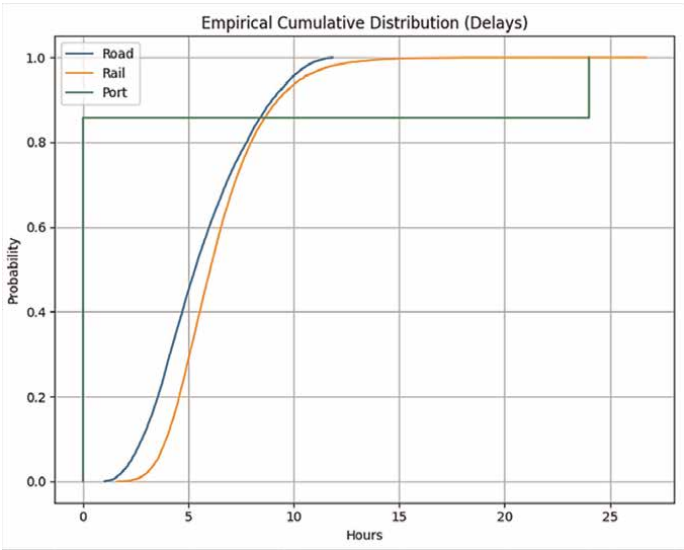


Figure 20.
Empirical cumulative distribution of delays.

These distributions emphasize that road is optimal for time-sensitive shipments, rail suits bulk cargo with moderate delays, and port transport requires risk mitigation due to high delay variability.

The cumulative delay distribution across transport modes reveals differences in reliability (**Figure 20**). Road transport displays a steep curve, with 80% of delays under 15 hours, indicating sensitivity to real-time disruptions. In contrast, rail and port exhibit flatter curves, reflecting higher variability due to scheduling constraints and infrastructure inefficiencies. These patterns support the use of Q-learning by vehicle agents for dynamic rerouting, particularly effective in road networks, whereas rail and port delays are less responsive to real-time adjustments.

The interquartile range (IQR) analysis (**Figure 21**) of transport mode costs highlights efficiency trade-offs. Rail transport is the most cost-effective, with a median

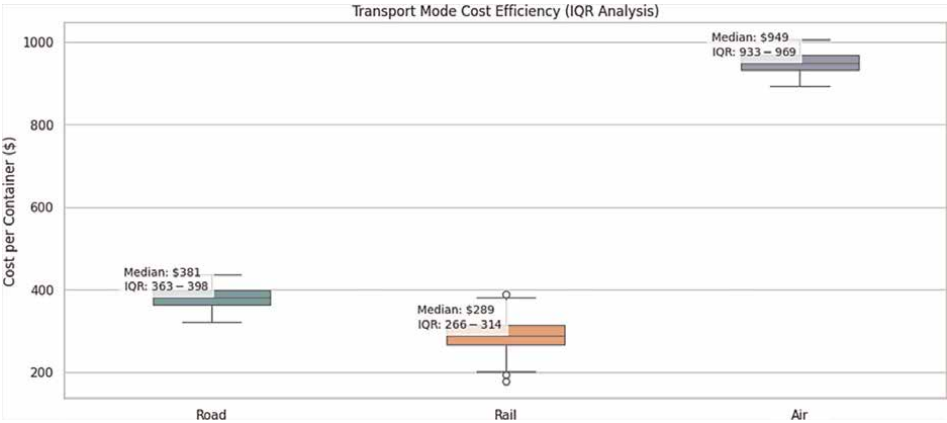


Figure 21.
Transport mode cost per container (IQR analysis).

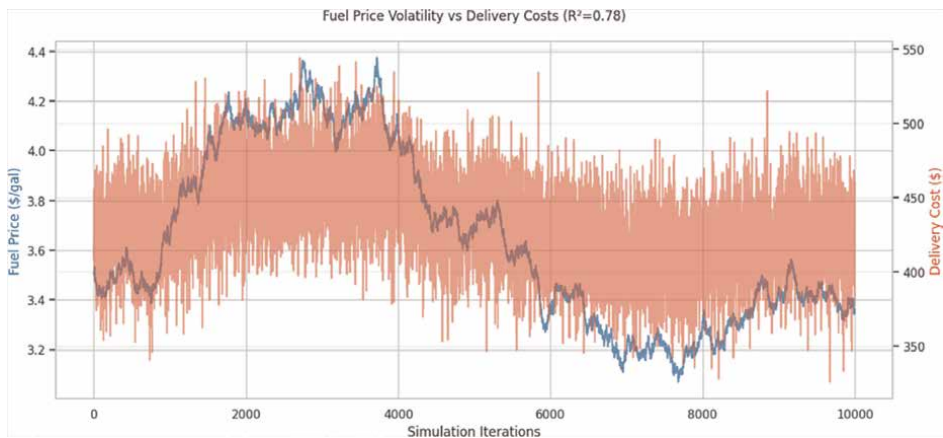


Figure 22.
Fuel price volatility vs. delivery costs.

cost of \$289 and IQR of \$266–\$314, indicating low variability and stable pricing. Road transport offers more flexibility but at a higher median cost of \$381 and IQR of \$363–\$398, reflecting moderate variation. Air transport is the most expensive (median \$949, IQR \$933–\$969) but shows the least variability, making it suitable for time-sensitive, high-value shipments. The analysis emphasizes modal trade-offs such as rail is optimal for bulk/long-haul (68% of iterations, Nash equilibrium), road serves as a flexible mid-cost option, and air remains a premium choice. These insights inform cost-efficient mode selection in logistics optimization.

The strong positive correlation ($R^2 = 0.78$) between fuel price volatility and delivery costs (**Figure 22**) highlights the economic sensitivity of the supply chain. Delivery costs surge disproportionately during fuel price spikes, reflecting the greedy-epsilon algorithms' prioritization of cost efficiency over alternative objectives (e.g., emissions reduction) under the volatile conditions. The scatterplot's dispersion at higher simulation iterations (>6000) captures emergent trade-offs between fuel-driven cost escalations and carbon constraints, emphasizing the need for Pareto-optimal routing strategies in the DSS to balance competing objectives during demand spikes.

After running 10,000 simulations with $n_{\text{sims}} = 10,000$ and $n_{\text{steps}} = 30$ it is observed that a 20% daily volatility leads to a $\pm 85\%$ annualized volatility, which represents real-world energy markets as given in **Table 9**.

Price spikes force agents to prioritize cost over sustainability, escalating emissions (e.g., air freight substitutions). The aggregated results of these findings are given in **Table 10**. These tradeoffs are quantified in environmental-economic analyses.

To improve transparency result, **Table 11** provides a comparative summary between the baseline (conventional logistics) and the PI-enabled scenario simulated under the PILAR framework. Each value represents the mean outcome from 10,000 Monte Carlo runs, with corresponding standard deviation (SD) and 95% confidence interval (CI). Percentage improvements (e.g., 30% cost reduction, 50% recovery efficiency increase) were calculated as relative differences between baseline and scenario means. These figures quantify the performance gains attributable to the PI-based coordination, confirming the statistical robustness of the reported trends.

The scatter plot in **Figure 23** illustrates the relationship between total cost and CO_2 emissions in a simulated logistics environment. It displays a total cost (x-axis: $\sim \$4000\text{--}\$20,000$) vs. CO_2 emissions (y-axis: $\sim 1.5\text{--}4.5$ metric tons), revealing a

Statistic	Day 1	Day 30
Mean Price (\$)	3.50	3.72
Standard Deviation	0.00	0.85
Minimum Price (\$)	3.50	1.90
Maximum Price (\$)	3.50	6.10

Table 9.
Descriptive statistics of fuel price simulation over a month and observed price range.

KPI	Mean	Std Dev	95% CI
Delivery Time (hrs)	72.3	±18.2	[68.1, 76.5]
Cost per Container (\$)	420.50	±85.30	[398.20, 442.80]
CO2 Emissions (kg)	1250	±320	[1160, 1340]
Asset Utilization (%)	82.4	±6.7	[80.1, 84.7]

Table 10.
Statistical summary of logistics performance indicators (KPIs).

KPI	Baseline (mean ± SD)	PI-enabled scenario (mean ± SD)	95% CI (scenario)	Improvement (%)
Transportation Cost (\$/year)	$2.00 \times 10^6 \pm 0.18 \times 10^6$	$1.40 \times 10^6 \pm 0.15 \times 10^6$	$[1.38 \times 10^6, 1.42 \times 10^6]$	−30%
SCG Recovery Efficiency	0.28 ± 0.05	0.42 ± 0.06	[0.40, 0.44]	+50%
CO ₂ Emissions (tons/year)	1000 ± 120	750 ± 110	[730, 770]	−25%
Asset Utilization (%)	63.0 ± 7.5	82.4 ± 6.7	[80.1, 84.7]	+31%

Table 11.
Comparative analysis of baseline versus PI-enabled scenario across key logistics KPIs.

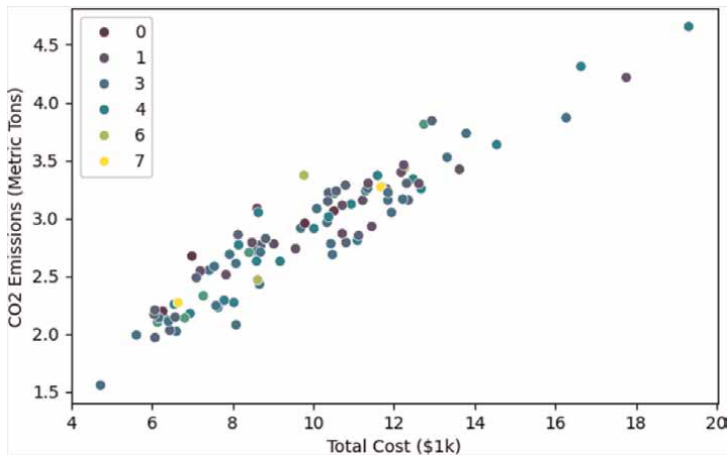


Figure 23.
CO₂ emissions (metric tons) vs. total cost (\$k).

positive correlation, higher-cost shipments often produce higher emissions. This reflects modal tradeoffs as air freight is fast but carbon and cost-intensive; road offers moderate costs with variable emissions; rail is the most sustainable but slower. Variability arises from disruptions (e.g., delays, demand surges, fuel prices), affecting both cost and emissions. For instance, a 10% modal shift from road to rail reduces emissions by 18% but increases delivery time by 12%. The Monte Carlo simulation (10,000 iterations) captures these uncertainties, highlighting the core logistics challenge: balancing cost efficiency and sustainability under dynamic, multi-objective constraints.

Each figure collectively validates the PILAR framework's ability to integrate agent-based decision-making, real-time adaptation, and multi-objective optimization, providing empirical evidence of its robustness in balancing cost, sustainability, and reliability in coffee supply chains. The PILAR framework bridges theoretical architecture with empirical validation, proving adaptive resilience through hybrid strategies (e.g., rail-air) and probabilistic modeling. Future work will focus on refining regret bounds and expanding state-action spaces for complex disruptions.

7. Analysis of technological and infrastructural barriers for PILAR model application

Implementing PILAR models in real-world supply chains faces key technological and infrastructural barriers. A major challenge is the lack of standardized modular π -containers, which hampers interoperability across legacy systems due to differences in geometry, RFID, and sensor interfaces. Adopting standards like ISO 668 and IoT protocols is essential for seamless tracking and integration. The data exchange layer requires secure communication protocols (e.g., MQTT, OPC-UA) with TLS/SSL encryption, aligned with ISO/IEC 27001 to mitigate cybersecurity risks in decentralized networks.

On the infrastructure side, retrofitting hubs with sensors, edge devices, and real-time analytics demand significant investment, typically managed through microservices (e.g., Kubernetes) and distributed engines (e.g., Apache Spark). These setups depend on high-bandwidth, low-latency networks to enable real-time digital twins, posing challenges in low-connectivity regions (e.g., PRISMA project). Integrating robust MILP and reinforcement learning into legacy systems also requires extensive recalibration. Regulatory fragmentation and lack of harmonized global standards hinder adoption, calling for collaboration among industry consortia and regulatory bodies. **Table 12** summarizes these challenges, emphasizing the need for standardization, secure data exchange, scalable computing, and regulatory alignment to support PI adoption at scale.

8. Impact assessment of PRISMA model on stakeholders, enterprises, and local communities and strategic recommendations for PI implementation

The PRISMA model introduces a transformative framework for supply chain optimization by applying PI principles and advanced digital technologies. As supply chains transition to smart, resilient systems, the model's technological, economic, and social impacts must be assessed across stakeholders, enterprises, and communities.

Category	Technical challenge	Impact and research direction
Physical standardization [15, 36]	Variability in π -container dimensions, RFID sensor calibrations, and harsh-environment durability standards; lack of a unified protocol for physical asset interoperability.	Develop and validate physical testbeds to establish robust calibration procedures and environmental standards (e.g., ISO 668 compliance extensions) to ensure reliable asset tracking and handling in diverse operating conditions.
Communication infrastructure [22, 37]	Inadequate support for ultra-low latency (e.g., <10 ms round-trip) and high-throughput networks required for real-time digital twin simulations; limitations in existing protocols (e.g., MQTT vs. OPC-UA) under high load.	Research optimal network architectures and middleware (e.g., edge computing integration) to meet stringent latency and bandwidth requirements, ensuring deterministic data exchange in large-scale PI networks.
Cybersecurity robustness [38]	Vulnerabilities in decentralized data exchange systems due to inconsistent encryption standards and legacy integration issues; challenges in applying frameworks like ISO/IEC 27001 across heterogeneous devices.	Investigate advanced cryptographic techniques and standardized security protocols to ensure end-to-end protection, with formal verification methods to assess system resilience against cyberattacks.
Infrastructure modernization [39, 40]	High capital expenditure for retrofitting existing hubs with state-of-the-art sensor networks, edge devices, and containerized microservices; energy and maintenance costs remain uncertain.	Conduct cost-benefit analyses and pilot studies to quantify ROI for infrastructure upgrades; explore modular, scalable deployment models using platforms like Kubernetes and Apache Spark to minimize retrofit disruptions.
Optimization integration [41]	Integrating stochastic optimization (e.g., robust MILP, reinforcement learning algorithms) with legacy operational systems, requiring extensive model recalibration and validation.	Develop hybrid simulation-optimization frameworks that bridge deterministic models with stochastic components; focus on algorithm tuning (e.g., parameter sensitivity in Greedy- ϵ Q-learning) to ensure compatibility and scalability.
Regulatory harmonization [42]	Diverse international standards and port handling rules (e.g., cabotage regulations) disrupt seamless PI integration; inconsistent data-sharing policies impede cross-border operations.	Formulate interoperable regulatory frameworks and standardized digital protocols for global logistics; promote collaborative initiatives among regulatory bodies and industry consortia to streamline cross-border PI operations.

Table 12.
Critical technical and infrastructural challenges in physical internet (PI) deployment.

Integrating intermodal infrastructure, DLT, and IoT-enabled tracking creates a complex yet high-impact logistics paradigm.

8.1 Stakeholder implications

PRISMA implementation demands structural changes in logistics networks, requiring stakeholders, including policymakers, LSPs, and regulators, to align with the international standards like ISO 668 (container specs), IEC 61499 (automation), and GS1 EPCIS (event tracking). Ensuring π -container interoperability also necessitates cross-border regulatory harmonization and cybersecurity compliance *via* ISO/IEC 27001 and NIST frameworks. Smart contracts on blockchain enforce governance, real-time visibility, and automated auditing. **Figure 24** presents a stakeholder impact

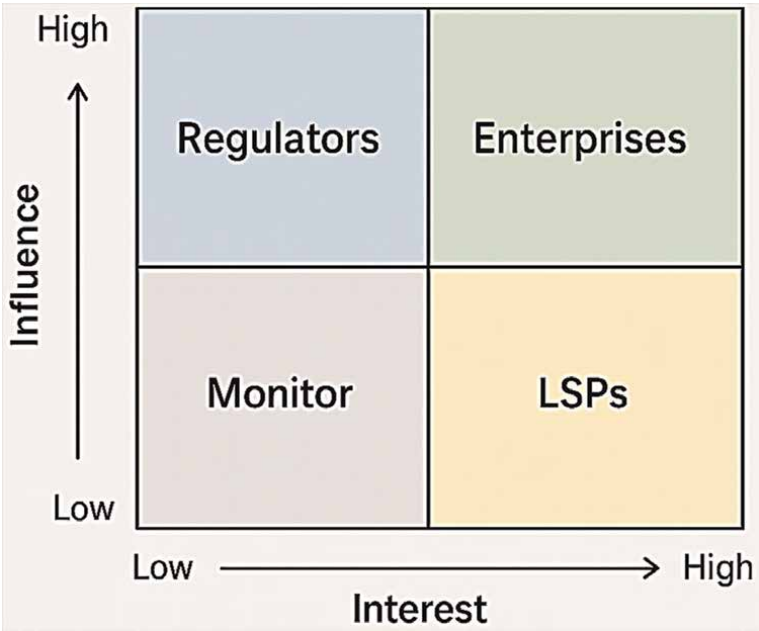


Figure 24.
Stakeholder impact matrix illustrating influence versus interest in PRISMA implementation.

matrix, mapping actors by influence and interest in PRISMA deployment, guiding engagement and policy strategies.

8.2 Corporate structural and operational overhaul

Enterprises adopting the PRISMA model undergo a fundamental shift in supply chain management, driven by the integration of digital twins, predictive analytics, and real-time IoT tracking. This transformation requires significant investment in edge computing, DLT, and microservices architectures (e.g., Kubernetes). To optimize routing, forecasting, and maintenance, firms must adopt stochastic optimization, MILP, and deep reinforcement learning (DRL) methods. Operational efficiency depends on deploying containerized microservices for orchestration, edge nodes for local processing, and high-fidelity digital twins to simulate logistics flows. To safeguard decentralized systems, PRISMA must implement TLS/SSL encryption, Zero-Trust security, and blockchain-based identity verification. Secure, real-time communication relies on protocols like MQTT, OPC-UA, and DDS, ensuring system-wide resilience and protection against cyber threats.

8.3 Socioeconomic and environmental considerations

The PRISMA model has notable implications for local communities, particularly due to AI-driven automation and autonomous vehicles (AVs), which may lead to workforce displacement. To address this, reskilling programs aligned with Industry 4.0 standards are essential. Environmentally, PRISMA reduces carbon emissions through V2X communication, dynamic AI routing, and modular energy-efficient hubs. Strategic urban planning and adoption of ISO 14064-1 enable accurate carbon tracking and congestion reduction. Technologies like Vehicle-to-Grid (V2G) and fleet

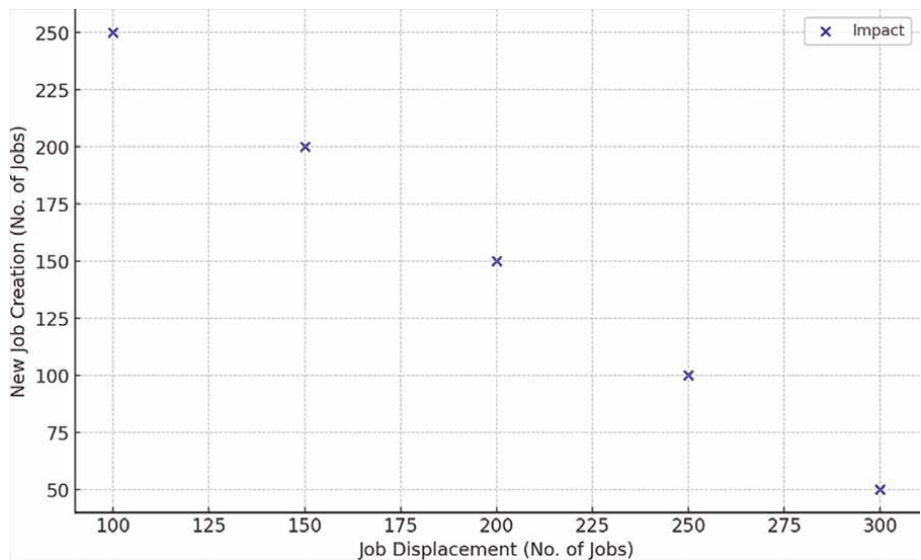


Figure 25.
Relationship between job displacement vs. new job creation due to AI/AV deployment.

electrification support circular economy goals and sustainability mandates. **Figure 25** shows an inverse relationship between job displacement and new job creation, suggesting that while AI/AV adoption may displace some roles, it also drives employment growth in emerging sectors.

8.4 Economic viability and scalability challenges

The PRISMA model offers long-term cost reductions through Just-in-Time (JIT) logistics and resilient supply chain configurations, but high initial investment remains

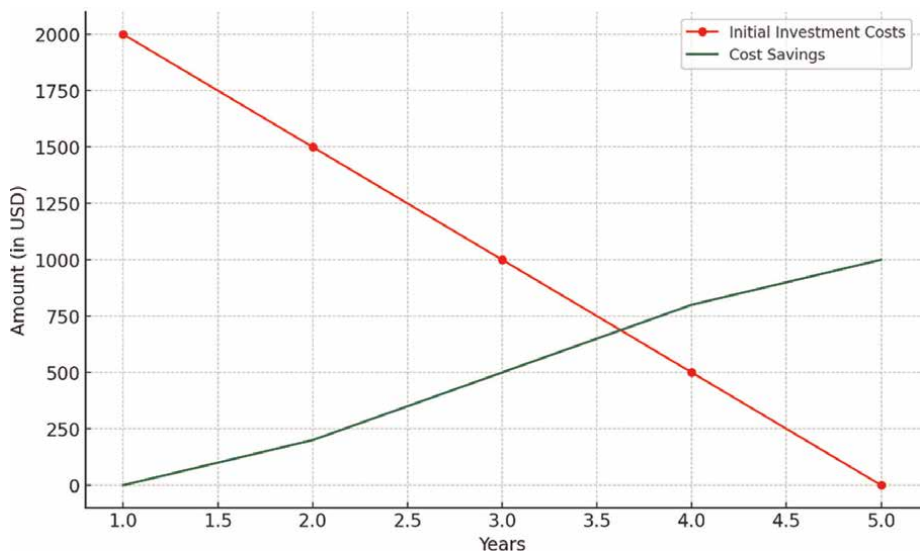


Figure 26.
Comparing initial investment costs against cost savings for SMEs adopting JIT logistics technologies.

a barrier, especially for SMEs. While blockchain-based smart contracts and DeFi enable flexible financing, their adoption is limited by regulatory uncertainty. To support real-time, autonomous decision-making, PRISMA requires 5G-enabled Multi-Access Edge Computing (MEC) for low-latency operations across distributed logistics networks. To manage cross-border complexity, integrating standardized e-Bill of Lading (eBL) and smart contract-based trade finance ensures compliance with UN/CEFACT and WCO SAFE frameworks. **Figure 26** shows that although SME investment costs are high initially, they decline over time, while JIT-related savings increase, ultimately surpassing the investment and demonstrating long-term financial viability.

While PRISMA offers clear benefits in efficiency, sustainability, and resilience, its success depends on addressing key barriers, including regulatory harmonization, economic feasibility, and workforce adaptation. Ensuring long-term scalability requires AI-driven optimization, strong cybersecurity frameworks, and sustainable urban integration strategies.

9. Conclusion

The PRISMA model, grounded in PI principles, presents a transformative approach to modernizing supply chains through modularity, decentralization, and digital intelligence. By integrating agent-based modeling, kanban-controlled flows, and multi-layered PILAR architecture, the framework enables real-time, autonomous logistics coordination across both forward and reverse chains exemplified by spent coffee ground recovery. Simulation results highlight how Q-learning, Monte Carlo methods, and stochastic optimization enhance adaptability, cost-efficiency, and environmental performance under uncertainty. However, successful implementation depends on overcoming challenges such as standardization gaps, high initial costs, cybersecurity risks, and regulatory fragmentation. Strategic investments in IoT, edge computing, blockchain, and reskilling programs are essential to achieving scalable, sustainable, and inclusive adoption. Overall, PRISMA demonstrates strong potential for enabling resilient, low-carbon, and digitally intelligent logistics networks aligned with global sustainability and circular economy goals.

Acknowledgements

We acknowledge financial support under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.1, Call for tender No. 104 published on February 2, 2022 by the Italian Ministry of University and Research (MUR), funded by the European Union – NextGenerationEU – Project Title PRISMA Platform (Physical internet Regenerative Sustainable MATerials) – CUP I53D23001660006 – Grant Assignment Decree No. 961 adopted on 30/June/2023 by the Italian Ministry of Ministry of University and Research (MUR).

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Circular Bioeconomy and Rural Ecosystems: A Systematic Review of Collaborative Innovation for Sustainable Agroindustry in Ecuador

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Abstract

The Ecuadorian agro-industrial sector continues to face persistent structural challenges, largely due to the predominance of linear production models characterized by intensive resource use, low waste recovery and institutional fragmentation. This systematic review examines how circular bioeconomy principles can drive sustainable transformations in rural and agro-industrial ecosystems, with a focus on coastal Ecuador. A comprehensive literature search was conducted in Scopus, Web of Science, SciELO and Google Scholar for 2000–2024, using Boolean operators and keywords. Eligible documents included peer-reviewed articles and technical reports addressing circular practices in rural or agro-industrial contexts in the developing countries. Of the 145 records initially identified, 25 duplicates were removed and 120 records were screened; 36 were excluded at title and abstract stage, and 84 studies were retained for full-text analysis and thematic synthesis. The findings reveal emerging circular initiatives in banana, cocoa and oil palm value chains, centered on waste valorization, resource recovery and collaborative innovation. However, these practices remain fragmented and constrained by financial limitations, infrastructural gaps and weak territorial governance. Despite these barriers, industrial symbiosis, regenerative design and adaptive circular ecosystems show strong potential to enhance sustainability, economic diversification and social inclusion. The review followed PRISMA 2020 guidelines; the protocol was not registered.

Keywords: circular ecosystems, rural bioeconomy, industrial symbiosis, territorial governance, sustainable innovation

1. Introduction

Contemporary agriculture is increasingly confronted with multifaceted challenges related to food waste and escalating pressure on natural ecosystems. It is estimated that over 30% of global food production is lost or wasted, while agricultural activities account for nearly 25% of global greenhouse gas emissions [1]. This situation poses a serious threat to the sustainability of food systems and underscores the urgent need for transformative shifts in both production and consumption patterns. If this trajectory is not reversed, global warming is projected to exceed the 1.5°C threshold within this century [2]. In Latin America, under a high-emissions scenario, per capita GDP could decline by up to 3.3% by 2050, exacerbating poverty and food insecurity [3].

This implies that developing countries are likely to face even deeper structural challenges, further aggravated by the persistence of linear production models characterized by intensive input use and high waste generation. Ecuador exemplifies this dynamic, given its strong reliance on agro-export industries, particularly in key value chains such as banana, cocoa and oil palm. The country continues to struggle with environmental degradation, inefficient resource utilization, waste accumulation and the underutilization of agro-industrial byproducts, which collectively hinder progress toward sustainable transformation [4–6]. Moreover, the intensification of agrochemical use and the absence of comprehensive waste management systems have led to soil degradation, water contamination and declining soil biodiversity, ultimately undermining Ecuador's competitiveness in increasingly sustainability-conscious international markets [7, 8]. From the challenges outlined above, alternative approaches grounded in the principles of circularity and regeneration are emerging as viable solutions. Multi-component biorefineries represent a promising technological strategy for converting agro-industrial residues into value-added products such as biofertilizers, bioplastics, bioenergy and other bio-based inputs, in alignment with the Sustainable Development Goals [9]. Within this context, two complementary frameworks converge: (1) the *bioeconomy*, which focuses on the sustainable use of biomass and renewable biological resources; and (2) the *circular economy*, which seeks to transition from linear models to productive systems that recirculate materials, minimize waste and foster collaborative innovation [10, 11].

In Ecuador, it is estimated that approximately 14,000 tons of solid waste are generated daily, of which more than 50% is organic. However, only a minimal fraction is effectively recycled [12]. This figure underscores the country's lag in adopting circular models, despite their proven potential to reduce emissions, diversify income streams and generate green employment in strategic sectors. Particularly in the coastal region, favorable conditions exist for the application of closed-loop technologies—such as anaerobic digestion—which could facilitate nutrient cycling, enhance energy efficiency and reduce ecological pressure on agricultural ecosystems [13–15].

Such strategies could be integrated into broader frameworks of industrial symbiosis, drawing inspiration from models like Kalundborg¹, and adapted to Latin American realities through territorial alliances between agro-industry, fisheries,

¹ The Kalundborg model (Denmark) is widely recognized as the first and most emblematic case of industrial symbiosis worldwide; emerging spontaneously during the 1960s and 1970s, it consists of a collaborative network of companies that exchange energy, water and by-products to optimize resource use and minimize waste. Key stakeholders include a coal-fired power plant, an oil refinery, a gypsum board facility and the local municipality. This industrial ecosystem has demonstrated that economic competitiveness can be effectively combined with the environmental sustainability through intersectoral cooperation and the efficient management of resources.

tourism and other regional sectors [16]. However, significant gaps remain in the scholarly literature regarding the effective integration of circular economy and bioeconomy principles in rural territories with the limited institutional capacity.

Most existing studies tend to focus on isolated technological solutions or on general regulatory frameworks, often overlooking the territorial, social and organizational conditions that critically shape the sustainable adoption of these approaches in agro-industrial contexts. In response to this gap, the present study adopts a *territorial ecosystem perspective*—that is, an approach that integrates multi-actor innovation processes, industrial symbiosis and resource regeneration—while assessing the practical applicability of these principles through an exploratory analysis of sectoral experiences in Ecuador’s coastal region.

The primary objective of this study is to examine the enabling conditions, structural barriers and collaborative dynamics that influence the integration of circular bioeconomy strategies into productive rural ecosystems. To this end, the analysis focuses on the banana, cocoa and African oil palm value chains, selected for their economic significance and latent potential for residual biomass valorization. These cases provide a representative lens to understand how circularity and regenerative approaches can be contextually grounded in specific territorial and institutional realities.

In line with this gap, this study is guided by the following research questions (RQs):

- **RQ1:** How are circular economy and circular bioeconomy principles currently being implemented in rural and agro-industrial ecosystems in Latin America, with a particular focus on coastal Ecuador?
- **RQ2:** What structural barriers and enabling conditions shape the adoption of circular practices in key agro-industrial value chains (banana, cocoa and African oil palm)?
- **RQ3:** To what extent do emerging circular ecosystems contribute to sustainability, resilience and inclusive innovation in rural territories, and what are the main opportunities and limitations for their scaling-up?

2. Methods

A qualitative research methodology was employed, structured in two complementary phases. This review followed the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for scoping reviews [17]. A completed PRISMA checklist is provided in the Supplementary Materials, and the source selection process is illustrated in the PRISMA 2020 flow diagram (**Figure 1**). Although the review protocol was not formally registered in platforms such as PROSPERO or OSF, the authors adhered strictly to the PRISMA 2020 guidelines. Future reviews will consider formal registration to enhance transparency and replicability.

The first phase consisted of a systematic review of scientific and technical literature, drawing on major academic databases including *Scopus*, *Web of Science*, *SciELO* and *Google Scholar*, selected for their relevance in the social, environmental and economic sciences. The search strategy integrated Boolean operators and a set of targeted keywords in both English and Spanish, such as “circular ecosystems,” “circular economy in agribusiness,” “sustainable innovation,” “bioeconomy” and “Ecuador.” The review covered the period from 2000 to 2024, ensuring both historical depth and contemporary relevance.

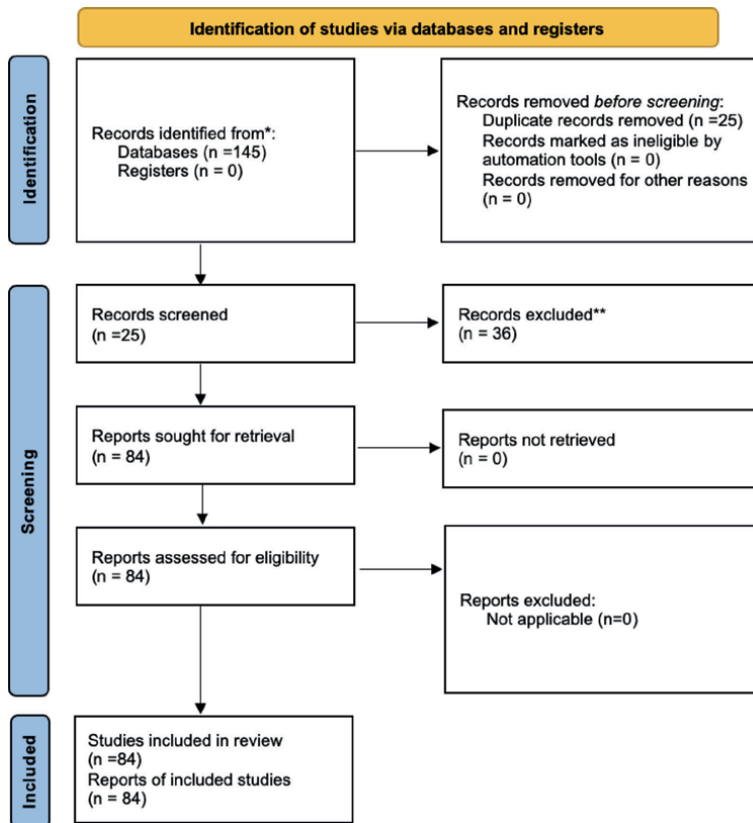


Figure 1. PRISMA 2020 flow diagram for study selection. Flow diagram summarizing the identification, screening, eligibility assessment and inclusion of records retrieved from Scopus, Web of Science, SciELO and Google Scholar for the period 2000–2024. In total, 145 records were identified, 25 duplicates were removed, 120 records were screened, 36 were excluded at title and abstract level and 84 full-text documents were included in the qualitative synthesis.

To ensure methodological rigor, the following inclusion criteria were applied:

1. Peer-reviewed articles;
2. Direct relevance to circular economy practices in agro-industrial or rural contexts; and
3. Empirical evidence or conceptual models applicable to developing countries.

Studies that adopted purely technological approaches without territorial or systemic integration were excluded.

The final selection consisted of 84 documents, including scientific journal articles, specialized books and reports from multilateral organizations such as the *Food and Agriculture Organization* (FAO), the *Economic Commission for Latin America and the Caribbean* (ECLAC) and the *Inter-American Development Bank* (IDB), along with institutional literature relevant to the Ecuadorian context. Document analysis was conducted through a qualitative thematic synthesis aimed at identifying conceptual

patterns, operational principles and critical dimensions of circular ecosystems, while distinguishing them from other organizational models such as clusters or linear value chains (**Figure 1**).

For the exploratory component of the study, we applied purposive sampling of documents from sectoral reports, NGO publications and government programs, guided by criteria such as explicit reference to circular practices, territorial focus and evidence of stakeholder collaboration. Analytical coding was conducted through a qualitative thematic synthesis centered on four dimensions: barriers, enabling factors, adoption practices and scalability potential. This methodological approach strengthened the interpretive validity of the study and aligned with the territorial ecosystem framework adopted.

Building on this foundation, we analyzed sectoral and territorial experiences in Ecuador's coastal region, focusing on three representative agro-industrial value chains: plantain, cocoa and African oil palm. These sectors were selected for their economic relevance, growing sustainability pressures and high volumes of residual biomass. The unit of observation was defined as rural productive ecosystems where public, private and community actors converge around the transformation and valorization of agro-industrial waste.

Triangulation of secondary sources—including academic literature, technical studies and institutional databases—enabled the identification of recurring patterns in circular adoption. Although not structured as formal case studies, this process

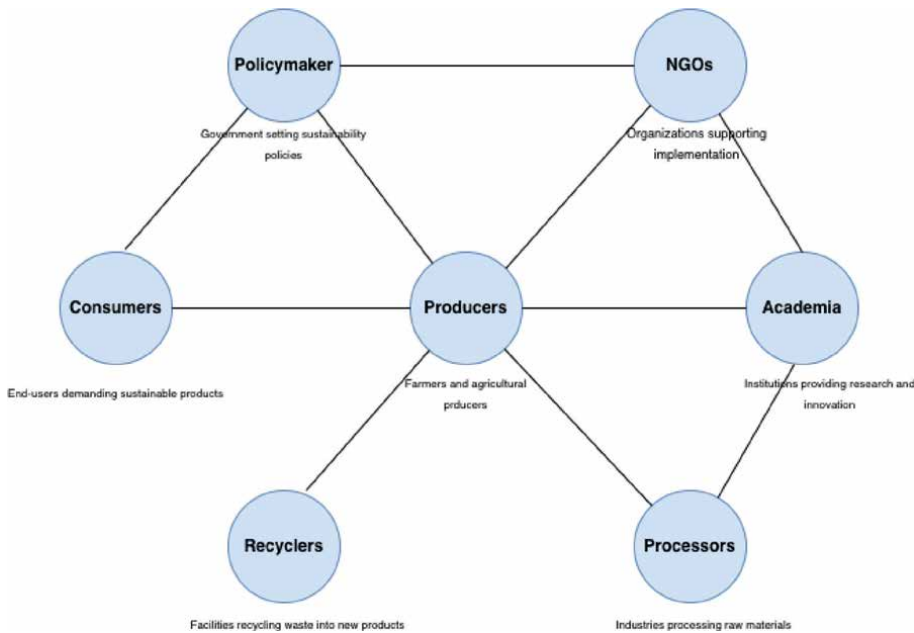


Figure 2.
Systemic map of material flows and collaboration networks in circular agro-industrial ecosystems in coastal Ecuador. This conceptual diagram synthesizes the main material and information flows among key actors in rural circular ecosystems (smallholder producers, cooperatives, local governments, universities, NGOs and private agro-industrial firms). Solid arrows represent physical flows of biomass, water, energy and by-products (e.g., plantain residues, cocoa husks and palm biomass) that are valorized through processes such as composting, anaerobic digestion and biorefinery schemes. Dashed arrows indicate institutional and knowledge flows (technical assistance, financing, regulatory support and digital tools for monitoring and traceability). The figure highlights how industrial symbiosis and territorial alliances create feedback loops that (i) reduce waste, (ii) increase resource-use efficiency and (iii) generate added value at the local level through circular bioeconomy strategies.

revealed critical insights into barriers, enabling conditions and opportunities for scaling. As a result, a conceptual map of circular interactions was developed (**Figure 2**), illustrating material flows, actor networks and key mechanisms for closing production loops.

Internal validity was ensured through cross-verification of multiple sources of evidence, while external validity was addressed by comparing the findings with similar experiences in Colombia, Brazil and Mexico. This comparative lens supports the potential transferability of the results to other rural Latin American contexts.

3. Results: Evidence in relation to the research questions

This section presents the main findings of the review in direct relation to the three research questions outlined in the Introduction.

3.1 Business ecosystem: Genesis and evolution

This subsection provides the conceptual background for RQ1, by revisiting the evolution of the business ecosystem approach and its progressive incorporation of circular and sustainability principles.

The concept of the business ecosystem originates from an analogy with biological ecosystems and was introduced into the field of management by James F. Moore in his influential article “Predators and Prey: A New Ecology of Competition” [18]. Moore argued that firms do not operate in isolation but within dynamic and interdependent networks involving competitors, suppliers, customers and other key stakeholders. In such systems, innovation and co-evolution play a central role in determining organizational success. Since its introduction, the ecosystem approach has evolved to describe collaborative environments and interconnected relationships among firms as essential conditions for sustaining competitive advantage [18].

Unlike classical models of organizational analysis, the ecosystem perspective emphasizes adaptability and resilience, shifting the analytical focus away from the individual firm and toward the broader constellation of relationships that sustain it.

In recent years, the business ecosystem concept has been expanded to incorporate sustainability principles, particularly within the framework of the circular economy. In this context, business ecosystems are reconfigured as cooperative systems oriented toward resource regeneration, waste reduction and the co-creation of environmental and social value [15].

Empirical evidence from Latin America suggests that these models become particularly relevant when adapted to rural contexts characterized by structural and institutional limitations. As Vasseur [19] notes, business ecosystems in rural Latin American settings must not only pursue economic objectives but also integrate social, cultural and environmental dimensions. This requires ecosystem models that are responsive to territorial specificities, acknowledging the diversity of natural resources, traditional agricultural practices and existing community networks.

3.2 Rural business ecosystems and circular economy principles

Addressing RQ1, this subsection synthesizes empirical evidence on how rural business ecosystems in Latin America have integrated circular economy principles, emphasizing multi-actor coordination and territorial specificities.

The consolidation of rural business ecosystems takes on particular significance when they are aligned with the principles of the circular economy. These principles—centered on resource regeneration, waste minimization and shared value creation—offer an operational framework to reconfigure productive systems in territories experiencing high pressure on natural resources. In such settings, which are often marked by fragmented production structures and limited technological infrastructure, the coordinated participation of stakeholders such as small-scale producers, cooperatives, universities and non-governmental organizations becomes essential. These actors play a key role in developing business models based on the valorization of by-products, efficient resource use and the strengthening of territorial value chains [20].

Nonetheless, the implementation of circular economy principles in rural contexts encounters several structural barriers, including limited integration with sustainable markets, low levels of technological development in the agricultural sector and increasing ecological vulnerability.

Various case studies across Latin America illustrate how rural business ecosystems can function as effective platforms for the deployment of circular strategies. In Colombia, for example, the coffee sector has incorporated circular practices through environmental and social certifications, promoting the valorization of organic waste and fostering technical training programs through partnerships between cooperatives such as the *National Federation of Coffee Growers* and public institutions like *SENA* [21, 22].

In Ecuador, community-based tourism has emerged as a viable strategy for embedding circular principles into rural economic activities. Initiatives such as the one in San Clemente—developed with support from NGOs and international cooperation programs—have implemented sustainable tourism circuits that combine heritage conservation with organic waste management [23].

Meanwhile, Mexico has fostered agroecological initiatives that merge traditional knowledge with technological innovation. These efforts have succeeded in closing nutrient cycles, reducing dependency on external inputs and enhancing the resilience of local productive systems, thereby advancing low-impact circular models [24].

From these case studies, several common patterns can be identified. These include multi-actor coordination, the presence of anchor institutions (such as cooperatives or local governments) and the gradual scaling of regenerative practices. While these initiatives remain localized, they provide empirical evidence supporting the hypothesis that circular principles can be effectively territorialized, even in settings with limited institutional capacity [25].

To contextualize the current situation in Latin America regarding the implementation of circular economy principles in the agricultural sector, the selected relevant indicators are presented in **Table 1**.

These indicators provide a clearer understanding of the regional progress and challenges in advancing circular agriculture, reinforcing the urgent need for collaborative frameworks that integrate public policy, technical capacity, and strategic financing.

From a circular bioeconomy perspective, business ecosystems—including those in rural areas—act as key drivers in the transition toward an economy that prioritizes regeneration and inclusivity. Three core strategies underpin this transition.

The first strategy emphasizes the valorization of waste and by-products by leveraging agricultural, forestry, aquaculture and livestock biomass to produce new outputs such as bioenergy, bioplastics and biofertilizers.

The second strategy aims to diversify local economies by fostering bio-based value chains (BVCs), thereby generating rural employment opportunities rooted in renewable biological resources.

Indicator	Latin America status	Source
Percentage of recycled agricultural waste	Country-specific data unavailable; biomass reuse is generally promoted.	[26]
CO ₂ emissions from the agricultural sector (Mt CO ₂ eq/year)	In 2022, agri-food system emissions in the Americas reached approximately 3.5 Gt CO ₂ eq.	[27]
Food loss and waste (% of total available food)	Estimated at 11.6% of food lost in Latin America.	[28]
Investment in circular economy in agriculture (% of GDP)	Specific data unavailable; ongoing investment in sustainable practices is reported.	[26]
Implementation of circular water management practices	Brazil, Colombia, and Peru are adopting circular water strategies in agriculture.	[29]

Table 1.
Circular economy indicators in agriculture in Latin America. This table summarizes data on key aspects of circularity in the agri-food sector.

The third strategy involves the integration of traditional knowledge with scientific expertise by incorporating ancestral practices with modern innovation in ways that respect the cultural and ecological contexts of each territory. This approach promotes territorial innovation by encouraging the implementation of clean technologies and biotechnological solutions through the collaborative models involving universities, local governments, private enterprises and civil society actors [30, 31]. Furthermore, it bolsters resilience and sustainability by supporting the responsible use of natural resources, conserving biodiversity and enhancing climate change adaptation capacities.

The circular bioeconomy has created new spaces for multisectoral collaboration, enabling the formulation of strategies that not only conserve natural capital but also foster robust rural business ecosystems. These ecosystems, in turn, enhance the vitality and global relevance of rural territories.

Furthermore, the circular economy framework provides rural business ecosystems with a strategic foundation for aligning local development with broader goals of sustainability, social equity and territorial cooperation. Unlike extractive or enclave-based models, this approach promotes the integration of regenerative practices and collaborative arrangements that effectively valorize endogenous resources—natural, cultural and social—in a manner that is both efficient and resilient.

In Latin America, various studies have documented how the activation of local cooperation networks can mitigate structural barriers associated with inequality, economic dependency and limited access to basic services. These networks function as catalysts for building local capacities, particularly in rural areas facing high levels of social exclusion [3, 32–34].

A compelling empirical example is found in the community of San Clemente, located in the province of Imbabura, Ecuador, where community-based tourism has been consolidated as part of a business ecosystem guided by circular economy principles. In this context, local families have developed a comprehensive offering that integrates lodging services, guided tours and cultural experiences, drawing upon traditional practices such as ecological agriculture, ancestral medicine and artisanal production [35].

Such experiences have not emerged in isolation. The consolidation of this model has been supported by public institutions such as the *Ecuadorian Ministry of Tourism*, which has provided support through certifications, technical training and promotion

strategies targeting responsible tourism niches [36]. This coordination between community actors, government agencies, non-governmental organizations and family-run enterprises exemplifies territorial symbiosis, wherein the flows of knowledge, services and resources are mutually reinforcing within a circular framework.

From a results-oriented perspective, recent studies in Latin America have reported significant increases in household income as a result of sustained community tourism initiatives. In the community of Misminay, located in Cusco (Peru), families involved in such initiatives have generated additional weekly income ranging from \$100 to \$400 depending on the type of activity undertaken. These earnings have contributed to improvements in key areas such as education and nutrition [37].

Similarly, a comparative analysis of experiences in Brazil, Costa Rica, Ecuador, Mexico and the Dominican Republic indicates that such projects have strengthened local capacities and contributed to the economic development of participating communities [38].

3.2.1 Case study: Community-based tourism in San Clemente, Ecuador

San Clemente, a rural community located in the Imbabura province of Ecuador, represents a compelling case of how circular economy principles can be grounded in local rural development. Local estimates suggest that over 60% of households are directly or indirectly engaged with the tourism ecosystem, either as a primary or complementary economic activity [35]. This engagement has yielded positive outcomes in terms of improved access to basic services, local economic revitalization and the strengthening of community cohesion.

This section presents a focused case study based on secondary sources and field reports, analyzing how circular economy principles—such as waste reuse, agroecological practices and inter-institutional coordination—have been integrated into the community's tourism initiatives. San Clemente has developed a comprehensive offering that includes lodging, guided tours and cultural experiences rooted in ancestral practices such as ecological agriculture and artisanal production.

The consolidation of this model has been supported by actors such as the Ministry of Tourism, NGOs and international cooperation agencies, through certifications, technical training and promotion strategies aimed at responsible tourism markets. This illustrates a model of territorial symbiosis in which flows of knowledge, services and resources are mutually reinforcing within a circular framework.

While these results should not be generalized without caution, they reinforce the hypothesis that circular ecosystems, when adapted to rural contexts, can serve as the effective vectors of social innovation and structural transformation.

3.3 Strategic applications of circular principles in agroindustry

Still in relation to RQ1, this subsection examines concrete applications of circular and regenerative strategies in agro-industrial contexts, with particular attention to biomass valorization, industrial symbiosis and closed-loop schemes.

In agro-industrial contexts within emerging economies such as Ecuador's coastal region, the principles of the bioeconomy and circular economy are increasingly positioned as the key tools to address structural challenges related to sustainability, production efficiency and climate resilience. Among the most salient principles are *industrial symbiosis*, *regenerative design* and the *closure of material and energy loops*. These frameworks offer a blueprint for the reconfiguration of production systems in accordance with circular logic.

Industrial symbiosis, in its broadest sense, can be defined as the interconnection of productive activities that enables the mutual utilization of energy, material and by-product flows. In Ecuador's agri-food sector, this strategy has begun to materialize through the transformation of agri-waste into biofertilizers, biogas or electricity. For instance, Magri et al. [39] report that digestate derived from anaerobic digestion contributes to the closure of agricultural nutrient cycles, enhancing soil fertility and reducing reliance on synthetic inputs. Similarly, innovations targeting the production of biodegradable packaging from agricultural waste offer promising solutions for reducing conventional plastic consumption and operational costs [40].

Regenerative design, in turn, aims to restore and sustain the ecological functionality of agroecosystems. This approach is exemplified by practices such as agroforestry, which integrates native trees into crops like cacao or plantain. This practice has been shown to promote biodiversity, enhance carbon sequestration capacity and improve soil health [41]. In Ecuador's Sierra and coastal regions, a decline in synthetic fertilizer use has been documented through the implementation of leguminous crop rotations, as well as the adoption of low-impact technologies such as drip irrigation and rain-water harvesting. These practices have proven effective in bolstering water resilience under heat stress conditions [42, 43].

Closing material and energy loops constitutes a structural pillar of the circular model. In the plantain production chain, organic residues are converted into compost and biofertilizers that improve soil structure, reduce emissions and promote more sustainable yields [44]. Similarly, residual biomass from African oil palm has begun to be used for on-site steam and electricity generation, thereby reducing dependence on fossil fuels and lowering the carbon footprint. Emerging technologies such as aquaponics, which combine fish farming with plant cultivation through water and nutrient recirculation systems, further exemplify closed-loop production schemes with high resource-use efficiency [45].

Although these applications are not yet widespread, they provide concrete evidence of the technical feasibility of circular principles in medium-scale and community-based agro-industries. Their adoption is not only a response to increasing environmental pressures but also a reaction to evolving market dynamics that favor products with verifiable sustainability attributes. Nevertheless, the diffusion of these practices must be analyzed in relation to structural conditions such as access to financing, availability of infrastructure and the technical capacities of local actors—issues that will be addressed in subsequent sections.

3.4 Latin America: Impacts, barriers and transformative potential

Responding primarily to RQ2 and RQ3, this subsection analyzes the main structural barriers, enabling factors and transformative potential associated with circular bioeconomy initiatives across Latin American agro-industrial systems.

The circular bioeconomy and the circular economy are increasingly recognized as the emerging approaches for addressing the structural challenges faced by resource-intensive sectors such as agroindustry. In theory, these models propose a shift from linear systems—based on extraction and disposal—toward regenerative systems that promote efficient material use, waste valorization and territorial integration. Their conceptual framework aligns closely with the Sustainable Development Goals (SDGs), as outlined by the *Department of Economic Development, Sustainability and Environment* [46] in the *Circular Economy and Bioeconomy Plan 2024* for the Basque Government. These alignments are particularly evident in goals such as Zero Hunger (SDG 2), Clean Water and

Sanitation (SDG 6), Affordable and Clean Energy (SDG 7), Decent Work and Economic Growth (SDG 8), Industry, Innovation and Infrastructure (SDG 9), Responsible Consumption and Production (SDG 12), Climate Action (SDG 13), Poverty Reduction (SDG 1), Life on Land (SDG 15) and Partnerships for the Goals (SDG 17) [47, 48].

In Ecuador, the agro-industrial sector plays a pivotal role due to its economic weight and direct connection to territorial and natural resources. The incorporation of circular principles into rural production systems has begun to yield partial benefits, including waste reduction, substitution of synthetic inputs and the rehabilitation of degraded soils [49]. However, these outcomes are highly dependent on structural conditions that are not always present, particularly in rural zones with the limited institutional capacity.

At the regional level, multiple barriers hinder the scaling-up of circular models. One of the most persistent is the lack of infrastructure for the collection, sorting and transformation of organic waste. In Ecuador, for instance, it is estimated that over 95% of solid waste ends up in landfills, despite a significant share being composed of potentially recoverable organic matter [50].

Additionally, a lack of awareness and limited technical knowledge regarding the potential of circular economy models restrict adoption, particularly among small- and medium-scale producers. Traditional practices—such as open burning of waste or the intensive use of agrochemicals—continue to prevail, even in areas where regenerative approaches have been promoted [51]. Another critical barrier is unequal access to financing. Key technologies such as biodigesters, industrial composting systems or biofiltration units require initial capital investments that many rural cooperatives are unable to afford. While green credit lines and multilateral incentives do exist, they tend to be concentrated in urban or large-scale projects, thereby excluding small or informal production units [52].

These limitations are further compounded by institutional fragility. Fragmented regulatory frameworks, the absence of specific fiscal incentives and insufficient local technical capacity to support the implementation of circular solutions all hinder progress [53]. Such deficiencies impede the capacity of subnational governments to facilitate productive transitions and attenuate the impact of sectoral innovation efforts.

Despite these challenges, several factors underpin the region's latent potential for transformative change. These include its rich biological diversity, a deep reservoir of traditional agricultural knowledge and a growing ecosystem of cooperatives, producer associations and grassroots organizations engaged in sustainable innovation. In this context, the circular economy could function as a catalyst for technological, social and institutional transformations. However, realizing this potential requires the implementation of inclusive governance frameworks and the creation of accessible financial mechanisms that prioritize support for the most vulnerable actors.

Figure 3 summarizes the main obstacles faced by rural territories in implementing circular economy and bioeconomy models, the enabling conditions required to overcome them, and the key actors responsible for driving this transition.

3.5 The productive transition in Latin America: Opportunities, limitations and scenarios

In Latin America, the *Economic Commission for Latin America and the Caribbean* (ECLAC) highlights that the bioeconomy has gained prominence as a reference framework for implementing innovative policies for the sustainable use of natural resources. In Ecuador, for instance, the relevance of the multicomponent biorefinery model (circular bioeconomy) has been underscored for advancing a high value-added bioeconomy,

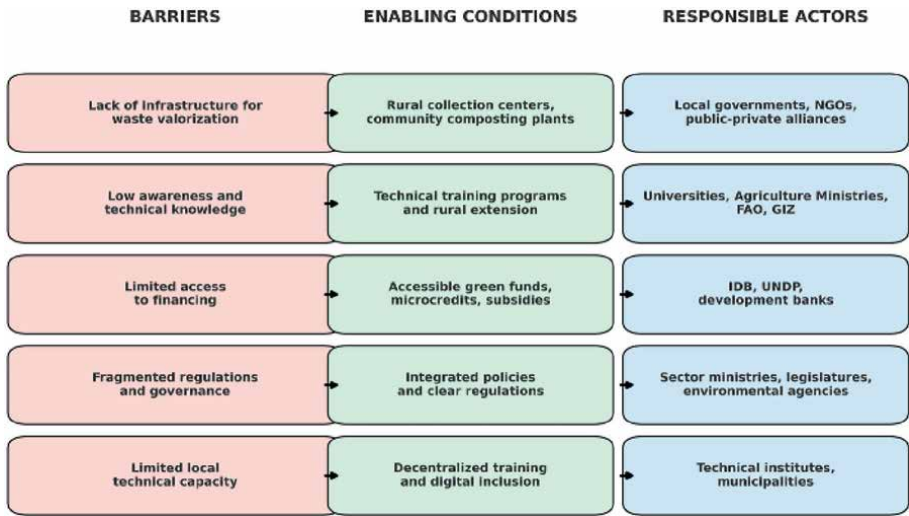


Figure 3.
Systemic enablers and barriers for circular economy adoption in rural contexts.

leveraging various types of biomass—including residual biomass [54]. At the same time, opportunities have been identified for scaling up innovative advanced bioeconomy initiatives that contribute to inclusive and sustainable productive development [9].

Moreover, the circular economy has emerged as a prominent conceptual framework for reorienting the productive transformation of agroindustrial sectors traditionally rooted in extractive models. The integration of sustainability and efficiency criteria in agricultural systems has positioned by-product valorization as increasingly strategic. This transition is driven by mounting environmental pressures and the evolution of global markets, which increasingly demand goods with certified provenance and a reduced ecological footprint.

According to ECLAC, average economic growth in 2024 was 2.1%, though structural limitations persist, including low levels of productive investment, weak diversification and insufficient innovation [3, 55]. In this context, multilateral organizations such as the *Food and Agriculture Organization* (FAO) and the *Organisation for Economic Co-operation and Development* (OECD) have emphasized that the efficient utilization of agro-industrial waste—when integrated within circular economy frameworks—can serve as a vector of productive transformation [1]. Market projections reinforce this view. For instance, the micronutrient fertilizer sector in Latin America, valued at USD 485.78 million in 2023, is expected to grow at an annual rate of 3.9% through 2032. Similarly, the global agricultural adjuvants market anticipates an annual expansion of 5.4% [56]. Although country-specific data remain limited, these trends reflect a growing interest in technologies that enhance resource efficiency and reduce waste.

From a material standpoint, the region enjoys a strategic advantage due to its biological wealth and large volumes of residual agro-industrial biomass, including by-products from plantain, cacao and African palm. It has been demonstrated that countries such as Ecuador, Colombia and Brazil possess the capacity to transform these residues into biofertilizers, bioplastics, biogas or compostable materials. When such solutions are combined with regenerative practices—such as agroforestry, crop rotation or efficient irrigation—they open up possibilities for redefining production models toward low-impact, territorially resilient systems [57, 58].

Concurrently, the mounting global demand for organic, sustainable and fair trade-certified products offers substantial opportunities for strategic repositioning of Latin America's agroindustry. In Ecuador, for instance, the export of cacao husk derivatives to the cosmetics industry has facilitated income diversification and value creation at the origin [57].

At the institutional level, several countries have initiated the development of policy frameworks designed to facilitate this transition. In Colombia, the *National Circular Economy Strategy* functions as a roadmap for formalizing circular practices and incentivizing sustainable value chains [58]. Initiatives spearheaded by the *Inter-American Development Bank* (IDB) and the *United Nations Development Programme* (UNDP) in countries such as Ecuador and Peru have furnished financing, technical assistance and regulatory support to pilot projects in biorefineries, bioenergy and agricultural recycling.

However, this transition is not without constraints. Infrastructure for waste treatment and recovery remains deficient in many rural areas. In Ecuador, for instance, significant agricultural regions are devoid of composting facilities, biodigesters or collection centers, resulting in augmented logistics expenditures and impediments to the expansion of circular solutions [59].

Additionally, the upfront investment required to implement technologies such as biodigesters, sensors or smart irrigation systems remains a barrier for many cooperatives and small agroindustrial enterprises. This limitation is compounded by weak alignment among regulatory frameworks, limited availability of incentives and unequal access to green financing mechanisms.

Beyond material conditions, the productive transition also demands a shift in managerial logic. This includes cultivating an organizational culture oriented toward sustainability, building local capacity, and consolidating collaborative networks among producers, technicians, institutions, and consumers. In this regard, initiatives led by social enterprises, universities and local governments have demonstrated

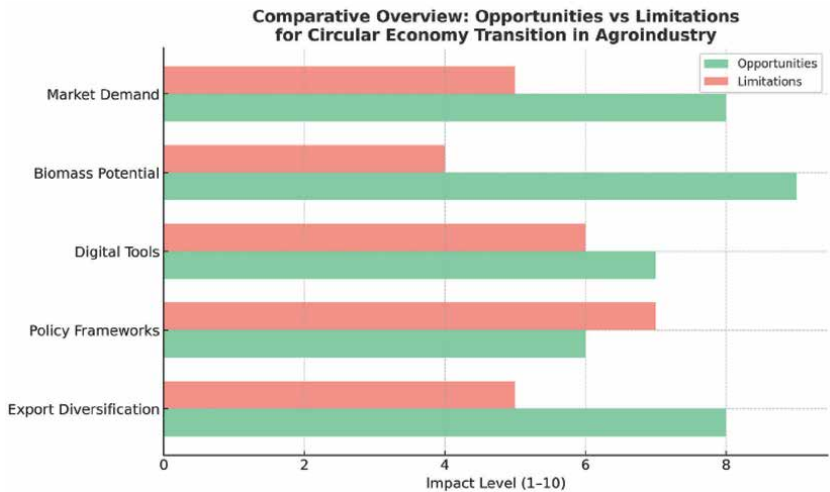


Figure 4. Comparative overview: opportunities vs. limitations for circular economy transition in the Latin American agroindustry. This figure illustrates a qualitative comparison of key enabling opportunities and persistent limitations influencing the adoption of circular economy practices in agroindustrial systems across Latin America. Data represent expert-informed scoring across five thematic axes: market demand, biomass availability, digital technologies, policy frameworks and export diversification potential.

that circular economy principles can be adapted through cooperative and territorial models—yielding positive impacts in employment, innovation and resilience [60, 61].

Digital tools—such as soil sensors, smart irrigation systems, mobile apps for waste management and traceability platforms—are increasingly being integrated into these dynamics as cross-cutting technological enablers. When coupled with inclusive policy design and strong territorial governance structures, these tools can significantly enhance the prospects for an effective transition toward regenerative agroindustrial development [62, 63]. **Figure 4** presents a comparative overview of these opportunities and limitations, summarizing five key dimensions that influence the adoption of circular practices in Latin American agroindustry.

4. Discussion

Building on the results presented in Section 3, this discussion returns to the three guiding research questions. First, regarding RQ1, the evidence shows that circular practices in coastal Ecuador and comparable Latin American contexts are emerging through localized initiatives focused on biomass valorization, regenerative design and nascent circular business ecosystems. Second, with respect to RQ2, the analysis highlights a persistent configuration of structural barriers—limited infrastructure, constrained access to finance, technological gaps and institutional fragmentation—which coexist with enabling factors such as rich biomass availability, traditional knowledge and growing demand for sustainable products. Third, in relation to RQ3, the study suggests that circular ecosystems can generate measurable contributions to environmental sustainability, resilience and rural innovation, but only when they are embedded in robust governance arrangements and long-term capacity-building processes.

The findings presented in the previous section highlight the emergence of circular practices within Ecuador's agro-industrial sector, particularly in the coastal region. Through diverse case-based evidence, the analysis revealed a set of strategies focused on waste valorization, regenerative design and the gradual formation of circular business ecosystems. These developments illustrate the growing relevance of circular and circular bioeconomy approaches in rural contexts, especially in sectors with high biomass availability and strong sustainability pressures.

In this section, we critically reflect on the feasibility, structural limitations and transformative contributions of circular ecosystems in Ecuadorian agro-industry. Drawing from empirical patterns and comparative insights, we explore the enabling conditions for circular transitions, the barriers that constrain scaling and the role of innovation and collaboration in shaping resilient and inclusive production models. The discussion is organized into thematic subsections that synthesize technical, institutional and territorial dimensions of the circular economy framework.

4.1 Feasibility, limits and contributions of circular ecosystems in Ecuadorian agro-industry

Circular ecosystems applied to Ecuador's coastal agro-industrial sector are emerging as a promising alternative to linear production models, particularly due to their capacity to integrate local actors into collaborative processes focused on resource regeneration. Through the valorization of agricultural by-products such as plantain peels, cacao residues and African oil palm waste, various experiences have been identified that move toward closed-loop systems, with documented economic, ecological and social benefits [64–66].

In these cases, materials previously treated as waste are being transformed into biofertilizers, biofuels, bioplastics or nutraceutical inputs. These transformations contribute to income diversification in rural areas, reduce dependence on imported inputs and improve soil health indicators. However, these advances remain confined to isolated initiatives, and their scaling is contingent on structural factors that require thorough analysis.

Among the main technological and economic constraints, high processing costs associated with biomass conversion stand out, as well as the lack of specialized infrastructure in rural areas. Technologies such as biodigesters or composting facilities require initial investments and technical maintenance beyond the capacity of many small- and medium-sized production units. This challenge has been widely cited as a key barrier to the large-scale adoption of circular practices [67, 68].

In addition to material limitations, cultural and educational factors also influence the low adoption rate of circular approaches. The persistence of conventional agricultural practices and limited familiarity with regenerative principles hinder the implementation of sustainable solutions. According to Gorgolewski [69], these gaps can be mitigated through context-sensitive technical training programs that incorporate local knowledge and promote the gradual appropriation of new technologies.

From a comparative perspective, Ecuador possesses a structural advantage: an abundance of residual biomass from agro-export sectors such as banana, cacao and African oil palm. These residues, in addition to having potential value in national and international markets, can significantly reduce the ecological footprint of production chains when managed within circular frameworks. This resource availability, combined with growing global demand for sustainable products, positions Ecuador as a potential reference case within the Andean region for regenerative production innovation [70].

The role of public policy and international cooperation has been critical in fostering enabling environments for sustainable innovation. Initiatives such as the *National Circular Economy Plan* and multilateral financing programs have begun to provide incentives, technical training and credit access for territory-based circular projects. However, their scope remains limited due to weak inter-institutional coordination and the absence of an integrated vision linking agricultural, industrial, environmental and technological policies.

In this scenario, agricultural digitalization emerges as a cross-cutting axis with the potential to reshape structural conditions in the sector. Tools such as traceability platforms, agricultural sensors, waste management systems and environmental monitoring technologies are being introduced into productive contexts, albeit with early-stage results. Their implementation enables more efficient resource use, reduces information asymmetries and strengthens connections between rural producers and sustainable markets [71].

In summary, the feasibility of circular ecosystems in Ecuadorian agroindustry does not rely solely on their technical justification, but rather on a constellation of enabling conditions involving intersectoral coordination, public and private investment, localized capacity building, and institutional strengthening. These factors define the parameters within which circular models can be consolidated as structural strategies for a sustainable productive transition.

4.2 The productive transition in Latin America: Opportunities, limitations and scenarios

Deepening RQ3, this subsection discusses medium- and long-term scenarios for a circular productive transition, highlighting policy frameworks, financial instruments and strategic sectors where circular models could be scaled up.

The adoption of circular approaches in Ecuadorian agro-industrial systems has begun to generate transformations that go beyond the technical-productive dimension, shaping structural processes with far-reaching environmental, economic and social implications. These impacts do not occur automatically; rather, they rely on the effective articulation of technological solutions, territorial knowledge and adaptive governance frameworks.

Empirical data reveal a reduction in solid waste of between 45 and 55%, as well as increases in agricultural productivity of up to 18% following the implementation of circular models, particularly in banana and coffee value chains. These quantifiable results validate the economic and environmental potential of the circular economy in rural contexts.

From an environmental standpoint, technologies such as anaerobic digestion enable the valorization of organic residues from intensive crops—such as African oil palm, banana and cacao—into clean energy (biogas), thereby reducing reliance on fossil fuels and lowering greenhouse gas emissions. Furthermore, the use of digestate as an organic amendment has improved key soil quality parameters, including water retention, fertility and microbiological biodiversity, in regions experiencing soil degradation [72, 73].

From an economic perspective, the valorization of co-products and by-products opens new pathways for productive integration. Previously discarded residues—such as peels, fibers and plant pulps—are being transformed into inputs for biofertilizer production, nutraceuticals and bioplastics. This productive diversification not only generates new income streams but also reduces dependence on imported inputs and enhances the autonomy of rural production units in the face of international agricultural market volatility [74].

At the social and territorial levels, the implementation of circular models stimulates the dynamism of local economies by creating demand for both skilled and unskilled labor in waste transformation and commercialization. This process, documented in cases such as Manabí and the Inter-Andean Highlands, has been particularly effective in promoting the inclusion of rural women and youth in formalized productive activities, challenging historically entrenched patterns of labor informality [74].

Moreover, the relocalization of value added—that is, transforming residues at their point of origin rather than at distant industrial centers—strengthens linkages between production systems and traditional knowledge. This synergy is critical in regions with a strong agroecological identity, where technological solutions have been co-designed based on cultural practices and pre-existing community networks.

Despite these advances, a latent risk persists: The generalized assumption that all circular practices inherently lead to improvements in sustainability. This presumption, often found in parts of the literature, can obscure underlying design, implementation or governance failures. As Le [22] warns, the net impacts of circular initiatives—whether environmental, economic or social—must be rigorously assessed, while taking into account the institutional and productive contexts in which they are embedded.

In the Ecuadorian case, marked by high territorial heterogeneity and uneven institutional capacities, the effectiveness of circular ecosystems will depend on their ability to adapt to local conditions rather than replicating decontextualized technocratic models. Therefore, instead of promoting specific technologies, an approach is required that prioritizes territorial learning, the social appropriation of innovation and collaborative governance as the foundational pillars to sustain long-term impacts.

Project	Biogas produced (m ³ /year)	Waste reduction (%)	Productivity increase (%)	Source
Banana Composting, Guayas (Ecuador)	150,000	45	12	[75]
Palm Biogas, Manabí (Ecuador)	200,000	55	15	[76]
Coffee Waste Valorization, Coffee Region (Colombia)	32,407,000	50	18	[76, 77]

Note: This table summarizes key performance indicators (KPIs) from selected empirical case studies in Ecuador and Colombia. Sources: Refs. [75–77].

Table 2.
Key performance indicators (KPIs) of circular economy projects in Ecuador and Colombia.

Quantitative results from various circular economy initiatives in agro-industrial sectors of Ecuador and Colombia demonstrate the transformative potential of these practices in terms of sustainability and efficiency. As shown in **Table 2**, the implemented projects have achieved significant reductions in waste generation, increases in agricultural productivity and considerable biogas production from the utilization of organic by-products. These data reinforce the technical and economic viability of circular models in rural Latin American contexts.

To strengthen the empirical basis, **Table 2** aggregates key performance indicators (KPIs) from the reviewed experiences. The average waste reduction reported across the three major initiatives analyzed is approximately 50%, while productivity increases average around 15%. These values suggest promising trends associated with circular practices. However, the observed outcomes also exhibit variation depending on the scale of implementation, availability of infrastructure and the level of technical support available to local actors, highlighting the contextual sensitivity of circular transitions.

4.3 Innovation, collaboration and scalability in the implementation of circular models

The transition toward circular models in Ecuadorian agro-industrial systems must be understood as a systemic process that integrates technology, socio-territorial relations and governance. In this context, innovation assumes a relational character, in which universities, local communities, governments, NGOs and multilateral organizations co-construct solutions tailored to specific rural conditions [78].

Applied research has played a pivotal role in this process. Universities and technological institutes have developed appropriate technologies—such as modular biodigesters, soil sensors and agro-environmental monitoring systems—that have reduced reliance on imported solutions and strengthened local technical capacities.

Likewise, international cooperation has enhanced territorial innovation ecosystems. Initiatives led by the *German Technical Cooperation* (GIZ) in provinces such as Manabí, Santa Elena and Guayas have supported the installation of community composting facilities and agricultural recycling systems, yielding positive outcomes in terms of sustainability and economic inclusion [32, 79].

Cases such as San Clemente and the Chocó Andino illustrate the feasibility of integrating contemporary technologies with traditional agroecological practices.

These experiences underscore the importance of local innovation networks and collaborative learning in generating viable socio-technical solutions.

The incorporation of digital technologies—including traceability platforms, smart water sensors and mobile waste management applications—has improved operational efficiency, reduced losses and facilitated access to sustainability-driven markets. However, scalability remains constrained by structural limitations: Many initiatives still depend on external funding and lack institutional frameworks for long-term consolidation.

The Kalundborg industrial symbiosis model (Denmark), frequently referenced in the circular economy literature, illustrates useful principles such as intersectoral flow exchange and public-private collaboration [49, 80, 81]. Nevertheless, its direct application in Latin America is limited by differences in institutional capacity, business culture and territorial planning [16, 82]. Its value lies less in replication and more in inspiring context-specific adaptations, such as the integration of agro-industry, fisheries and tourism in Ecuador’s coastal regions.

The literature consistently emphasizes that circular innovation depends on knowledge networks, trust among actors and adaptive territorial governance structures [83–86]. In countries such as Brazil and Colombia, the most sustainable progress has occurred in contexts where multi-level coordination and intermediary nodes facilitate implementation [87]. In Ecuador, the absence of stable platforms for territorial governance constrains scalability.

To consolidate these models, fiscal incentives, coherent regulatory frameworks and participatory mechanisms that engage all ecosystem actors are required. It is essential to recognize that circular economy models are not universally transferable. Their implementation must emerge from adaptive co-design processes, grounded in institutional capacity, productive diversity and socio-territorial conditions. Without these elements, initiatives risk becoming fragmented or structurally unviable (Figure 5).

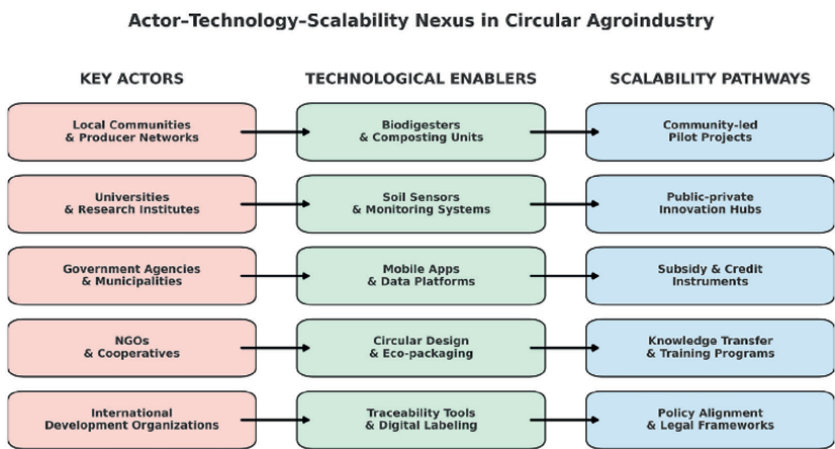


Figure 5. Systemic linkages between actors, circular technologies and enablers of scalability. This infographic visualizes the dynamic articulation among key actors (such as universities, NGOs and local producers), circular economy technologies and critical enabling conditions for the scalability of circular models in rural agroindustry. The model highlights the need for multilevel coordination, context-sensitive technological adoption and institutional support for sustainable transition.

5. Conclusions

This study has explored the feasibility, challenges and opportunities associated with integrating circular economy and circular bioeconomy principles into Ecuador's coastal agroindustrial sector, with a particular focus on the banana, cacao and African palm value chains. Through a systematic literature review and a contextualized analysis of case studies, the research identified key patterns underlying the emergence of rural circular ecosystems as sustainable strategies for territorial transformation.

The findings underscore that principles such as industrial symbiosis, regenerative design and closed-loop systems offer significant potential to transition toward more resilient, inclusive and environmentally sustainable production models. However, these transformations are neither automatic nor evenly distributed. Their success depends on the presence of critical enabling conditions, including adequate infrastructure, accessible financing, inter-institutional coordination and the development of local capacities. Technological innovation, while essential, is insufficient if not embedded in socio-institutional contexts that ensure its appropriation and long-term viability.

Methodologically, this study contributes by bridging the conceptual frameworks of business ecosystems and territorial circular economy. This integrated perspective allows for the reconceptualization of productive transition not merely as a technical shift, but as a systemic transformation embedded in local social and territorial dynamics. Empirically, the research provides valuable evidence from Ecuadorian initiatives, emphasizing their adaptive, multi-actor nature and their potential to generate added value at the origin.

Nonetheless, limitations remain. The absence of harmonized regional datasets complicates the accurate estimation of environmental and economic impacts, while the exploratory nature of the case analysis restricts the generalizability of findings. Future research should aim to assess net sustainability outcomes, conduct comparative analyses across agroindustrial chains and identify the institutional drivers and barriers shaping success or failure.

Although still at an incipient stage, circular and bio-circular economy initiatives in Ecuador's coastal agroindustry show promising signs of structural consolidation. In light of pressing global challenges—ranging from biodiversity loss and climate change to ecosystem degradation and waste accumulation—these models emerge as both viable and necessary alternatives. Their transformative potential, however, will ultimately depend on the capacity of public institutions, civil society and productive actors to co-create a development pathway that integrates ecological efficiency, social equity and territorial competitiveness. The introduction section should provide a context for your manuscript and should be numbered as first heading. When preparing the introduction, please bear in mind that some readers will not be experts in your field of research.

Acknowledgements

The authors express their gratitude to the authorities of Universidad Estatal Península de Santa Elena (UPSE).

Conflict of interest

The authors declare no conflict of interest.

Acronyms and abbreviations

FAO	Food and Agriculture Organization of the United Nations
IPCC	Intergovernmental Panel on Climate Change
ECLAC	Economic Commission for Latin America and the Caribbean (CEPAL)
INEC	National Institute of Statistics and Censuses (Ecuador)
GIZ	German Agency for International Cooperation (Deutsche Gesellschaft für Internationale Zusammenarbeit)
IDB	Inter-American Development Bank (Banco Interamericano de Desarrollo)
UNEP	United Nations Environment Programme
SDGs	Sustainable Development Goals (Objetivos de Desarrollo Sostenible)
MDPI	Multidisciplinary Digital Publishing Institute
WoS	Web of Science
IICA	Inter-American Institute for Cooperation on Agriculture
NGO	non-governmental organization
PRISMA	preferred reporting items for systematic reviews and meta-analyses

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Section 2

Health and Wellbeing

One Health: Implementation Challenges and Need

Muhiuddin Haider, Sameen Ahmed and Allysha Choudhary

Abstract

One Health is based upon the core principle of collaboration and interdisciplinary work when relating to public health- specifically communicable diseases and illnesses. The One Health framework was initially established to address the transmittance of disease from animal reservoirs to human vectors. When animals, humans, and the environment coexist in various areas of life, emphasis should be placed on their codependency and interactions- both healthy and potentially threatening. The COVID-19 pandemic has further enhanced the need for an interdisciplinary workforce in all public health sectors to combat future threats and address the impacts of the recent pandemic. One Health is not only rooted in disease prevention, but also in solutions. Doctors, veterinarians, politicians, public health workers, and all other stakeholders must increase communication to establish such a framework. Once accepted by stakeholders, the One Health framework can be utilized in addressing both communicable illnesses and non-communicable illnesses. In this paper, the background and usage of the One Health framework will be analyzed, and case studies, such as food security and maternal and child health, and associated problems and solutions will be outlined through a One Health framework, one that is not conventionally applied to such non-communicable issues.

Keywords: One Health, One Medicine, food security, maternal child health, interdisciplinary framework

1. Introduction

The foundations of the One Health framework were initially introduced to public health and medical fields in 1964 by veterinarian Dr. Calvin Schwabe. Dr. Schwabe formulated the term 'One Medicine' which was used to emphasize similarities between human and veterinary medicine [1]. As 'One Medicine' became an accepted idea, the thinking did not become widely practiced until 2003 when 'One Health' was introduced during the emergence of severe acute respiratory diseases (SARS) and the H5N1 avian influenza. The term was formalized through the Manhattan principles which outlined the initial understanding of the connection among major areas- disease, environment, humans, and economic development [1, 2]. Recently, a framework has been developed by multiple global agencies including the World Health Organization, UNICEF, Food and Agriculture Organization, and World Organization for Animal Health, to formalize the ideology. This framework has increased global

interest in the approach and its potential implementation areas [3]. The framework describes the connection between people, animals, and our shared ecosystems. As new social determinants of health relating to overall wellness have been addressed including food security, poverty, gender roles, and health systems, the definition of the framework has evolved to consider each of these factors. This has allowed the implementation of the framework in non-communicable areas when looking for prevention and improvement [4, 5].

The foundation of the One Health approach lies in the coexistence and interactions between humans and animals. Many animal species provide a shared reservoir for pathogen exchange and growth, causing infectious diseases to harbor through human-animal interactions [6]. Such interactions include those with pets, during outdoor activities, bug bites, or human consumption of animal products. According to a journal article published in the Indian Journal of Medical Research, 60% of all human diseases are transmitted from animals and 75% of all emerging infectious diseases originate from animals [3]. An example of this link between human and animal health can be seen with bovine tuberculosis (TB) and brucellosis. Both diseases are bacterial zoonotic diseases that are commonly found in cattle and other livestock like sheep and bison [7]. Such diseases can be spread to humans through the consumption of contaminated animal products such as meat or dairy, or through direct contact with infected animals or carcasses. A One Health approach to eliminate the disease in cattle, through vaccination and antibiotics, has significantly reduced the number of TB cases among animals and thus humans, showing the relationship between infections [7].

Another prominent area of zoonotic infection is seen in domesticated animals or pets. Domesticated animals often serve as intermediate hosts for disease transmission. Cats and dogs provide emotional support and comfort for many families globally. While cases of pets, especially cats and dogs, have been noted for playing a role in disease transmission, public health officials have struggled to address the concern, as a strong bond between domesticated animals and humans exists for a large portion of the population. For successful intervention, officials must consider this bond when implementing changes to reduce the risks of these animals serving as disease vectors [2]. While domesticated animals have not been associated with many of the more widespread zoonotic outbreaks, assessing potential disease transmission through pet-human interaction is important in understanding the animal-human interface that the One Health approach discusses.

The environment is another key component of the One Health approach. Changes in climate and other environmental conditions cause animal species to migrate and inhabit new regions. This can create a wide range of human and animal interactions and prove to be dangerous for other species in various niches [2]. Ecological determinants play an important role in determining disease vectors including but not limited to “climate, vegetation, soil, and other conditions that influence habitat suitability [2].”

Environmental health is associated with levels of environmental pollutants and toxins in the air and climate which are often a result of human behavior. As countries interconnect, the risk of communicable disease is obvious, however the indirect implications on climate and vegetation create a large threat to the longevity of the environment and thus human and animal health and security. Clean air, water cleanliness, and plant purity are all aspects of the environment that are vital to the production of food and resources that humans and animals live and interact with. When these aspects are minimized due to human development and activity such as construction, technological development, usage of greenhouse gasses, plants and living resources are negatively burdened with the indirect consequences [8]. Increase

in such human behavior and urbanization has led to an increase in climate change resulting in many of the vital environmental features such as rainforests and ice caps to diminish, slowly resulting in irreversible changes in weather and climate. As these changes occur and environmental threats increase, many chronic diseases related to food, water, and air pollution increase. Some of associated diseases includes Lyme disease, cancer, gastric disease, heart disease, and diabetes [9]. For animals, changes in the environment directly impact their habitats, available nutrients and food, and overall health due to displacement. Looking to how environmental health interacts with human and animal health, may lead to motivation to address such behaviors, as seen with food safety.

While the environment is relevant in all areas, socioeconomic determinants are also important to consider when assessing the level of environmental exposure for individual families and thus associated disease contraction. Those with higher economic security, often live in areas less affected by environmental determinants or can protect themselves from environmental changes. For example, the Chagas disease, said to originate from countries in Latin America, is associated with poor housing living conditions due to inadequate sanitation and less maintained communities, while wealthier communities are less prone to outbreaks [2]. While these discrepancies can be applied within small communities, they can also be applied when looking at the differences in health outcomes across nations. As discussed in this paper, global health of non-communicable diseases often varies drastically by region. Health outcomes in low-and-middle-income (LMIC) countries are often lower than that of wealthier nations such as America. This can be attributed to the differences in exposure to the three main roots of the framework, as well as the resources available to protect from certainly associated threats [1].

As the world continues to become more interconnected through trade, travel, and shared routes of knowledge, the threat of disease has increased on local, regional, and global levels [1].

The 1999 emergence of encephalitis cases in people and birds, which was linked to the emergence of the West Nile virus in the US, left public health officials challenged with controlling the outbreak and identifying its origin. Insight from the veterinary community who was investigating associated bird mortalities helped public health officials determine the origin [1]. This outbreak proved to officials that the need for communication between practitioners is vital for understanding disease epidemiology and treatment. Rabies is another disease that is associated with the interaction between humans and animals. However, parts of North America and Western Europe have controlled rabies using the One Health approach. Canine vaccinations have proved to be an effective strategy to reduce disease by reducing the risk of human infection through the reduction of disease within the animal reservoirs themselves [1].

Connections between animals, humans, and the environment have also been shown through the COVID-19 pandemic. Initially, the virus was traced to an animal reservoir, and mutations of the virus through these reservoirs have been noted. Additionally, cases of the virus were found in different animals globally, affecting both human and animal populations [10]. The lack of a robust One Health approach in dealing with the virus, led to universal impacts on all nations and countries, socially, politically, and economically. The inability of governments to address the outbreak effectively has further exposed gaps in the healthcare systems and the existing public health response plans.

Implementation of the One Health framework has been difficult to establish due to various perspectives of the framework, lack of formal institutionalization,

various understandings of the approach, and limited case study examples of its implementation. The US Agency for International Development's (USAID) Emerging Pandemic Threats (EPT) Program PREDICT project has worked to address this issue by using a One Health approach that is focused on early detection and response to zoonotic threats before they widely impact humans. The PREDICT project surveys hot spots for emerging infectious diseases, this data is then shared across platforms for coordination of response by multiple stakeholders including government agencies and university partners [1]. According to a study published in Biomed Central (BMC), the PREDICT Project "empowered health care providers in more than 30 LMIC by connecting them with animal and environmental health professionals [1]." The PREDICT project collects data about the environment, animals, and humans when looking at a specific problem with all three prongs of One Health in mind. For example, weather conditions have been studied to predict Rift Valley fever and other outbreaks of disease relating to climate change. This was done through vaccination and mosquito control campaigns at a time close to when the findings concerning weather conditions were approaching to reduce the risk of human infection [1].

Additionally, the recent emergence of the Monkeypox virus, a variation of the once-eradicated smallpox virus, has also shown the link between infection and transmission between humans and animals. While Monkeypox is still fairly novel and research is still limited on the virus, its contraction, spread, and treatment, it has been proven and reported by the CDC that disease transmission to humans can occur between infected animals or humans [11]. While the exact disease host has not been identified, the CDC suggests it is likely that the virus mutated in rodents and spread to humans through animals [11]. As public health officials work to address this new outbreak, they are looking to the animal-human interaction, hoping to understand mutations when designing treatment.

2. Framework in practice

2.1 Importance of one health in maternal and child health

The One Health framework has many applications for a broad range of public health issues, as previously discussed, many of the common applications of the approach are related to communicable zoonotic diseases. However, the framework is also relevant and necessary to understand the complexities of other health conditions globally, including maternal, newborn, and child health. Complex systems with interlinkages between the environment, human health, agriculture, and zoonosis influence many aspects of population health. A notable reflection of the One Health framework within maternal and child health is that of child stunting.

Stunting, which is low height for age, is a historic and pervasive global nutrition health issue – roughly 22 percent of children under age five are stunted, translating to 149.2 million children [12] Stunting is associated with several negative health outcomes, including the risk of mortality from common infections, impaired motor, and cognitive development, the risk of future chronic disease, and contracting infections [13]. Though traditional interventions such as nutrition education and counseling, immunization programs, school feeding programs, distribution of nutrition packets, and water, sanitation, and hygiene (WASH) programs have attempted to reduce stunting in LMIC, there still remains a gap in sustained reductions in stunting in these settings [14].

Utilizing a One Health approach may better address the root causes of childhood stunting and offer solutions that address multiple potential leverage points in the animal, environmental, and human systems that impact childhood nutrition [15]. Animal-human links through livestock, a common exposure for communities in rural areas of LMIC, provide opportunities for fecal contamination, which can spur the vicious infection-malnutrition cycle [16, 17]. However, livestock can also be valuable for child nutrition as they can act as a source of essential micronutrients through milk, eggs, and meat [18]. Next, animal-environmental links such as unregulated management of animal feces can lead to contamination of food sources in the absence of adequate WASH infrastructure, further impacting childhood stunting by contributing to the infection-malnutrition cycle [19, 20]. The impact of a balanced diet through healthy agriculture and the environment also impacts livestock health, which in turn affects the quality of dairy and meat consumption by children [21, 22].

Lastly, the environmental-human links are notable factors contributing to stunting. Human fecal contamination from poor WASH systems, contamination from bacteria in soils, and exposure to fecal contamination from livestock put young children at higher risk for infections that exacerbate stunting [23–25]. This is especially problematic for young infants that often engage in the exploratory behavior of hand- and object-mouthing as they develop, which increases the risk of infections through fecal and soil contamination [26]. Additionally, the quality of crops influences the quality and diverse diet for children, further impacting nutrition and subsequent stunting [27, 28].

Especially in the face of climate change, public health interventions to address prominent maternal and child health issues can utilize a One Health approach combined with systems thinking to analyze interactions between the environment, humans, and animals to order to design better multi-pronged programs to intervene in multiple areas that influence maternal and child health and identify potential leverage points for interventions [29]. A notable benefit of a One Health approach is in the many improvements to multiple facets of health that would occur given shared root causes of poor health outcomes and inequities – a One Health method to designing public health programs would not only lead to positive health outcomes but potentially poverty reduction and education and social outcome improvements as well [30].

2.2 Food security and Rwanda

Another example of the potential of the One Health framework being applied to nonconventional and nonzoonotic issues is food security. Rwanda is one of the most densely populated countries with an average of 415 people per square mile. This has caused disasters to occur on a large scale and affect a large number of people. The high population density has also led to increased food insecurity, soil erosion, decreased grazing land, and forest degradation, which in turn has caused issues with food insecurity and thus poorer health outcomes [31]. In a report by the World Food Programme, it was estimated that 38.2% of the country lived below the poverty line, with about one-fifth of the 12 million population being considered food insecure, leading to developmental and growth issues in adults and children [32].

While Rwanda is a densely populated country, its economic resources are not substantial to support the large population, which consistently changes as pastoral communities increase. This has contributed to the high levels of poverty and food insecurity [33]. A large portion of the land in Rwanda is used for pastoral communities as the number of travelers, especially in the Eastern region of Rwanda is vast. Rwanda thus experiences an influx of many novel interactions between people, animals, practices, and

microbes. This further contributed to the food insecurity that occurs due to changes in agriculture, population density, and consistent changes in the land and soil (Nyatanyi). Pastoralists often pick up animal pathogens and carry them as they migrate, affecting livestock populations and leading to disease in communities (Nyatanyi). This leaves many travelers and natives at risk of contracting diseases and spreading them as they migrate. Rwanda also has a high number of refugee communities, which often increases the demand for resources such as food and water, however, is difficult to supply as the natives of the country also have trouble receiving such resources [34].

In order to combat many of these challenges, Rwanda has adopted initiatives rooted in the One Health principles to help eliminate some of these food access concerns in order to provide a sustainable food source for families, while limiting the risk of unsafe food contamination and microbial diseases. One way this has been achieved is through the Girinka system [31]. Through the Girinka program, one cow is gifted to each family in an attempt to alleviate malnutrition [31, 32]. The Girinka program has helped provide a stable source of food and security to families and contributed to various other stakeholders involved in the public health sector to combat the issue of food security. In addition to the Girinka program, improvements in public health indicators such as maternal health and HIV cases have been identified, and efforts towards environmental sustainability to improve the soil and agricultural land in Rwanda have been initiated [31]. Through analysis of each component of the framework, Rwanda's public health sectors have been successful in working towards solving the issue of food security.

The goals established to improve food security and associated health risks are all rooted in promoting overall health and wellness to account for the large population density of the country and to protect neighboring countries as pastoral culture exists in this region of the world. Collaboration between the University of Rwanda, the Ministries of Health, Agriculture and Animal Resources and Education, The Wildlife Unit of the Rwanda Development Board, and other ministries and civil society have been reported and are increasing efforts on the problem as stakeholders are united in their work through an interdisciplinary approach [31]. Using the animal-human-environment relationship to study how food security has been linked to each of these components has led to successful solutions for Rwanda. Continued efforts through programs such as Girinka are promising in further decreasing food insecurity.

3. Implementation challenges of the one health framework

While the One Health approach is gaining traction and being supported by governmental agencies such as WHO and APHA, there are various challenges that prevent communities and governments from implementing the framework. One large concern from agencies is socio-political factors. An emphasis on a direct-harm approach rather than prevention is prevalent in many countries and is reflected by disproportionate focus and resources towards medical treatment rather than public health system strengthening [6]. Political beliefs can also be an obstacle faced by stakeholders attempting to establish a One Health-based framework, as governments emphasize public health research and importance differently.

Much of the One Health approach is surrounded around the "precautionary principle" to reduce the risk of harm. However, this requires upfront sacrifices such as financial investments that the governments of most countries are not willing to make, despite the long-term benefits where an initial investment can save millions of dollars

and lives [6]. According to an analysis by the World Bank, upfront global investments of \$3.4 billion per year for One Health, through veterinary and public health services, could save over \$30 billion in response and treatment of zoonotic diseases annually worldwide [1]. However, often these upfront investments seem too large for already struggling governments. This has led to weakened public health sectors, causing outbreaks to reach levels of endemism and even pandemics.

Another large implementation challenge for One Health is seen in ethics. During a significant outbreak of disease, resources are limited and decisions about which groups receive supplies and treatments need to be made. This can create ethical concerns and raise questions regarding decisions of distribution of resources. This may also create disagreement about who is qualified to make such decisions [6]. For example, in Canada during the SARS outbreak, leaders were not prepared for the range of ethical concerns that were brought to their attention. These concerns included individual freedom versus the common good, healthcare workers' safety versus their duty to care for the sick, and economic costs versus the need for containment.

Additionally, for many religious groups, the desire to go to their place of worship was also something government officials had to make decisions about, creating two groups of people, one content with the decision and another angered by it [6]. These issues resurfaced during COVID-19 as the symptoms and transmission of SARS and COVID-19 are rooted in similar physiology. Considering these factors is vital for the successful implementation of a risk management technique rooted in One Health as community members must oblige to recommendations in order for its success.

Finally, legal challenges are another major factor that government workers, public health professionals, and medical practitioners must consider when implementing the framework. Different states, countries, and other leading bodies have individual laws and expectations for addressing re-emerging and emerging health concerns. This can create conflicting plans and further lead to chaos among citizens and confusion about which guidelines to follow [6]. Confusion between state and national laws can lead to prolonged responses in dealing with crises and increase risk and damage. Additionally, majority of laws regarding the emergence of disease and public health crises look at preventing cross-border pathogen transfer and community outbreaks, rather than interactions between animals, the environment, and people [6]. To combat this, there must be organized and widely accepted guidelines for governing bodies to refer to, which would increase likelihood of stakeholder participation in implementation and thus success of a One Health approach to prevention and solution.

4. Looking forward and conclusions

An important aspect of One Health's implementation is the need for globalized and institutionalized definitions and guidelines that can be available to all nations through public health organizations. A variety of interpretations of the framework and its practice have left nations skeptical of adopting it into their emergency plans when health concerns erupt [35]. A standardized framework would help with the identification of the value of interdisciplinary work in addressing communicable and noncommunicable concerns by eliminating discussion about how this can be done. Efforts of various health sectors must be united to create a globally understood and accessible framework with a breakdown of how each stakeholder plays a role in practical application [35, 36].

Another way to increase One Health awareness is by including its teachings in the curriculum and training potential stakeholders of the approach such as doctors, veterinarians, policymakers, lawyers, etc. These stakeholders should be trained in the framework and gain a deeper understanding of its applications through the advocacy of case studies that have proven its effectiveness and potential application such as those outlined in this paper. While the One Health framework has become increasingly accepted due to increased public health education, many practicing doctors and veterinarians were not taught the framework - this is problematic as they are often the first line of defense in controlling zoonosis. Increasing public health curricula in medical and veterinary schools will better equip the next generation of officials to understand a preventative outlook, this is especially important as once eradicated diseases are reemerging.

The establishment of clinics and partnerships that function using a combined approach is another way to increase One Health usage for communicable and noncommunicable areas of concern. A clinic in California, Knights Landing One Health Monthly Clinic, provides both animal and human services for economically disadvantaged communities [37]. This clinic was developed by the UC Davis School of Medicine and Veterinary Medicine and is run by students who desire the promotion of a One Health approach that harbors holistic treatment. Clinics and health services such as this promote communication and the vision of a united goal for health that includes animals, humans, and the environment [37]. With proper execution and medical practice, clinics such as this can be successful in looking at treatment and prevention as an extension of the codependent relationship humans and animals live within.

As previously emphasized, the interaction between humans, animals, and the environment is what makes the One Health approach different from others - this means the public sector of nations must be involved in the implementation of a successful outcome as they harbor this trifold interaction. The public should be educated about the risk of disease to increase awareness about the animal, human, and environmental interface. This will not only help promote the framework, but also help with risk assessment. Community members being involved in their own health has proven to show improved health outcomes, this is especially important for developing countries as their threat to community safety is larger due to living conditions and large populations [37]. Through increased training and education on the framework, different stakeholders will be united in their efforts, harboring stronger communication.

The One Health framework is widely known among public health officials, however, is not often seen as a solution by stakeholders previously mentioned. This has limited capabilities and applications of a potentially vital component of risk management. As outlined in this paper, the One Health framework is most often applied to zoonotic diseases which can be transferred from humans to animals. These diseases are communicable and pose a great threat to communities, especially those which are close-knit with dense populations. While the approach can be successful to limit such outbreaks, the core principles of the framework make it adaptable to other areas of concern as well. Studying the interface between three major interacting components of our world can help to explain other illnesses as well, such as those explained in the paper with maternal and child health and food security. Addressing how the three areas coexist and influence noncommunicable areas of concern can help provide public health officials and medical practitioners with robust and multifaceted solutions to both communicable and chronic health issues.

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Resilience in Mexican Women Who Have Experienced a Situation of Sexual Harassment

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Abstract

Introduction: Resilience provides victims of violence with the necessary strength to get out of difficult situations, increases self-esteem, and provides tools for women concerning the environment that surrounds them to act on it and create protective barriers. In Mexico, a high number of victims of sexual violence is established, however, no mechanisms or interventions are observed to increase resilience skills in people who have suffered some type of sexual harassment. **Objective:** to describe the resilience factors in a group of young people who have suffered sexual harassment. **Methodology:** Quantitative, observational, cross-sectional study with a descriptive scope, applied through a virtual survey using the Google Forms tool. **Results:** with 88 participants of which 80.7% were female, it is established that most of the subjects were at a high level of 90.9% (80), followed by a medium level of 9.1% (8); with an average of 5.79 (0.59 SD) of identification in the questions (I identify myself easily), while in the total score of 652, with a minimum of 451 and a maximum of 752. For men, the average resilience was 5.72 and for women 5.81, slightly higher. **Conclusion:** Resilience skills are essential to achieve a better adaptation to bullying situations, and not aggravate the consequences generated by people who exercise this type of violence.

Keywords: resilience, Mexican, women, sexual harassment, vulnerability groups

1. Introduction

For Fergus and Zimmerman cited above, resilience is referred to as that process linked to overcoming the negative effects after having been exposed to risk and successfully coping with the traumatic experience. They also raise risk and protective factors. Some definitions of resilience can be found in **Table 1**. Resilience in women

Group	Definition
They relate the phenomenon to the adaptability component.	He expresses that resilience is considered as the successful adaptation of an individual, being exposed to risk factors, mainly of biological order; but it also implies a low susceptibility of the subject to future stressors.
	It takes as an example the definition of Grotberg [1], which proposes resilience as a universal human capacity, mainly of a biological nature.
They include the concept of capacity or ability.	resilience as a universal human capacity, which allows facing life's adversities, overcoming them and transforming oneself as a result. He also refers to it as part of the evolutionary process and that it can be learned and developed from childhood.
Emphasize the conjunction of	According to Vanistendael [2], resilience has two components: likewise resistance to destruction, and on the other, the capacity to build positive behaviors in spite of difficult experiences.

Taken from: [3].

Table 1.
Definitions of resilience according to their applicability.

who have experienced sexual harassment is the process by which they adapt with some degree of well-being to the adversities of the traumatic situation [3].

These resilience processes such as the interaction of social support factors, i.e. I have, skills and personal strengths, have characteristics such as the individual's confidence in himself and in others, which is the basis of other pillars and is the key to facilitate the process of resilience, constant self-confidence. Dignity and identity, recognition of one's own achievements and self-acceptance, introspection, reflection and critical awareness is asking questions, talking to oneself and giving honest answers, being autonomous and independent, knowing how to set boundaries between oneself and others with problematic conditions or capabilities. Keeping emotional and physical distance [4].

The relevant subcategories for this study are support networks, institutions, family, friends, women's groups (that's me), and for resilience to be important, in addition to personal factors, dynamic processes related to the environment and support networks are required, place or from the strengths that each individual has to respond to the traumatic situation caused by sexual violence and develop successfully to achieve personal, psychological, social, family growth (what can I do) and promote the resilience of victims of sexual violence as a dynamic process which allows them to work here and strengthen the process.

Likewise, harassment can be delimited as any practice of implicit or explicit sexual connotation coming from a person (known or unknown) and with a unidirectional character, that is, without the consent of the person to whom it is directed, occurring in public or private spaces with the potential to produce discomfort in the person harassed [5].

In Mexico, 19.2 million women have suffered some form of intimidation, harassment, bullying or sexual abuse at some point in their lives (Encuesta Nacional sobre Dinámica en las Relaciones Familiares [6]). 1 in 9 sexual crimes against women Sexual crimes against men (Encuesta Nacional de Victimización y Percepciones de Seguridad Ciudadana [7]). 40,303 women were raped in Mexico in the National Survey of Perceptions of Victimization and Public Safety 2018 [7].

32.8% of 15–17 year olds have experienced some form of sexual violence in the community (Statistical Review of Violence Against Children and UNICEF [8]). In 2021 you will see more and more dark images of sexual violence. 99.7% of cases go unreported. In the second half of 2021, almost 5 million women were victims of sexual crimes, 0.8 percentage points more than the previous year. Between July 2021 and December 2021, 99.7% of sexual assault cases against women over the age of 18 were reported. In 2020, the black figure is 98.6%. The cities with the highest cases of sexual crimes are Tlaxcala, Merida and Tampico (National Urban Public Safety Survey [9]).

For victims, this type of behavior has serious consequences on their physical and mental health, such as loss of self-confidence and self-esteem, increased nervous tension and irritability, and even anxiety, fear, depression and sleep disorders. Likewise, the increase in the level of stress can cause eating problems, difficulty concentrating at school or work, stigmatization and lead to the abandonment of daily life activities [10].

These two phenomena are related in the degree of affectation for these consequences, since resilience as a personal factor can provide mechanisms of adaptability and response to this type of violence, in addition to enhancing the victims' ability to cope with, assimilate and respond to these events [11].

Health interventions can provide basic results to increase their resilience, and it is important to highlight that, according to Humphrey's description of the impact of protective factors, public health is the basis for comprehensive treatment of women victims of sexual violence. The physical and mental health of women and research on the resilience of victimized women provide elements to understand the effective adaptation of these women and show how they can recover from trauma and achieve personal and successful lives and relationships [12–14].

Derived from this, it is established that non-violence prevention campaigns in public spaces and workspaces should be based on methodologies that are broader than a risk perspective, but should instead focus on disseminating messages related to the empowerment of women, the active participation of men, and the promotion of health [15].

For all of the above, the objective of this study is to describe the resilience factors in a group of young people who have suffered sexual harassment through the application of an instrument.

2. Materials and method

This is an observational study, descriptive in scope and cross-sectional, which worked with 88 participants, through a virtual survey on the Google Forms platform, using a non-probabilistic sampling by convenience, as inclusion criteria were established as young people who wished to respond to the survey and the most important elimination criterion was that they had not suffered a bullying event.

The questionnaire (Edith Henderson Grotberg Resilience Test) consists of 107 statements with which individuals could identify themselves from: 7. I identify myself totally (100–95%), with some rare exceptions, 6. I identify myself very easily and as a general rule, 5. I identify myself easily, 4.

The responses were grouped into 4 components:

- The “I am” and “I am”: indicates the degree of resilience or inner strength.

- The “I can” indicates the degree of social, interpersonal and conflict resolution skills.
- The “I have” refers to external resilience factors, support networks or social support (family, friends, social).
- The “I believe” refers to the convictions we have.

It is important to establish that during this process the Regulations of the General Law of Research in Health Research were considered, through a welcome screen the informed consent was collected and the objectives were shared, as well as the perceived benefits and risks.

3. Results

A total of 88 surveys were applied through the Google Forms tool. When measuring the reliability of the instrument, through Cronbach's Alpha, a total of .974 was obtained, which indicates a high reliability at the time of application. In the sociodemographic data, 19.3% (17) were male and 80.7% (71) were female; the average age was 22 years (1.16 SD), of this group, 59.1% (52) were without a partner at the time of the survey, followed by 35.2% (31) who were in a relationship, and finally, with 5.7% (5), who were in a free union. Chi-square tests of independence established that the variables were not dependent on sex ($p = .608$) or marital status ($p = .856$) (**Table 2**).

In the first component, which establishes the “I am” and “I am” to describe the degree of internal resistance, high degrees of identification are described, especially for the items I am someone who likes to help and serve others, with 52.3% (I identify myself totally), for the statement I am compassionate (a) to the suffering of others with 45.5% (40) and for the sentence I am aware that I am a unique and unrepeatable person a total of 51.1% (45) of this same response. In this section, an average of 5.77 pts. (0.581 SD) is obtained, which indicates that on average people identify easily with the statements made, and when categorized, most of the subjects were found at a high level 88.6% (77).

For the next component that evaluates the degree of social, interpersonal and conflict resolution skills, it is obtained that on average people identify easily with the statements made with 5.72 pts. (0.572 SD), in which the following items stand out whose distribution was grouped in the response I identify myself totally: I can make decisions by myself with 50% (44), I can face problems and learn from them 42% (37) and I can face and work through adverse situations for as long as necessary 44.3% (39). Likewise, a phrase with which they identified very little was I can experience the desire to continue struggling with sometimes I can identify myself and sometimes not with 27.3% (24).

Gender	Civil status		
	Single	With a partner	In free union
Male	8 (10%)	8 (6%)	1 (1%)
Female	44 (42%)	23 (25%)	4 (4%)

Table 2.
Cross-tabulation of marital status and sex in the participating subjects.

Subsequently, to delimit the external factors of resilience, the support or social support networks such as family, friends, social networks is determined by establishing the average at 5.91 with a standard deviation of 0.688. In the analysis by items it is observed that the sentences in which most of the subjects identify themselves totally were: I am willing to recognize my mistakes and my responsibilities 67% (59), also the sentence I am willing to face adverse situations knowing that the solution depends on my own abilities and strength 65.9% (58) and finally I am willing to continue with courage and to the end the tasks or projects in which I have committed myself 55.7% (44).

Finally, in the component corresponding to the convictions that influence resilience, the statements with which the majority of the participants identified themselves as a whole were I have a structured home with rules 56.8% (50) and I have parents who encourage self-esteem 50% (44). The average identifying responses centered on 6.01 with a standard deviation of 0.70, placing them at the level of I identify very easily and as a rule. The percentages according to level can be seen in **Table 3**.

Regarding the general level of resilience evaluated, it is established that most of the subjects were at a high level 90.9% (80), followed by a medium level 9.1% (8); with an average of 5.79 (0.59 SD) of identification in the questions (I identify myself

Level	Resilience component			
	Internal strength	Social abilities	Support networks	Conviction
Low	0	0	0	0
Medium	10 (11.4%)	17 (19.3%)	11 (12.5%)	2 (2.3%)
High	78 (88.6%)	71 (80.7%)	77 (87.5%)	86 (97.7%)

Table 3.
Classification according to the level of the components of the resilience instrument.

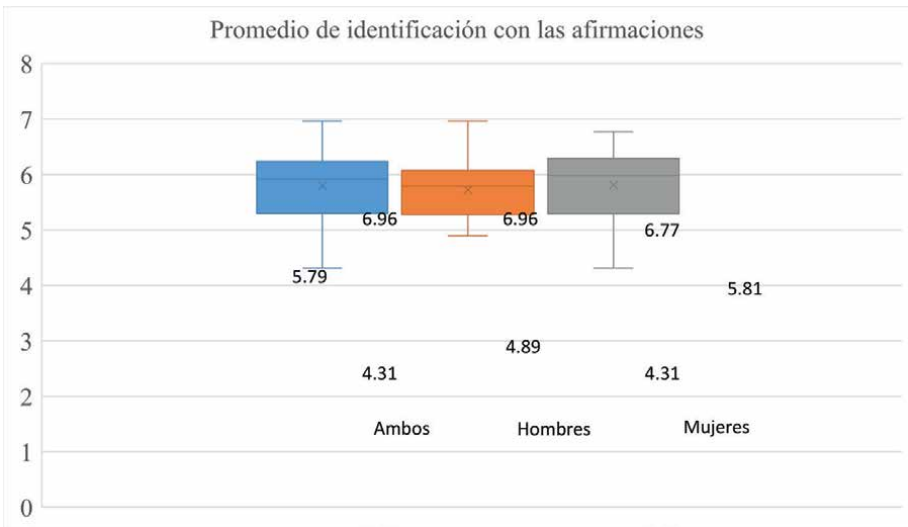


Figure 1.
Distribution of self-identification affirmation averages by gender and overall.

easily), while in the total score of 652, with a minimum of 451 and a maximum of 752. For men, the average resilience was 5.72 and for women 5.81, slightly higher. The distribution between sexes and in general can be found in **Figure 1**.

4. Discussion

Resilience can be understood as the capacity or characteristic that people must have in order to come out on top when touched by violence is resilience and currently, there is little research that addresses this problem from a quantitative perspective.

In this research, most of the participants identify themselves at a high level in all components. Regarding inner strength, a high level is noted with 88.6% of identification at this level, which coincides with that reported by Moreano in 2018, who establishes through in-depth interviews that most participants state that inner strength is a decisive factor in facing this type of problem, because it allows rethinking questions about power and how public institutions can facilitate the empowerment of women in today's society [16].

Secondly, for social skills, in this research a high level was obtained in 80.7% of the participants, which differs with what was found by Cordero and Teyes in 2016, who evaluate the level of resilience of women in a situation of domestic violence in a community in Venezuela, by establishing that family or social factors influence this capacity at a high level with only 46.1%, which establishes an important difference in the public sphere since most of these women establish a loss of confidence in the close family and social nucleus due to the situation of harassment [17].

Subsequently for the support networks, the participants of this research indicate to be at a high level up to 87.5%, according to the identification of the phrases. This coincides with what was reported by Ramírez and Trujillo in 2019, who through their work groups report that support networks are the fundamental pillar on which the process of overcoming this violence is structured, since it contributes to generate the conditions for the identification of aggression. On many occasions, this is the factor that motivates the victims to take legal action and to break all types of relationship with the aggressor, in case they are in their social circle [18].

Then, in the last component, conviction, that is, what people believe can help them in situations of violence in this research a high level is obtained with 96.7%, which coincides with that reported by Ortiz in 2020, who states that among the most important factors of overcoming for women victims of sexual violence is the belief that the situation will improve, together with social and family support [19].

In general, the persons evaluated established a high identification with the statements contained in the instrument, as well as in each of the components, this is important, since as established by Lazo in 2021, resilience provides women victims of violence with the necessary strength to get out of difficult situations, increases self-esteem, and provides tools so that the woman in relation to the environment that surrounds her can act on it and create protective barriers [3].

5. Conclusions

During the development of the study, it became evident that those who generated the process of resistance had protective and risk factors that favored or limited such recovery, and in this case, it was clear how these factors play the role of women. Matter of victims of sexual harassment.

The emphasis on lack of support networks, negative emotions, lack of independence and autonomy, all common, become accepted traits from their life experiences and background.

The experience of sexual harassment affects the whole person, endangering their physical, mental and general health, and after sexual abuse it can be seen that to acquire the qualities of resilience, the person needs to have a rich and useful psychosocial support network. Visualize the positive in all bad events. These support networks reduce risk factors.

In this case, we see when confronted with these situations that he faced, he was somehow able to face the events from a different angle in life and change his mind about his purpose in life. Single parent), work, social, personal.

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Hand Hygiene: What's New!

Rakesh Gupta, Ruchika Bhatnagar and Akanksha Mahajan

Abstract

Hand hygiene (HH) has been highlighted as the most important technique in the prevention of COVID-19 and all other communicable diseases significantly. There is paradigm shift observed while practicing HH in post pandemic situation. It is applicable to both health care workers (hcws) and individuals as a whole. Healthcare-associated infections (HAIs) are posing the biggest threat to healthcare systems globally. Healthcare workers' hands are considered to be the important source for the transmission of pathogens; thus, effective HH is the single most important action to prevent HAI. The COVID-19 pandemic has truly served as a wake-up call in this regard. Strengthening the HH compliance rates with a subsequent decline of HAIs may be achieved through national, systematic and rigorous education, and training programs. The global implementation of the WHO multimodal hand hygiene improvement strategy and constant efforts to replace the use of soap and water with alcohol-based hand rub have led to a faster and more efficient hand cleaning method. These strategies have strongly contributed to the behavior change, and a subsequent decrease in HAI. The WHO multimodal behavior change strategy requires a series of elements, including system change as one of the pre-requisite education, monitoring and performance feedback, reminders in the workplace, and an institutional safety climate.

Keywords: hand hygiene, COVID-19, infection control, asepsis, nosocomial infections

1. Introduction

The most important measure to prevent hospital-acquired infection is following meticulous hand hygiene. Now, as we sail through COVID-19 pandemic and embrace the new normal, hand hygiene has become an integral part of our lives. World hand hygiene day is observed every year on May 5, to highlight and raise awareness about hand hygiene and infection prevention control (IPC) measures to save lives. This year's theme for world hand hygiene say was unite for safety: clean your hands. The six-step hand hygiene technique recommended by the WHO serves as a benchmark and is followed globally. During the past years, measures to strengthen hand hygiene compliance ranged from new teaching tools to precise, effective, and accurate surveillance strategies. Rationalizing and simplifying the WHO six-step model in terms of reducing the steps or time is recently being recognized as the need of the hour, as it affects the compliance rate in daily clinical practice to a large extent. A simplified hand hygiene technique proposing merely three steps was shown to be non-inferior in terms of microbiological efficacy in a standardized experimental setting as compared with the

standard six-step technique [1]. The concept of reducing or amending the six WHO hand hygiene steps is emerging and serves as a promising area for future research.

2. Historical perspective

The concept of cleansing hands with an antiseptic agent came in the nineteenth century. In 1822, a French pharmacist demonstrated that solutions containing chlorides could be used as disinfectants and antiseptics. In 1846, Ignaz Semmelweis observed that women whose babies were delivered by physicians of the general hospital of Vienna consistently had a higher incidence of puerperal fever as the doctor's carried infection from autopsy rooms to the delivery rooms. He introduced the practice of hand sanitization with chlorine solutions, which led to a dramatic decline in the maternal mortality rate. In 1975 and 1985, formal written guidelines on handwashing practices in hospitals were published by the Centre for Disease Control (CDC) [2].

3. Normal bacterial flora

Normal human skin is colonized with bacteria. The bacteria recovered from the hands were divided into two categories: transient and resident. Transient flora, which colonizes the superficial layers of the skin, can be removed by routine handwashing. They are often acquired by healthcare workers during direct contact with patients or contact with contaminated environmental surfaces within close proximity of the patient. Transient flora is the organisms most frequently associated with healthcare-associated infections. Resident flora, which is attached to deeper layers of the skin, is more resistant to removal. In addition, resident flora, such as coagulase-negative staphylococci and diphtheroid, is less likely to be associated with such infections.

4. Methods of transmission of pathogens

Healthcare workers may come in contact with pathogens upon contact with patients or fomites in their environment. These pathogens will survive in the absence of use of antiseptic or inadequate use. These bacteria should be capable of surviving upon host skin for some time. These can then be transmitted to another patient or host himself.

5. What is hand hygiene?

Hand hygiene means cleaning your hands by using either handwashing (washing hands with soap and water), antiseptic hand wash, antiseptic hand rub (i.e., alcohol-based hand sanitizer, including foam or gel), or surgical hand antiseptics.

6. Use of hand hygiene

Hand hygiene practices ensure that there is no cross-transmission of potentially hazardous microorganisms between the healthcare worker, patient, and environment.

People unknowingly touch their face, eyes, and mouth and, hence, transmit these organisms that could lead to many respiratory or diarrheal diseases. People come in contact with these pathogens through other sick individuals and fomites, such as handrails, table tops, or toys.

There is a significant risk of infections among immunocompromised individuals that could have life-threatening consequences. Hence, hand hygiene is a simple measure to prevent cross-transmission of infectious agents in healthcare facilities.

Antibiotics are often prescribed unnecessarily for these health issues. Reducing the number of these infections by washing hands frequently helps prevent the overuse of antibiotics, the single most important factor leading to antibiotic resistance around the world.

7. Where should we follow hand hygiene?

It should be done at the following:

7.1 Outpatient setting

The hand hygiene principles are not well established in the OPD setting. Often, it is assumed that the patients seen in OPD are not infectious and that there is little time to execute hand hygiene in busy clinics. Nowadays, several procedures are done on an ambulatory basis or at home, such as dialysis or administration of anticancer drugs in daycare settings. This requires efficient hand sanitization to prevent nosocomial infections in already immunocompromised patients.

7.2 Inpatient setting

Five essential moments or indications, when hand hygiene is required during healthcare delivery, have been identified by WHO [3].

The patient zone is defined as the patient and his/her belongings and surroundings that are temporarily and exclusively dedicated to him/her. Specific sites within the patient zone that can act as an entry point for pathogens into a patient or facilitate the transfer of microbial organisms from the patient to the healthcare provider are called critical zones. All areas outside the patient zone in a healthcare setting are known as healthcare area. The five moments of hand hygiene are as follows:

- i. Before touching a patient
- ii. Before a clean procedure
- iii. After body fluid exposure risk
- iv. After touching a patient
- v. After touching the patient's surroundings

7.3 At home

Home-based care may be required for a disabled patient. The helper may be required to bathe the patient, change the dressing of an ulcerated wound, or assist

the patient to go to the toilet. This may involve grooming and change of patient linen, thus acting as a source of critical zones.

7.4 At school

Hand hygiene is important in primary schools to prevent the spread of infectious illnesses, such as respiratory and gastrointestinal diseases, reduce absenteeism of teachers and pupils in schools, and also community transmission of bacteria and viruses, reduce health service costs, and lower the burden on families.

The practice of handwashing needs to be taught to pupils and reinforced by daily routines. Children need to be supervised and often assisted in their task. An adequate supply of handwashing soap and alcohol-based sanitizer should be ensured with colorful visual reminders to make the process an interesting one.

7.5 In family

Hand hygiene should be practiced by all members of a family. This way, it can be adopted as a habit by children. Parents should lead by example and give reminders to young ones. This is an effective measure to prevent the transmission of respiratory infections among siblings, especially in overcrowded houses.

8. Five moments of hand hygiene

This approach defines the key moments when healthcare workers should perform hand hygiene [3].

This is an evidence-based, field-tested, and user-centered approach designed to be easy to learn, logical, and applicable in a wide range of settings.

Hand hygiene must be followed at five prominent places. The reasons for the same have been mentioned as follows:

- i. Before touching a patient to prevent transmission of potentially infectious microorganisms from the healthcare area to the patient through healthcare worker's hands.
- ii. Before a clean procedure to prevent transmission of pathogens to the already suffering individual by direct inoculation or contact with the healthcare area.
- iii. After body fluid exposure risk to prevent the risk of colonization and disease in the healthcare worker by a patient's microbial flora. This also checks the spread of disease in the environment.
- iv. After touching a patient to minimize the exposure of the healthcare provider by limiting the growth and spread of infectious agents.
- v. After touching the patient's surroundings to limit the transmission of the patient's infection to the healthcare area.

There are certain limitations to the five moments of hand hygiene [4]:

1. The development of the five moments did not include the perspectives of stakeholders.
2. It is not always possible to implement five moments for all patients all the time.
3. The patient zone is not a fixed entity.
4. The five moments overlook barriers that reduce hand hygiene adherence.
5. Adherence to the five moments cannot prevent all risks of transmission.

9. Agents of hand hygiene

9.1 Chlorhexidine

The antimicrobial activity of chlorhexidine is attributable to the disruption of cytoplasmic membranes, resulting in precipitation of cellular contents. It has good activity against gram-positive bacteria. The antimicrobial activity of chlorhexidine is only minimally affected by the presence of organic material. Chlorhexidine has substantial residual activity. It is minimally absorbed through the skin and can cause ototoxicity and conjunctivitis if in contact with the mucous membrane of ear or eye, respectively.

9.2 Soaps

These are detergent-based products that contain esterified fatty acids and sodium or potassium hydroxide. They remove dirt and organic material, but a non-antiseptic soap may paradoxically increase the contamination of hands by bacteria.

9.3 Alcohol

The majority of alcohol-based hand antiseptics contain isopropanol, ethanol, or n-propanol. The antimicrobial activity of alcohols can be attributed to their ability to denature proteins. Alcohol solution containing 60–95% alcohol is the most effective antiseptic. Alcohols are not appropriate for use when hands are visibly dirty or contaminated with proteinaceous materials. Alcohols have excellent germicidal activity against gram-positive and gram-negative vegetative bacteria, including multidrug-resistant pathogens (e.g., MRSA and VRE), mycobacterium tuberculosis, fungi, and nonenveloped viruses.

9.4 Iodine and iodophore

Iodophors are composed of elemental iodine, iodide or triiodide, and a polymer carrier. These have bactericidal activity against gram-positive, gram-negative, and certain spore-forming bacteria (e.g., clostridia and *Bacillus* spp.) and are active against mycobacteria, viruses, and fungi, but are not sporicidal. The majority of iodophor preparations used for hand hygiene contain 7.5–10% povidone-iodine. These products can cause allergic reactions and staining.

9.5 Quaternary ammonium compounds

These are nitrogen-containing substances that disrupt microbial cell membranes and cause leakage of cell constituents. Quaternary ammonium compounds are primarily bacteriostatic and fungistatic. Their action is adversely affected by organic matter.

9.6 Triclosan

It has a broad range of antimicrobial activity, but it is often bacteriostatic, more so against gram-positive bacteria. It has persistent action on the skin after application.

9.7 Chloroxylenol

It is also known as parachlorometaxylenol (PCMX), and is a halogen-substituted phenolic compound. The antimicrobial activity of PCMX likely is attributable to the inactivation of bacterial enzymes and alteration of cell walls. PCMX is available in concentrations of 0.3–3.75%. It is active against both gram-positive and gram-negative organisms.

The antimicrobial spectrum and properties of different agents have been tabulated in **Table 1**.

Agent	Mechanism of action	Action on bacteria	Action on spores	Example	Side effect
Alcohols	Denature proteins	Gram-positive, negative, mycobacteria, and viruses	None	Ethanol and isopropyl alcohol	Inflammable
Chlorhexidine	Disrupt cell membrane	Gram-positive and negative bacteria	none		Ototoxicity and conjunctivitis
Iodine / Iodophores	Bactericidal	Gram-positive and negative	Moderate action		Skin burns
Phenol derivatives	Cell membrane lysis	Gram-positive mostly		Lysol and cresol	Toxic to humans
Triclosan		Gram-positive and viruses			
Quaternary ammonium compounds		Mostly gram-positive	None	Cetavlon / cetrimide	Inactivated by organic matter, slow

Table 1.
Antimicrobial spectrum and mechanism of action of hand hygiene agents.

10. Hand hygiene technique

Hand washing is the ideal method of hand hygiene. It is done by applying an adequate amount of soap to hands, and rubbing them together vigorously, covering all surfaces of the hands and fingers. This is followed by rinsing hands with water and letting them dry in the air.

When doing the surgical hand scrub rings, watches, and bracelets should be removed beforehand.

When decontaminating hands with an alcohol-based hand rub, it is applied to the palm of one hand and rub the hands together, covering all surfaces of hands and fingers, until hands are dry. Alcohol-based hand rubs should be used as the preferred means for routine hand hygiene in healthcare, for both outpatient settings and those admitted. They have a broad antimicrobial spectrum compared to other agents; quick onset of action, better skin tolerability, and ease of administration with minimum need for training for correct use.

The effectiveness of the WHO six-step hand hygiene (HH) technique in reducing microbial load on hands and covering hand surfaces was reviewed, and compared with other techniques. Eight studies included in this systematic review found that the WHO six-step technique reduced microbial load on healthcare workers' hands, but the studies were heterogeneous and further research is required to identify the most effective, yet feasible technique [5].

11. Areas to be checked for ensuring hand hygiene

Only cleaning hands with an antiseptic is not sufficient for the prevention of transmission of infection. Other factors that have to be looked into are:

1. The periungual region as a source of bacterial pathogens. Subungual areas of the hand harbor high concentrations of bacteria, most frequently coagulase-negative staphylococci, gram-negative rods (including *Pseudomonas* spp.), *Corynebacteria*, and yeasts majority of bacterial growth occurs along the proximal 1 mm of the nail adjacent to subungual skin. There is increased growth of bacteria from long nails, artificial nails, and under nails with chipped nail polish.
2. CDC has recommended that HCWs wear gloves to reduce the risk of personnel acquiring infections from patients, prevent healthcare worker flora from being transmitted to patients, and reduce transient contamination of the hands of personnel by flora that can be transmitted from one patient to another. There are several points to consider when using gloves. These do not provide a substitute for handwashing. Certain pathogens may contaminate the hands of healthcare workers despite the use of gloves, such as hepatitis B virus and herpes simplex virus. This may occur due to small defects in the gloves or while removing them. An important finding is the occurrence of latex allergy among people. Hence, it is important to ensure the availability of alternatives, such as vinyl, nitrile, or neoprene gloves.
3. Avoiding wearing of jewelry. Ornaments like rings have been shown to grow an excess colony count of bacteria, such as gram-negative organisms; hence, it should be avoided, especially in intensive care units.

12. Adherence to hand hygiene measures

Compliance with hand hygiene is poor as per several studies. Erasmus et al. analyzed 96 studies to report that the median compliance rate was only 40% among

healthcare workers. Healthcare workers had a 21% and 47% compliance rate with hand hygiene before and after patient contact, respectively [6]. Zilágyi et al. reported that only 72% of healthcare workers could adequately clean all hand surfaces immediately after hand hygiene training [7]. Hence, it has been recognized to give feedback to the healthcare workers to improve this basic health practice.

13. Reasons for poor adherence to hand hygiene

Hand hygiene products, such as hand rubs, may not be adequately available in hospitals, in proportion to the number of healthcare workers or patient load. The healthcare worker may find it cumbersome to go to the washing basin and use soap and water between patients, especially in overcrowded wards. Moreover, the sink may be located at a corner of the patient observation area, leading to the need for the significant time being spent on the disinfection of hands alone. Often the soap dispenser may be empty making the entire task futile. Therefore, many healthcare providers may prioritize patient care rather than hand hygiene. Several healthcare workers may believe that wearing gloves can be a substitution to use of hand hygiene. Many workers are not motivated enough, are not aware of the benefits of hand washing, or are simply forgetful; hence, do not use hand sanitization methods. Sometimes healthcare workers develop irritant dermatitis upon frequent exposure to hand rubs, which can act as a deterrent to further use.

14. Adverse effects of hand hygiene products

These products can lead to allergic/contact dermatitis. The use of antimicrobial agents may minimize dermatitis, but can lead to dryness and irritation. Alcohol-based hand rubs are effective alternatives, especially those containing glycerin acting as an emollient.

15. Methods used to promote improved hand hygiene

Hand hygiene is a practice to be inculcated in our daily practice rather than a policy to be preached. Several methods have been used over time to encourage healthcare workers to sanitize their hands before and after patient exposure. It has been noted that hand hygiene can be encouraged by health education, health promotion practices, and a positive health-seeking attitude [8].

Spreading education *via* leaflets, lectures, and putting up charts as visual reminders and involvement of institution heads is recommended to reiterate among the healthcare workers. Availability of adequate hand sanitizers, dispensers containing handwashing soaps, and designated washing area should be of utmost importance to ensure compliance. When handwashing is difficult, as in a busy clinic, use of alcohol-based hand rubs should be used instead. These take less time and are faster and more acceptable. There should be a provision of small bottles of antiseptic hand rubs that can be carried by healthcare workers in their pockets to ensure compliance. An automatic dispensing machine is user-friendly method to provide easy access to hand sanitizer at key points in the hospital or public gathering. Hand hygiene adherence and promotion involve factors at both the individual and system level.

Adherence should be ensured verbally and also by surprise hand culture monitoring and rewarded occasionally.

16. Steps to monitor hand hygiene

Hand hygiene is an integral part of patient care as it ensures the best possible care at a facility with the least risk of cross infections. However, this is not practically followed for several reasons. Hence, monitoring hand hygiene practices and providing HCWs with feedback regarding their performance are essential to promote compliance. Some of the methods recommended are direct observation by trained auditors, self-reporting by health professionals, or using fluorescent UV lamps to detect surface coverage hand hygiene products. Self-reporting tends to overestimate hand hygiene and cannot be used to assess the quality.

Newer methods are used that can electronically monitor the compliance and quality of hand hygiene [9]. Compliance monitoring systems include application-assisted direct observation, camera-assisted observation, sensor-assisted observation, and real-time locating systems (RTLs). Quality monitoring systems include measuring compliance with the WHO six-step hand hygiene techniques and detecting surface coverage or illumination reduction of fluorescent substances. Camera-assisted observation requires human resources for monitoring, which can be avoided by sensor-assisted observation. However, electronic dispensers cannot detect the hand hygiene opportunities specified by the WHO 5-moments for hand hygiene. The RTL was originally used to identify and track the location of objects or people in real time within a specified area. By sensing dispenser actuation and HCWs' movements, servers from an RTL can measure HCWs' hand hygiene compliance rates as the ratio of dispenser actuation to the patient room or area entry or exit events. To assess the quality of hand hygiene, one key step is to measure the duration of hand washing. Other methods include installing sensors that detect hand motion to ensure the steps of hand washing are being carried out in sequence. Fluorescent UV lamps that detect microbiological efficacy following hand hygiene have low cost, but can be time consuming and can only be used on a limited sample size.

Implementing an electronic hand hygiene monitoring system in healthcare facilities comes with high costs and infrastructure, a big deterrent to their installation.

17. Hand hygiene and COVID-19 pandemic: before vs. after

Healthcare workers' hands are considered to be the important source for transmission of pathogens; thus, effective hand hygiene is the single most important action to prevent HAI. COVID-19 pandemic has truly served as a wake-up call in this regard. During the COVID-19 pandemic, the compliance of healthcare providers' HH showed a great improvement. The fever clinics have become the focused departments for HH monitoring. The estimated overall hand hygiene compliance (HHC) was 74%, which was higher than that reported in previous studies (5–89%). Nurses had the highest HHC, while auxiliary workers had the lowest. For the WHO 5-moments, the healthcare providers had the highest HHC after contact with the body fluids of the patients, while before contact with the patient, healthcare providers had the lowest HHC, which was consistent with before the pandemic [10].

18. Recent measures to improve hand hygiene

1. The six steps of handwashing are a useful practice introduced by WHO to ensure the complete cleansing of hands. The steps are to apply adequate liquid soap to rub the palms against each other, followed by the back of the hands with fingers interlacing in both steps. This is followed by rubbing the backs of fingers to opposing palms with fingers interlocked and then rotational rubbing of the left thumb clasped in the right palm and *vice versa*. The clasped fingertips should be cleaned in step five by the rotational movements against the palms and the process is completed by scrubbing the wrists. Regions such as fingers, knuckles, and thumbs have a high density of hidden organisms.
2. The WHO 5-moments of hand hygiene have been introduced.
3. The World Hand Hygiene Day (WHHD) theme for 2022 is a “healthcare quality and safety climate or culture” and the slogan is “unite for safety: clean your hands.” It was celebrated on May 5, 2022.

19. Conclusion

Hand hygiene is one of the most cost-effective measures to prevent infection and a core measure in improving the patient outcome in the healthcare settings. During the COVID-19 pandemic, hand hygiene received unprecedented attention and became a central pillar amongst all IPC strategies. Alcohol-based hand rubs (ABHRs) are the gold standard for the conduct of hand hygiene, because of their cost-effectiveness, availability, their water independence, and proven effectiveness in reducing microbial load. HH compliance depends largely on personal, institutional, and product-related factors. Education and auditing at appropriate time intervals improve compliance effectively and can be optimized through electronic devices.

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Section 3

Inclusivity and Social Equity

Leadership, Openness, Ethics, and AI: Navigating Uncertainty in Education

Ebba Ossiannilsson

Abstract

Global education is changing rapidly due to disruptions and global challenges aligned with UNESCO's 2030 Agenda. These shifts are redefining educational paradigms and require adaptive, ethical, and inclusive leadership capable of navigating uncertainty and supporting sustainable transformation. As learning ecosystems expand, leaders face increasing complexity accelerated by digital transformation and AI-driven innovation. AI presents opportunities for personalized learning, streamlined processes, and informed decision-making, while also raising ethical, governance, and accessibility concerns that demand responsible, human-centered leadership. This perspective chapter examines how leadership, openness, ethics, and technology intersect to shape the future of education. Drawing on desktop research, professional practice, and ongoing studies, it presents a reflective, forward-looking framework for leadership in the age of AI. Rather than providing empirical data, the chapter synthesizes existing knowledge and offers conceptual and anticipatory insights relevant across the diverse higher education contexts. Central to the discussion is the “three Cs” leadership framework – Care, Curiosity, and Challenge – identified as core dimensions of inclusive, resilient, and adaptive leadership. These principles foster empathy, agility, and innovation, equipping leaders to respond to evolving demands in the post-digital era. The framework outlines a values-driven pathway for inclusive, sustainable, and scalable leadership and supports enablers such as openness and global collaboration. Aligned with SDG 4 on quality education and SDG 17 on partnerships, the chapter emphasizes ethical and collaborative practice as foundations for transforming leadership. It concludes by reflecting on AI's role in higher education, highlighting both its transformative potential and the ethical imperatives required for a just, human-centered digital future.

Keywords: AI, education, ethics, Leadership, openness, three Cs framework, uncertainty

1. Introduction

Global education landscapes are transforming at an accelerating pace, driven by complex global challenges aligned with UNESCO's 2030 Agenda [1]. These include

demographic shifts, sustainability imperatives, rapid technological advancements such as artificial intelligence (AI), the deepening digital transformation, evolving societal expectations, and the long-term effects of the COVID-19 pandemic. Together, these forces create pervasive uncertainty that demands adaptive and ethically grounded leadership [2–9]. In response, the European Commission’s strategy for the digital transformation of education emphasizes the need for resilient, inclusive, and future-oriented educational leadership [5]. To navigate this dynamic environment, leaders must demonstrate agility, foster collaborative and inclusive decision-making, and embrace the principles of open education to ensure learning remains accessible, high quality, scalable, and sustainable [10–12]. The overarching research question explores the intersections of leadership, openness, ethics, and technological advancement—particularly AI—in shaping the future of education and leadership amid uncertainty. This chapter develops a conceptual framework that promotes inclusive, sustainable, and transformative leadership grounded in the three Cs—Caring, Curiosity, and Challenge—core principles of the International Council for Open and Distance Education (ICDE) Strategic Plan 2025–2028 [11, 12]. These dimensions guide leadership practices that foster resilience, agility, and adaptability in an unpredictable world. A desktop research design was employed to synthesize existing knowledge efficiently and transparently [13]. Secondary data from peer-reviewed journals, policy documents, industry reports, and credible gray literature published within the past five years were systematically analyzed. Searches using key terms such as *ethical leadership*, *sustainability*, *paradigm shift in global education*, *leading through uncertainty*, and *AI in education* were conducted across major academic databases. A thematic analysis identified recurring patterns related to ethics, openness, sustainability, and AI, ensuring a comprehensive and credible understanding of leadership through uncertainty.

The structure of the chapter is as follows. After this brief introduction (1), the research questions, and the method, a short overview of the paradigm shift in global education is given, including the role of open education for a better world and the implementation of UNESCO’s Agenda 2030 with its SDG4—Quality Education for All, Leaving No One Behind (2). AI in education, opportunities, and challenges is discussed (3). AI in ethical leadership is then examined (4). It then explores the three Cs for ethical leadership and the journey through uncertainty for sustainable, scalable, and inclusive education with care, curiosity, and challenge in the age of AI (5). This is followed by a section looking at the key challenges of AI in an ever-changing learning environment from a critical and forward-looking perspective (6), before discussing the prospects of AI in education and leadership as we move toward inclusive, ethical, and transformative learning systems (7). Finally, conclusions and further recommendations are discussed (8).

2. The changing paradigm in global education

The global education sector has been transformed by rapid technological innovation, the rise of online learning, and the increased accessibility of digital resources. Some of the key global changes are (i) climate change and environmental sustainability, (ii) change in global demographics, (iii) increase in the elderly population, (iv) unforeseen crises such as climate, wars, health crises, and diseases, (v) change in demands of the labor market, (vi) lifelong learning and skills development, with AI-driven platforms supporting continuous learning, upskilling, and reskilling,

to meet the changing needs of the workforce, (vii) globalization and glocalization in education, where educational institutions need to balance global best practices with local needs to ensure cultural and contextual relevance, (viii) the digital transformation of education and the proliferation of digital tools, platforms, and AI-driven solutions that are changing the way students learn and teachers teach, and (ix) hybrid and online learning models, where institutions around the world have adopted blended learning approaches to ensure continuity and flexibility in education, not least post-COVID19 and the responses to it. The COVID-19 pandemic has underscored the need for resilient and adaptable education systems and highlighted the importance of flexibility, innovation, and equity in learning. In addition, challenges such as the digital divide, data privacy concerns, and the need for sustainable educational practices require a strategic leadership approach [2].

A few years ago, with the advent of the fourth industrial revolution, there was a call for collaborative, forward-looking strategies to ensure that technological progress serves humanity and promotes equal access to knowledge. In his 2017 publication *The Fourth Industrial Revolution*, Klaus Schwab [14] argued that humanity is on the cusp of a transformative era that will fundamentally change the way we live, work, communicate, perform, interact with each other, and even the way we learn. Unlike previous industrial revolutions, this fourth phase is characterized by a fusion of new technologies that integrate the physical, digital, and biological spheres. These developments are transforming disciplines, economies, and industries worldwide and even redefining what it means to be human. Schwab believes that this era brings with it both immense opportunities and serious risks. He envisions a world in which billions of people could be connected via digital networks, greatly increasing organizational efficiency and enabling more sustainable resource management—potentially reversing the environmental damage caused by previous industrial revolutions. Nevertheless, Schwab also expresses profound concerns. He identifies five key challenges: (i) the risk that organizations will struggle to adapt, (ii) that governments will not be able to effectively implement and regulate the new technologies, (iii) that emerging power shifts could lead to new geopolitical tensions, (iv) that socio-economic inequality could deepen, and (v) that social cohesion could erode. Placing these technological changes in a broader historical context, Schwab outlines the key innovations driving this revolution and examines their impact on governments, businesses, civil society, and individuals. He emphasizes the need for a coordinated and comprehensive global response and calls for collaboration across countries, sectors, and disciplines. At the heart of Schwab's analysis is the conviction that the fourth industrial revolution can be shaped for the common good—if humanity acts proactively and inclusively. He calls on leaders and citizens alike to co-create a future centered on human well-being and to use technology as a tool to empower and advance people. Ultimately, Schwab emphasizes that the biggest challenge is not only to harness these advances but also to ensure that they serve the broader interests of society. With the introduction of AI in education from November 2022, new opportunities and pitfalls have emerged [15–18]. AI technologies offer personalized, adaptive learning systems and improved educational tools, such as intelligent tutoring systems and AI-curated Open Educational Resources (OER). However, these benefits are offset by serious challenges in terms of data privacy, algorithm bias, and the potential erosion of critical thinking skills. Future educational strategies must therefore prioritize inclusive data practices and human-centered design. More recently, Risse [19], like Schwab, argues that the emergence of far-reaching technological innovations,

from artificial intelligence to big data, has increasingly shaped human existence in digital lifeworld's. Although these developments have changed the way we live on an unprecedented scale, our political practices have not kept pace with these significant changes. Risse has laid a foundation for the philosophy of technology that allows for an analysis of how the digital age can change fundamental political practices and ideas. He extends key concepts of political philosophy to address issues in digital environments, such as AI and democracy, synthetic media, surveillance capitalism, and how AI might affect our understanding of the meaning of life. His research provides a comprehensive framework for assessing the impact of AI, allowing us to predict and understand the impact of technological advancement on our political systems in a timely manner. AI offers enormous potential to improve education, including personalized learning, automation of administrative tasks and data-driven decision-making. However, it also brings challenges, such as ethical concerns, bias, accessibility issues, and complex governance issues [20–23]. These paradigm shifts require adaptable ethical leadership that combines scalable, sustainable, and inclusive education with three core values: Caring, Curiosity, and Challenges [11, 12]. This approach is essential to successfully navigate the dynamic and unpredictable educational landscape.

3. AI in education: Opportunities and challenges

This section analyzes the opportunities and challenges of artificial intelligence in education. Personalized learning and adaptive education, AI-supported OER, intelligent tutoring systems, and virtual assistants as well as AI applications in assessment and quality assurance are examined. The following four goals are of particular importance when using AI in education [16–18, 20]:

- *Personalized learning and adaptive education:* AI-driven platforms can analyze student data to personalize learning experiences. Intelligent tutoring systems and adaptive learning environments can dynamically adapt to individual learning needs. AI-powered platforms can provide real-time feedback and personalized learning plans. These technologies lead to better learning outcomes by tailoring lessons to content, mode, style, type, media, and languages. However, the biggest challenges include ensuring data privacy and the ethical use of student data.
- *AI-powered OER:* AI is capable of curating, tagging, and recommending OER based on user preferences, making educational resources more accessible and customizable. UNESCO's OER initiatives, for example, use AI tools to classify resources. The benefits include better accessibility and efficiency in content delivery. However, a major challenge is to ensure that AI-generated recommendations are unbiased and culturally inclusive [6, 24, 25].
- *Intelligent tutoring and virtual assistants:* Modern AI-powered tutors and chatbots offer learners real-time support, automated assessments, and personalized guidance. These tools provide learners with continuous support and increase their engagement. However, a potential drawback is the risk of over-reliance on AI, which can impair critical thinking skills and reduce human interaction in the learning process.

- *AI in assessment and quality assurance:* Automated assessment tools can improve grading and feedback processes by ensuring consistency and fairness. An example of such an AI-powered tool is Turnitin's plagiarism detection system. The benefits include time-efficient and objective assessment processes. However, a challenge associated with these tools is the potential for algorithmic bias and ethical concerns associated with AI-assisted grading [26].

4. AI in educational leadership

In this section on AI in educational leadership, explore some examples of its application and the associated benefits and challenges. Three key areas are in focus: (i) artificial intelligence as a strategic tool for educational leadership, (ii) artificial intelligence and institutional digital transformation, and (iii) ethical artificial intelligence governance and leadership. Below is a summary followed by examples categorized for policymakers, school administrators, and academic researchers.

4.1 Artificial intelligence as a strategic tool for educational leadership

Artificial intelligence supports education leaders by transforming complex institutional data into actionable insights. Using advanced analytics, AI can identify patterns and trends in student performance, institutional efficiency, and operational needs. This enables more informed and strategic decision-making, particularly in areas such as budgeting, staffing, curriculum development, and student support. Artificial intelligence provides robust tools for educational strategy development through data-driven insights into systemic trends and institutional performance [27–29]. By analyzing comprehensive education data, AI identifies areas of need, assesses the impact of existing interventions, and guides evidence-based policy formulation. For education leaders, AI provides valuable insights by scrutinizing institutional data, identifying trends and optimizing resource allocation [27, 29].

In summary, AI can be used to analyze student retention and academic success. The benefits are mainly in supporting proactive interventions and strategic improvements. The challenges are the risk of relying too much on data without human oversight.

4.1.1 For policymakers

Artificial intelligence offers valuable tools for education policy development by providing data-driven insights into systemic trends and institutional performance. By analyzing comprehensive education data, AI helps to identify areas of need, assess the impact of current policies, and formulate evidence-based strategies. One example is predictive analytics, which can be used at a policy level to understand the factors influencing school dropout rates and to develop interventions aligned with national or regional educational goals. It enables proactive, scalable strategies that improve equity, access, and outcomes across the education system while increasing the efficiency of public resource allocation. One challenge may be that policymakers must remain vigilant regarding the ethical use of AI. Over-reliance on algorithmic insights without human judgment can exacerbate systemic biases and overlook contextual factors that are critical to educational equity and inclusion.

4.1.2 For school administrators

Artificial intelligence technologies can be used as a decision-support tool in institutional management by helping school and college administrators turn institutional data into strategic insights. In areas such as resource management and student support, AI improves the ability to anticipate challenges and plan more efficiently. One example is that predictive analytics systems can identify students at risk of academic failure early in the semester, allowing administrators to coordinate academic and social support in a timely manner. This means AI can enable smarter allocation of resources, improve student retention and success, and support a more agile response to institutional challenges. While AI can help with operational decisions, it should complement, not replace, professional judgment and the experience of educators. Human oversight is essential to ensure ethical, inclusive, and student-centered practices.

4.1.3 For academic researchers

Artificial intelligence is both a methodological tool and an important field of research for researchers. It enables the analysis of large, complex datasets to identify patterns that support theoretical development, pedagogical improvements, and the optimization of institutional efficiency. Machine learning models can be used to examine the longitudinal effects of teaching methods on different groups of learners. Such methodological tools can improve the rigor and scope of educational research, and support the development of evidence-based strategies that are aligned with learner needs and institutional goals. However, researchers need to critically evaluate algorithmic biases, the transparency of AI models, and the epistemological implications of data-driven knowledge production in education.

The strategic use of AI in education is represented by the Insights-Actions-Ethics model, including the feedback loop, as shown in **Figure 1**. The figure illustrates that

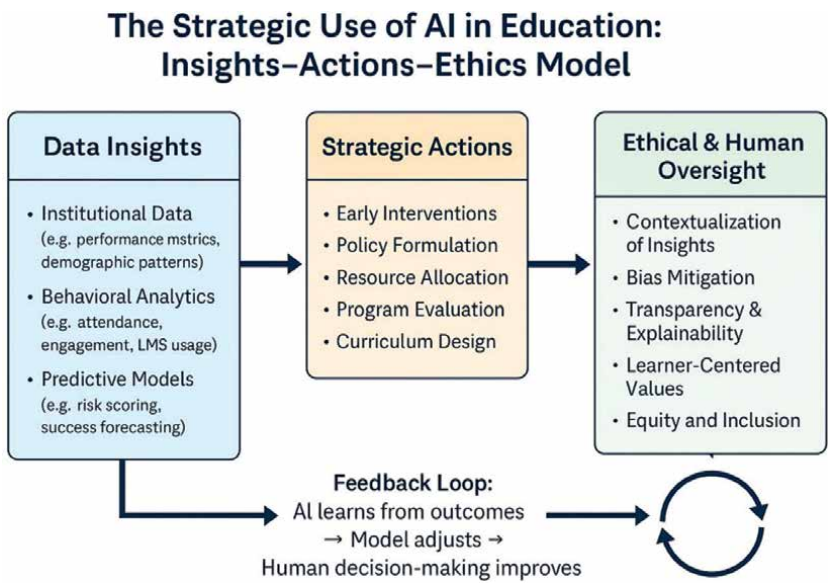


Figure 1.
The strategic use of AI in education: insight-action-ethics model, including the feedback loop (created by ChatGPT).

data insights lead to strategic actions, as early interventions, policy formulations, resource allocation, program evaluation, and curriculum design, which in turn lead to ethical and human oversight. The feedback loop shows how AI learns from its output, while human decision-making improves.

4.2 AI as a catalyst for digital transformation in education

AI plays a crucial role in driving digital transformation in higher education institutions. By automating routine administrative functions, improving communication channels, and optimizing digital platforms such as learning management systems (LMS), AI helps institutions become more agile, efficient, and learner-centric [27–29]. AI-driven chatbots can handle a wide range of student requests—from admissions to course registration to technical support—providing a 24/7 service and freeing up staff for more complex tasks. The benefits are clear: institutions benefit from reduced administrative burden, faster service delivery, and an improved user experience for students and staff. The challenges are that AI adoption is often hindered by institutional resistance to change, concerns about staff churn, and persistent digital inequality that limits access to transformative technologies.

4.2.1 For policymakers and for school administrators

Artificial intelligence is a fundamental element in the modernization of higher education systems. By automating administrative processes and optimizing digital platforms, AI supports systemic change that shapes an equitable digital transformation that improves institutional efficiency and student engagement. For example, government-backed AI tools, such as multilingual chatbots can support national education strategies by improving access and service delivery for diverse populations. This can enable scalable digital solutions that reduce costs, improve educational equity, and support lifelong learning goals. However, it can be a challenge to tackle digital inequality by investing in infrastructure, education, and inclusive policy frameworks to ensure that AI does not widen the digital divide.

4.2.2 For academic researchers

Artificial intelligence is a powerful tool for studying institutional change and educational innovation. Its application in automating systems and enhancing learning environments is changing the digital transformation of the educational landscape and raises important research questions. Research on AI-powered student support systems (e.g. adaptive LMS and dialog agents) shows that they have the potential to scale services and support different learning needs. It lends itself to examining the impact of AI on institutional governance, staff roles, and student outcomes, and exploring ethical and equitable inclusion in digitally transformed institutions. The challenges are to explore how resistance to change and digital exclusion impact the adoption of AI, and propose models of inclusive design to mitigate these issues.

4.3 Ethical AI governance and leadership in education

As artificial intelligence is increasingly integrated into educational environments, strong ethical leadership is essential. Leaders must proactively address important

issues, such as algorithmic bias, data privacy, and the transparency of AI systems [30–33]. Establishing clear governance structures and ethical guidelines will ensure that AI is deployed in a way that supports fairness, accountability, and the overarching goals of education. Frameworks such as the European Union AI Law [28] and the UNESCO Recommendation on the Ethics of Artificial Intelligence provide comprehensive guidelines for the responsible development and use of AI and can serve as good examples [34]. The benefits are that institutions gain credibility and public trust through responsible innovation while minimizing legal and ethical risks. The challenges are that education leaders must strike a delicate balance between embracing innovation, complying with new regulations, and ensuring ethical integrity throughout the AI lifecycle.

4.3.1 For policymakers

Policymakers play a crucial role in setting the ethical boundaries for AI in education. By establishing ethical AI governance and legislation at national and global levels, and through collaboration, policymakers can create a framework that ensures fair and responsible use of AI. AI risk classifications and regulatory obligations, as well as ensuring transparency and human oversight in education systems, are set out in the EU AI law [28] for example. This includes harmonizing AI ethics internationally, supporting institutions with policy instruments and ensuring that the use of AI in education respects human rights and democratic values. However, developing adaptable regulatory models that keep pace with AI innovation without stifling its transformative potential could be a challenge.

4.3.2 For school administrators

As pioneers in the adoption of AI tools, school and university leaders are responsible for setting internal standards for ethical leadership in an AI-driven educational environment. This includes establishing review boards, ensuring transparency in AI applications, and training staff in ethical decision-making. One strategy is to establish an institutional ethics committee to review the use of AI-powered learning analytics to avoid unintended bias in mentoring students. This approach could foster a culture of trust that protects student data and ensures that all AI tools are aligned with institutional values. The key is to navigate within the ecosystem and resolve the tension between innovation requirements, regulatory compliance, and ethical leadership with limited time and resources.

4.3.3 For academic researchers

Academic researchers are in a unique position to question the ethical implications of AI in education, both as analysts and innovators. Their role is to explore and inform ethical AI practices in education. Their work helps to develop evidence-based governance models and inform institutional policy. Studies examining algorithmic bias in AI assessment systems underscore the need for transparent and accountable machine learning models. With interdisciplinary research on AI ethics, there is an opportunity to investigate the power dynamics in algorithmic decision-making and develop evaluation frameworks for responsible AI in education. Finally, the gap between theoretical insights and practical applications in policy and leadership contexts needs to be bridged.

5. The three Cs for ethical leadership: Care, curiosity, and challenges in the era of AI

The core principles of **inclusivity, scalability, and sustainability** are inherently multifaceted. The ICDE Global Advocacy Campaign (GAC) taskforce in Europe has recently articulated how these principles shape open, online, distance, and technology-enhanced education (ICDE GAC, unpublished). **Inclusivity** is understood as a universal yet personalized approach that ensures equitable access, respect, and opportunity for all learners and staff. It values diversity without reducing individuals to their characteristics, emphasizing co-creation with students to design supportive digital and physical environments that foster engagement, critical thinking, and openness. **Scalability** refers to the capacity to expand learning and support systems dynamically while maintaining quality and accessibility. It relies on agile, interoperable, and ethical digital infrastructures, flexible pedagogical design, and institutional alignment to ensure consistent, high-quality experiences across diverse contexts. **Sustainability** entails building adaptable and ethical educational ecosystems that balance environmental, technological, economic, and human needs. It promotes eco-conscious digital practices, well-being, and resilience while embedding the UN Sustainable Development Goals to ensure higher education remains socially responsible, resource-efficient, and future-oriented amid ongoing global change.

The three other principles, i.e. Care, Curiosity, and Challenge, emphasize the need for leadership that not only sets direction but also fosters trust, cohesion, and inclusivity—key elements of a resilient academic culture. Ossiannilsson, Stratton-Maher, and Nerantzi [12] observe that leading universities increasingly incorporate interdisciplinarity, innovation, and inclusivity into their strategic frameworks, indicating a shift from structural to philosophical transformation. The three Cs thus offer a values-driven foundation that enables leaders to navigate uncertainty with clarity, compassion, and courage. Care consistently stands out as a cornerstone of effective leadership in turbulent times (Stratton-Maher, Ossiannilsson, Manousou, and Arumugam, unpublished), encompassing empathy, well-being, and ethical stewardship. It also supports inclusive leadership, ensuring that AI integration remains equitable, culturally responsive, and ethically grounded. Curiosity represents openness to innovation, responsiveness to emerging trends, and a strong commitment to lifelong learning in the evolving context of AI and digital transformation. It requires leaders not only to develop technical understanding but also to ask meaningful questions, address ethical dilemmas, and collaborate across disciplines. Challenge, in turn, calls for courage, critical reflection, and principled decision-making amid uncertainty. As generative AI reshapes higher education, this dimension encourages leaders to move beyond passive adaptation toward purposeful transformation—shaping change ethically and strategically rather than merely responding to it.

5.1 Care-centered and ethical AI for inclusive educational leadership

In the age of AI, educational leadership must be based on an ethic of care, social justice, and a commitment to inclusion, scalability, and sustainability. Leaders are responsible for ensuring that AI technologies actively promote equity, respect diversity, and provide equitable access to digital learning environments. This includes developing and deploying AI tools that are accessible to all learners, such as real-time

captioning, screen readers, and adaptive learning platforms that support students with disabilities or language barriers, especially those from marginalized or under-represented communities. The benefits are improved digital equity and meaningful participation for all learners, leading to more equitable and inclusive educational experiences. One of the bigger challenges is dealing with algorithmic bias, data inequality, and the potential exclusion of vulnerable populations when there is a lack of ethical design and oversight. ICDE emphasizes in its strategy [11] the importance of creating and fostering a culture of care, curiosity, and challenge for inclusive, scalable, and sustainable education, in line with the UNESCO 2030 Agenda. This was also underlined at the Global Presidents' Forum [10] with ICDE's new Technology and Innovation Networks [34] and Open Education Network [35].

5.1.1 For policymakers

Political leaders and policymakers who advocate for inclusive and ethical AI in education have a duty to ensure that the adoption of AI in education serves the public good and protects vulnerable groups. Policymakers must mandate ethical, equity-based standards in AI development, support inclusive technology design, and invest in accessible infrastructure. National or regional policies are needed to mandate that AI tools used in public education meet accessibility and non-discrimination standards. Policymakers could create a legal framework that embeds inclusion, equality, and the ethical use of AI in national education strategies. Addressing systemic inequalities in data access and digital infrastructure, particularly in rural or underserved communities, is one of the policy challenges.

5.1.2 For school administrators

Educational leaders must use ethically inclusive AI in a way that supports all learners, especially those who have been excluded from full participation in the past. This means selecting inclusive tools, including diverse voices in decision-making and ensuring accessibility across all digital platforms. An example of this is the procurement of LMS platforms with AI-powered features that adapt content to visual, auditory, or cognitive impairments. A learning environment that is inclusive from the outset, rather than created as an afterthought, builds trust and belonging among diverse groups of students. One challenge can be ensuring that staff are trained to recognize bias in AI outcomes and align AI tools with the school's values of caring, equity, and diversity.

5.1.3 For academic researchers

Researchers play a key role in critically examining how AI relates to issues of equity, care, and social inclusion in education. They can evaluate the experiences of marginalized learners with AI systems and explore how inclusive AI can be co-designed with communities. Participatory action research that involves students with disabilities in the co-design of AI-based learning tools is just one example. Developing frameworks for algorithmic fairness, inclusive design, and ethical care in AI systems tailored to education are research opportunities. It can be challenging to challenge normative assumptions in AI datasets and address gaps in representation in sociocultural and linguistic contexts.

5.2 Curiosity as a catalyst for innovation and lifelong learning in AI-enhanced education

Cultivating a culture of curiosity is essential to fostering innovation and resilience in the evolving educational landscape. In the context of AI, curiosity encourages experimentation, adaptability, and the pursuit of lifelong learning. Educational leaders and institutions that embed curiosity in their organizational culture are better able to explore new technologies, challenge assumptions, and co-create sustainable learning ecosystems [11, 23]. One explicit example is professional development programs that encourage educators and leaders to explore AI tools, experiment with pedagogical applications, and co-create new practices. Building a dynamic learning culture that supports curiosity, empowers educators, and encourages proactive engagement with technological change is critical as a catalyst for innovation. Rapid advances in AI require continuous learning, flexibility, and institutional support to avoid stagnation or tech fatigue, which is always a challenge.

5.2.1 For policymakers

Fostering curiosity and a culture of innovation at system level means creating policies that incentivize innovation and invest in continuous professional learning. Policies should support experimental spaces in education, fund lifelong learning opportunities, and promote ethical research in AI. One example is national AI innovation centers that fund educators and institutions to test new AI tools and share the results. Policies that position lifelong learning as a cornerstone of national AI strategies and ensure that educators can lead change, not just react to it. Designing long-term professional development frameworks that are flexible, inclusive, and responsive to the rapid pace of AI development is always a challenge at the policy level, but especially in communicating such strategies within the organization.

5.2.2 For school administrators

School and institutional leaders can exemplify curiosity-driven leadership by enabling innovation through lifelong learning and creating safe spaces for AI exploration, experimentation, and collaboration. Encouraging inquiry, providing time for professional reflection, and recognizing innovation are important actions. This can be done by establishing “innovation fellowships” or AI learning laboratories in schools where educators can explore new tools and share their findings. This can strengthen internal capacity for AI integration, encourage employee engagement, and ensure that innovation is placed in the right context. However, it is a challenge to balance day-to-day operational requirements with the need for continuous, meaningful professional development in the context of rapidly changing technologies.

5.2.3 For academic researchers

For researchers, curiosity is the driving force to explore the role of AI in innovating and transforming learning and institutional practices. Research informed by curiosity leads to interdisciplinary collaboration, critical inquiry, and the reshaping of the future of education. Collaborative action research can pave the way to explore how AI can improve personalized learning or assessment practices. Good research opportunities

include developing models for inquiry-based AI learning, analyzing curiosity as a leadership trait in digital transformation, and creating case studies of innovation in practice. A balance and challenge are maintaining critical curiosity in the face of hype cycles and resisting pressure to adopt AI without evidence-based testing.

5.3 Challenges on navigating the complexities of ethical AI, Leadership, agility, and institutional resilience

The integration of artificial intelligence into education holds not only transformative potential but also critical challenges. Effective leadership in this area requires challenging legacy systems, promoting institutional flexibility, and building organizational resilience. Leaders must champion ethical AI practices, proactively address risks such as algorithmic bias, data misuse, and data breaches, and guide their institutions through change while upholding human-centered values [28]. National or institutional policies mandating ethical audits, stakeholder consultations, and transparent AI procurement processes in educational institutions are considered good examples. This promotes responsible, sustainable use of AI that builds trust, reduces harm, and supports long-term innovation. However, resistance to change is always a challenge, often caused by uncertainty, fear of disruption or lack of preparation, and can undermine the successful integration of AI in education.

5.3.1 For policymakers

Policymakers need to anticipate and mitigate the unintended consequences of AI by building regulatory ecosystems and creating comprehensive frameworks that ensure ethical use, resilience, institutional flexibility, and public accountability for the adoption of AI in education. Educational institutions need support mechanisms in adapting to AI, which requires legal clarity, resource allocation, and strategic foresight. National AI education strategies that include ethical guidelines, public funding for resilience building, and regulatory sandboxes for testing AI in controlled environments are one such example. Policymakers can design a values-driven digital transformation that is agile yet ethically grounded and has guardrails to protect the public interest. The challenges addressed require a balance between incentives for innovation and monitoring mechanisms, as well as equitable implementation in different education systems.

5.3.2 For school administrators

Leaders in schools and universities must not only understand the opportunities presented by AI but also actively prepare their organizations to adapt, pivot, and respond to the technical and ethical demands of implementation. This requires forward-thinking leadership: ethical AI, readiness for change, and institutional resilience. It also requires internal training and capacity building, open dialog, and systems thinking. By establishing cross-functional AI task forces that include IT, faculty, legal, and students to assess and guide implementation, this ecosystem will set an example that paves the way for inclusion, scalability, and sustainability. This improves institutional adaptability, reinforces ethical standards, and ensures that change is inclusive and grounded. Challenges can include cultural resistance, resource constraints, and competing priorities, which can slow down AI integration if change is not strategically managed.

Leadership through Uncertainty



Figure 2.
The intersections of leading through uncertainty with a culture of care, curiosity, and challenges in the era of AI for inclusive, scalable, and sustainable education (Created by Author).

5.3.3 For academic researchers

Researchers play an important role in exploring the structural, social, and philosophical implications of AI in education. In doing so, they often encounter tensions between innovation, ethics, technological progress, and ethical governance. There is a need to explore how institutions deal with uncertainty and change. Examples include longitudinal studies of how universities adapt to changes brought about by AI in administration, pedagogy, or student support systems. Research can develop new models for adaptive leadership, ethical AI ecosystems, and institutional resilience. However, it is difficult to account for the complexity and interdisciplinary nature of research and translate findings into actionable insights for policy and practice.

In this section, the three Cs were further explored, and examples were provided for the different stakeholders. **Figure 2** illustrates the intersections of leadership through uncertainty with a culture of care, curiosity, and challenge in the age of AI for inclusive, scalable, and sustainable education.

6. Key challenges of AI in an ever-changing learning environment: A critical and future-oriented perspective

The increasing integration of artificial intelligence into the education system harbors both opportunities and complexity. While AI has the potential to improve access, personalization, and efficiency, it also raises critical questions about equity, human agency, and long-term impact. In an educational landscape characterized by rapid change, addressing these challenges requires proactive, ethical, and systemic approaches [12, 15, 28].

AI systems are only as fair as the data and assumptions on which they are based. Critical insights are that biased algorithms can replicate and reinforce existing social inequalities, leading to discriminatory outcomes in areas, such as admissions,

assessment, and learner support. Algorithmic bias is not a technical glitch, but a structural problem rooted in social inequalities. AI can encode biases if not intervened at every level in data sourcing, model design, application, and interpretation. Solutions may include designing inclusive AI systems by integrating intersectional datasets, conducting impact assessments, and including diverse perspectives on development teams. Establishing oversight bodies to assess fairness and ensure the transparency of algorithms. The effectiveness of AI depends on the collection of large amounts of data, often containing sensitive personal information. Without strong safeguards, this raises serious concerns about privacy, surveillance, digital trust, consent, and learner autonomy. The datafication of learners' risks reducing individuals to behavioral profiles, which can undermine trust and violate rights, especially when commercial platforms are involved. The development of robust data governance frameworks that go beyond legal compliance, introduce ethical standards for transparency, informed consent and data minimization, and integrate decentralized and privacy friendly technologies (e.g. differentiated privacy, federated learning) could be an appropriate, resilient, and sustainable solution. To the extent that AI automates instruction, assessment, and student support, human-AI interaction and the erosion of pedagogical relationships are critical because there is a risk that meaningful human relationships—the cornerstone of transformative education—will be diminished or pushed back. The danger lies not in automation itself but in its uncritical adoption. Education is not just a question of transaction but more a question of relationship, emotion, and ethos. AI cannot map these dimensions. The solution could be to promote hybrid pedagogical models that combine the scalability of AI with the empathy, mentorship, and critical judgment of educators. Redefining the role of the educator as a human-AI collaborator and ethical advisor could be seen as crucial.

Many AI initiatives in education do not progress beyond the pilot stage or become obsolete due to vendor lock-in, financial constraints, or lack of system-wide integration. In addition, the development of AI has an impact on the environment that is often ignored in education planning. The long-term impact of AI must be measured not only in terms of innovation but also in terms of sustainability, interoperability, and equity across regions and generations. Develop national and institutional AI strategies that prioritize open standards, digital sovereignty, green computing practices, and collaborative public infrastructures. To achieve impact, AI adoption must be embedded in the broader goals of sustainable digital transformation and the ecosystem must be communicated, understood, and implemented. To think ahead and effectively address these challenges, AI must not just be seen as a set of tools but as a socio-technical system embedded in power structures, values, and visions of the future. Ethical foresight, participatory design, and proactive governance must be incorporated into the planning, implementation, and further development of AI in education. This will ensure that AI supports not only learning outcomes but also democratic values, ethics, human rights, inclusion, diversity, social justice, human well-being, scalability, and sustainability.

7. The future prospects of AI in education and leadership: Toward inclusive, ethical, and transformative learning systems

Artificial intelligence is rapidly changing the landscape of education and leadership. Far from being just a technological upgrade, artificial intelligence represents a profound shift in the way we conceptualize learning, teaching, and institutional

leadership. When viewed critically and ethically, AI has the potential to support the development of inclusive, equitable, and high-quality education systems that meet the complex demands of the twenty-first century [36–39]. However, realizing this potential will require visionary leadership, sound governance, and an unwavering commitment to social justice.

As AI increasingly informs decision-making—from student assessment and curricula design to the allocation of institutional resources—there is an urgent need for comprehensive ethical and governance frameworks to guide its use. This includes consideration of issues of data sovereignty, algorithmic accountability, equity, and human rights. There are needs to move beyond reactive approaches to risk mitigation to proactive governance that actively shapes the development of AI to align it with the values of education. This requires interdisciplinary policymaking, participatory design with different stakeholders (including learners), and transparent mechanisms for oversight and redress. In the future, national and international governance models need to be developed that are flexible, enforceable, and based on the principles of democracy, equity, and the common good. In the future, AI can support dynamic, competency-based education and learning models that tailor learning pathways to individual progress and mastery rather than traditional time-based measures. By analyzing learner interactions, performance, and preferences, AI systems can deliver personalized content, recommend appropriate challenges, and support just-in-time feedback. This can dramatically improve learner engagement and outcomes especially for those who have historically been underserved by standardized, one-size-fits-all education systems. This shift also raises important pedagogical and ethical questions. These questions include: (i) How can we ensure that such systems do not simply automate outdated teaching models? (ii) How can we preserve critical thinking, creativity, and human relationships in algorithm-driven environments? Going forward, it is therefore imperative to invest in the research and development of AI-powered competency-based education systems that focus on learner agency, cultural relevance, and depth of development, not just efficiency or performance metrics. Future strategies for implementing AI in education need to be sustainable and scalable, not only in financially and technologically terms but also in socially and environmentally terms. Many current implementations are short-term, fragmented, or vendor-dependent and risk disillusionment, inequality and waste. Scalability should not come at the expense of sustainability. Future strategies must prioritize open source ecosystems, digital sovereignty, teacher capacity building, and cross-sector collaboration. Environmental aspects, such as the carbon footprint of large-scale AI systems, must also become the focus of planning. Going forward, it is imperative that the adoption of AI is accompanied by long-term education transformation strategies that are inclusive, climate-aware, resilient, and encompass different educational contexts.

8. Conclusion and recommendations

This perspective chapter aims to provide a reflective, forward-looking framework for leadership under uncertainty. Its value lies in synthesis, conceptual framing, and future-oriented analysis rather than new data. It seeks to offer a strong, thought-provoking contribution to this book. The chapter conceptualizes leadership for inclusivity, scalability, and sustainability through the lens of the three-Cs leadership framework. Building on the foundational principles of inclusivity, scalability, and

sustainability, the three-Cs framework—Care, Curiosity, and Challenge—provides a complementary and practical approach for translating these values into leadership practice. It does not represent separate attributes but rather interdependent dimensions of effective, values-driven leadership. Together, the three Cs form an integrated and ecosystemic model that reflects the convergence of equity, ethics, innovation, responsiveness, and strategic risk-taking. This interconnection fosters a resilient, adaptive, and future-oriented leadership culture capable of meeting the complex demands of contemporary higher education. In an era marked by rapid change and pervasive uncertainty, higher education leadership must move beyond traditional paradigms to address the complexities of an AI-enabled and globally connected world. The three-Cs leadership framework advances the principles of the UN UNESCO Sustainable Development Goal 4 (Quality Education) by promoting inclusive, equitable, and high-quality learning for all. It also aligns with SDG 17 (Partnerships for the Goals) through its emphasis on glocalized collaboration and shared leadership, fostering innovation and resilience. By addressing educational equity, digital inclusion, and ethical leadership amid generative AI and global uncertainty, the framework provides a strategic, values-driven foundation for inclusive, sustainable, and scalable leadership in the evolving landscape of higher education. Leaders who demonstrate empathy, ethical integrity, and emotional intelligence are best equipped to guide institutions with purpose and adaptability. By fostering inclusive and collaborative cultures, embracing innovation with discernment, and exercising principled courage in decision-making, leaders can effectively navigate the ethical and strategic challenges of the postdigital era. Ultimately, this glocalized, human-centered framework offers a timely and theoretically grounded pathway for reimagining leadership in the future of higher education.

The chapter discusses the challenges and opportunities facing education leaders as they navigate the changing landscape of global education influenced by technology, societal demands, and recent uncertainties such as the COVID-19 pandemic. It highlights the potential of AI to improve education while highlighting ethical concerns and issues of access and governance. The need for resilient and adaptable education systems is emphasized, as are the principles of inclusivity and openness. The conceptual leadership framework with the three Cs—care, curiosity and challenge—is presented as essential components of ethical leadership for ethically effective, inclusive, scalable, and sustainable education. This promotes resilient, agile, and adaptable leadership values and approaches in an unpredictable educational landscape. AI in education and leadership presents both complex challenges and transformative opportunities. To maximize its benefits, stakeholders must adopt ethical AI governance, improve digital literacy, and promote inclusive education. AI strategies and collaborative global efforts will be critical to shaping the future of education. The path of AI in education is not predetermined, it will be shaped by the decisions of today's leaders. Leadership in education must be redefined in the age of AI to include ethical foresight, digital literacy, participatory engagement, and systemic thinking. Leaders must manage not only the technology but also values, narratives, and cultures that ensure AI serves the collective human good. If we want to create learning systems that are equitable, adaptable, and sustainable, then AI must be just more than a tool. It must become part of a larger societal dialog about what kind of education—and what kind of future—we aspire to. The future of global education depends not only on the technology but also on values we bring to its development and use. Leadership must evolve to integrate ethical foresight, participatory leadership, and caring action. Only by aligning AI with the principles of inclusion, equity, and sustainability,

learning systems that truly serve all of humanity can be built. AI promises to enable competency-based, adaptive learning systems that are tailored to individual progress. Future strategies must include ethical governance, prioritize open source development, support cross-sector collaboration, and empower educators. Leaders who are committed to the future of AI in education can balance the benefits of AI with their ethical concerns by taking a multifaceted approach that includes the strategies listed below:

- *Create an ethical governance framework:* Leaders should put in place a comprehensive ethics and governance framework that addresses algorithm accountability, privacy, and equity. This includes creating policies to ensure that AI tools are used responsibly and inclusively, and that their use is compatible with educational and social justice values.
- *Encourage collaborative decision-making:* Involving multiple stakeholders—such as educators, learners, and parents in the decision-making process—ensures that multiple perspectives are considered, which can help identify and mitigate potential ethical risks associated with AI implementations.
- *Encourage ongoing education and training:* Education leaders should invest in professional development that focuses on AI capabilities, including their potential benefits and ethical implications. This will equip employees with the knowledge and skills to critically evaluate AI applications and avoid pitfalls related to bias and discrimination.
- *Focus on inclusive AI design:* When selecting or developing AI tools, leaders should prioritize inclusive technologies that meet the diverse needs of learners. This includes ensuring that AI systems are accessible to marginalized groups and designed to improve equity in learning.
- *Maintain transparency and accountability:* It is important that educational institutions establish transparent processes for the use of AI systems. This includes being open about the data collected and how it is used, and creating mechanisms for accountability and redress in the event of negative outcomes.
- *Address algorithmic bias:* Leaders need to be aware of the possibility of bias in AI decisions. They should work with data scientists and ethicists to regularly evaluate and review the algorithms used in their institutions to ensure that they do not perpetuate existing inequalities or create new forms of discrimination.
- *Encourage ethical innovation:* By fostering a culture of care, curiosity, and challenge among faculty, leaders can encourage innovative uses of AI that are ethical. This includes not only adopting new technologies but also critically reflecting on their impact on learning and teaching.
- *Engage in policy:* Leaders can advocate for national and international policies that regulate the ethical use of AI in education and ensure that it complies with the principles of democracy, equity, and the common good. The creation of a comprehensive legal framework can help to mitigate the risks associated with the use of AI in educational institutions.

To ensure inclusion in the evolving educational landscape, education leaders can employ various strategies that focus on equity, accessibility, and community engagement. To promote an inclusive and equitable educational environment, it is important to implement the principles of *universal design for learning (UDL)*. UDL promotes the development of flexible learning frameworks that accommodate individual variability by providing multiple opportunities for participation, representation, and expression. This approach ensures that all learners, regardless of ability or background, are given equal opportunities to participate, access content, and demonstrate their understanding in different ways. It is equally important to ensure *accessibility of educational resources*. All educational materials, including digital content and AI-driven tools, must be designed to be accessible to students with disabilities as well as students from culturally and linguistically diverse backgrounds. This includes the integration of assistive technologies such as screen readers, real-time captioning, and adaptive learning platforms that support different learning needs. The *active involvement of multiple stakeholders* including students, parents, educators, and community members is critical in shaping the integration of educational technologies. A participatory decision-making process ensures that diverse perspectives are incorporated into the development and implementation of curricula and technology tools, promoting inclusivity and strengthening shared ownership of educational change. The use of AI-powered *personalized learning systems* offers significant opportunities to meet the diverse needs, abilities, and interests of individual students. By adapting instruction to the specific learning styles and pace of students, especially those who have been historically underserved, AI can contribute to a more responsive and effective learning environment. Inclusion must be systematically embedded through the *implementation of clear institutional policies and practices*. These policies should prescribe inclusive approaches to curriculum design, instructional methods, and technological applications to break down systemic barriers and provide equal access to learning opportunities for all students. *Ongoing professional development and training* for educators and administrators are essential to support inclusive practices. Such initiatives should address inclusive pedagogy, cultural competence, and the ethical use of educational technologies. A primary focus should be on recognizing and mitigating bias in both human and algorithmic decision-making processes in education. *Building strong partnerships with community organizations, advocacy groups, and local support services* can further enhance efforts to support marginalized students and their families. These collaborations expand access to important resources and contribute to a more comprehensive network of support for underserved populations. To maintain alignment with inclusive goals, it is necessary to regularly assess and review *educational policies and practices*. Establishing mechanisms to gather feedback, particularly from students and community stakeholders, can help identify gaps and areas for improvement and ensure that inclusion initiatives are both relevant and effective. In addition, creating *flexible learning environments* is key to accommodating learners' different preferences and circumstances. By enabling different teaching modalities, e.g. face-to-face, online and blended learning, educational institutions can offer more personalized and accessible learning experiences. Finally, it is essential to *advocate for the ethical use of AI in education*. Ethical frameworks should guide the development and use of AI tools to ensure inclusivity, fairness, and transparency. Particular attention must be paid to mitigating algorithmic bias and ensuring that technological solutions are validated and effective for diverse groups of learners. By implementing these strategies, educational institutions and educational leaders can foster for an inclusive environment that values diversity and promotes equitable

learning opportunities for all students, in a culture of caring, curiosity, and challenge for inclusive, sustainable, and scalable learning environment and education for all in line with the 2030 Agenda and the Sustainable Development Goals, especially SDG 4, but also many of the others, as SDG 4, influences, affects or leads to the achievement of the other goals.

In conclusion, this chapter contributes to the ongoing discourse on educational leadership by presenting a reflective and future-oriented framework for leading through uncertainty in the age of AI and digital transformation. By integrating the foundational principles of inclusivity, scalability, and sustainability with the interrelated dimensions of Care, Curiosity, and Challenge, it advances a glocalized, human-centered model of leadership grounded in ethics, empathy, and innovation. This synthesis highlights the need for leaders who can balance technological advancement with social responsibility, ensuring that transformation in higher education remains equitable, transparent, and purpose-driven. Ultimately, the framework calls for a paradigm shift—one that redefines leadership not merely as administration or governance but as a moral, adaptive, and transformative practice essential for shaping the future of global education.

Acknowledgements

This research is funded by the 2024 Youth Fund for Humanities and Social Sciences Research, Ministry of Education, China (Project No. 24YJC880123).

The author gratefully acknowledges the use of ChatGPT to confirm and enrich her own research and experience, and for her reflections based on the reference evidence of the benefits and challenges for stakeholders described in Sections 4 and 5. **Figure 1** was created by ChatGPT with the prompt—The strategic use of AI in education.

Conflict of interest

The author declares no conflict of interest.

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Section 4

Urban Planning and
Environmental Management

SPeAR as a Tool for Sustainability Impact Assessment of Hospital Master Plans: King Hamad University Hospital, Bahrain

Abdurrahman Mohamed

Abstract

Sustainability impact assessment (SIA) has been developed as a tool for the evaluation of proposed or existing development projects to improve their environmental quality, economic feasibility, and social commitment. Several approaches and tools have been used for SIA to facilitate the study and analysis of sustainability levels. Increasing attention has been directed to sustainability in hospital master plans yet little attention is paid to SIA as a tool for the management and control of their sustainability levels. King Hamad University Hospital (KHUH) in Bahrain is a leading health institution in the country and the region. There are no publicly available documents of its master planning and there is no reference for sustainability planning and management in any of the available resources. This research uses the sustainable project appraisal routine “SPeAR” as an SIA tool for the assessment of social and environmental components of the master plan of KHUH. The research reveals that there is a need for the preparation of a sustainable master plan for KHUH with suitable sustainability indicators and measures with continuous monitoring. The research represents the first attempt to study the master plan of KHUH and its sustainability levels. It provides a guideline for other hospitals in Bahrain and the region.

Keywords: sustainability, assessment, master plans, hospitals, Bahrain

1. Introduction

Hospitals are considered among the most important components of the built environment because of their functional, operational, and spatial complexity. They also represent the institutions for the protection of human life, which is one of the main five essential objectives of Islamic law “Makasid Al-Shari’ah” [1]. The development of hospital planning, design, and management is therefore considered a vital necessity for community development and a serious responsibility for both private and governmental bodies and institutions. Healthcare services consume quite a considerable percentage of the gross national product and domestic national product worldwide. From this expenditure, hospital development consumes the largest portion. Although

statistics can be available through the World Health Organization, research on hospital development and investment does not respond to the increasing demand for hospitals [2]. Modern hospitals have changed the nineteenth-century image as places where people wait to die. In the twenty-first century, hospitals have been facing many changes, for example, mobility of healthcare workers, new treatment technologies, changing patterns of diseases, and complying with sustainability demands in planning construction and function. Hospital planning is increasingly affected by several factors that include new trends in community healthcare services and innovations in building materials and construction technologies [3]. One new approach to the planning of hospitals is that which concentrates on the circulation of both pedestrians and vehicles with an emphasis on visibility and easy access to the main entrance, clear connection with the main public space, separation between different types of entrances, and convenient drop-off and parking [4]. This planning approach, in addition to other considerations, such as required services, the number of users, required spaces, and building systems, all need to be adjusted and tuned until arriving at a flexible and expandable hospital design concept.

The hospital is a distinguished component of the built environment where all issues of the three pillars of sustainability mingle together in a very complex manner. The need here is for a sort of framework to bring balance and tranquility to the interrelated connections of many factors [5]. Social and cultural manifestations express the way people look at hospitals in terms of the sense of place, the spatial experience, and the attitudes toward services. They also do exist in the conduct ethics of the staff and their values. Sustainable hospitals need to provide a venue where all these interactions can positively enhance the health of the community. More importantly, it is the master plan, which can cater to this through the treatment of interior and exterior spaces, buildings, and the landscape. It is this treatment that also can provide for the care for resources in terms of land area, built-up area, building cost, and energy consumption. All this eventually will determine to what extent this hospital is hostile to the environment or friendly, adding to its value by decreasing pollution, preserving natural habitat, and preventing contamination [6]. Sustainability has evolved as a response to the escalating environmental, social, and economic problems of the modern production cycles. Healthcare is one of the important fields desperately striving for sustainability [7]. Sustainability is not only needed for the management and operation of hospitals, to cut costs and increase savings, or to control hazardous materials. It starts from the early stages of searching for a site and extends to site development and building construction. The development of sustainable hospitals would never fulfill its goals without the availability of sustainable sites and buildings for hospital services.

The master plan is a document of long-term planning to establish a framework for development and improvement, setting out inputs, outputs, gains, and costs. This is in addition to steps, phases, work plans, and monitoring and feedback. All these processes are time-bound, and the temporal framework of the master plan has great importance to define points of fulfilling goals and evaluating progress [8]. As a form of planning, the master plan is future-oriented and depends on past outcomes and present developments. It draws the overall framework for steps to follow. In the built environment, the master plan of a development project is part of the planning system, which is the government program for the control and management of land use development [9]. The master plan is usually a set of site maps, plans, images, and documents that all illustrate the development process of an area. Its level varies from regional scale to medium and small scale. It includes present and future land use, urban design, and landscaping. The main purpose of the master plan is to help create the most suitable

form of the built environment with high-quality standards of living. It connects people and spaces in such a way to enhance social interaction and the sense of place [8]. The master plan is by nature a sustainability framework for the preservation of land, the conservation of the environment, and providing prosperous happy living places.

2. Sustainable hospital master plans in Arab countries

A survey for sustainable hospital master plans in some of the Arab countries in the Gulf Region was conducted at the beginning of 2022 using Google search. The aim was to discover to what extent these hospitals and healthcare facilities are concerned about sustainability and sustainable hospital master plans.

The hospitals that were reviewed included:

- Citymed Hospital, Riyadh, Saudi Arabia [10].
- Johns Hopkins Aramco Healthcare [11].
- Jeddah Medical City, Jeddah, Saudi Arabia [12].
- Interhealth Canada [13].
- King Saud University—Medical City, Riyadh, Saudi Arabia [14].
- Farwaniya Hospital in Kuwait [15].
- Jahra Medical City, Kuwait [16].
- Primary Health Care Corporation “PHCC,” Qatar [17].
- The American Hospital Dubai [18].

These hospitals and similar Arab hospitals, medical cities, and healthcare facilities constitute multi-billion industries and many of them represent giant projects of millions of square meters. Despite their distinguished master plans and the special environmental, economic, and social settings, they provide very little information, if nothing at all, about these master plans and their relationships with their special contexts. No documentation is publicly available about sustainability issues to present their achievements and to educate the public. This highlights the need to work hard on the preparation of comprehensive hospital master plans within the framework of sustainability and its assessment indicators and measures.

3. Sustainable hospital master plans in North America

Case studies for this purpose have been chosen through an online search using the Google search engine. They have been randomly chosen according to their consideration of sustainability. It is regrettably admitted here that nothing was found on precise consideration of SIA in these master plans.

3.1 Children's hospital and regional medical center concept plan, City of Seattle, USA

This master plan carefully dealt with the goals, objectives, design principles, and environment. Generally, many aspects of sustainability are considered without any concentration on sustainability or SIA. Design principles and environmental stewardship sections of the master plan indirectly considered some sustainability issues [19].

3.2 The Cayuga Medical Centre, Ithaca, USA

The master plan's main purpose was to provide a comprehensive indoor and outdoor healing environment. Great concern was paid to the landscape not only in outdoor spaces but also to bringing it forward to indoor spaces as well. Architecture, landscape, stormwater management, and sustainable agriculture all met together to enhance the sustainability of the master plan. This interest in providing an increased dose of natural environment and landscaping to provide a distinguished healing environment helps the hospital to achieve LEED silver certificate for sustainable sites [20].

3.3 Delta hospital high level concept plan, delta, British Columbia, Canada

The master plan report of March 2012 provides a good account of several sustainability issues, including environmental, economic, and social parts. Sustainability is namely used twice: the first time as a guiding planning principle and the second as an approach to rethinking healthcare facilities. No consideration is given to the assessment of these sustainability practices [21].

3.4 The University of Texas at Austin Medical District Master Plan, USA

Several recommendations were made to enhance the sustainability level of the medical district. Interestingly, they constitute a way for measurement and assessment. Despite the importance of these points, they did not formulate a comprehensive framework for sustainability assessment, especially in the land-use master plan. The planning and development of the medical district paid attention to many sustainability issues that would be applied in the master plan. They include, among many other points, parking, stormwater, energy, landscape, community, mobility, and economic development [22].

4. Concluding remarks on North American hospitals

On the contrary to Arab hospitals presented in the previous section, the North American hospitals showed since the late twentieth century, a well-informed consideration of hospital master planning with some level of consideration of sustainability criteria and environmental quality. The above hospital master plans show interest in enhancing the level of sustainability. This reflects a belief in the importance of sustainability for the development of hospitals as vital environmental and socioeconomic institutions. The main concern in these projects remained too much bounded by environmental issues, such as resource conservation, especially energy and water. It is also evident that these master plans did not show a common ground for any kind of framework for sustainability applications, evaluation, and assessment. This clearly highlights the need to search for such a framework.

5. Sustainability impact assessment, SIA

In the built environment, it is no longer acceptable to limit sustainability to the use of solar panels or to increasing green areas or providing bicycle lanes. There is a need for a more holistic approach that considers all the three pillars of sustainability: environment, economy, and society [23]. This is in addition to their branches and sub-branches as one complete set. This process is continuous and needs continuous input and monitoring. It also includes assessment and measurements using both qualitative and quantitative techniques that provide more controls on the sustainable development process [24]. To measure the level of sustainability in any project, and to know to what extent it is committed to sustainability, several sustainability indicators and measures need to be determined. It is argued that the number of sustainable indicators sets in use worldwide exceeds 600. Indicators are a means of collecting data in a systematic way regarding sustainability issues and practices. They provide the base for the understanding, analysis, and counting of these data [25]. Indicators are used to control and manage urban development and its sustainable impacts. Yet it should be addressed here that using indicators would never mean achieving sustainability in an ideal form. They only provide a tool to examine successes and failures in caring for the environment, resources, and community in a more general wishful manner. And therefore, with the use of indicators, SIA can help to prepare policies for development and strategies for improvement. It can help to identify objectives and to apply monitoring and control. SIA also provides a comprehensive framework to link the site with buildings and with the surrounding context [26]. At the same time, it is argued that SIA is not easy and straightforward, and it includes difficult decision-making process that might sometimes restrain the decision makers [27]. This highlights the need for careful introduction of SIA in the planning and design of healthcare facilities, especially large hospitals.

6. SPeAR tool for SIA

Several approaches and frameworks have been studied to get deeper insight on the suitable tool to be used for the assessment of this research. It is beyond the scope of this research to provide a comprehensive survey of these tools and their characteristics or to provide a comparative analysis of them. Sieber Stefan et al. ([23], p. 76) evaluated five SIA tools based on seven criteria that included: “fairness, transparency, information quality, neutrality of process, opportunity to influence outcome, cost effectiveness, and ability to lead to out of the box solutions”. Looking at the tool of SPeAR with a relevant perspective, McGregor and Cole [28], believe that SPeAR has many advantages including adaptability, transparency of the assessment methodology, identification of improvement opportunities, optimization of the indicators and measures, and the possibility to trace all assessment steps easily and clearly. Within this framework, it was decided to use SPeAR tool for the study and analysis of sustainability levels at KHUH.

Sustainable Project Appraisal Routine (SPeAR) was developed by ARUP company as a holistic flexible software tool for sustainability assessment of development projects throughout their whole life cycle [29]. It referred to several internationally common indicator-based frameworks, such as leadership in energy and environmental design, LEED, GRI Draft CRESS (construction & real estate sector supplement), UN Indicators of Sustainable Development, and UK Indicators for Sustainable Development [30]. The aim was to arrive at the best sets of indicators and sub-indicators

that cover the widest spectrum of sustainability main segments: environmental, economic, and social. SPeAR uses questions to evaluate all these sets of indicators and sub-indicators on a scale from (−1) for the worst case to (3) for the best case (Figure 1). This scale does not represent actual numerical values for the indicators or sub-indicators. It is like the scale of the Likert questionnaires. Some of the questions can be answered based on qualitative judgment and many others can use quantitative measures. It also has no representations for geographical information of any type to link the indicators, sub-indicators, and measures with project sites and contexts. On the other hand, SPeAR is distinguished by its comprehensiveness and its easy and simple maneuvering of the assessment process.

7. King Hamad University Hospital

King Hamad University Hospital (KHUH) was established by Royal Decree No. 31 of 2010, which affiliated it to the Bahrain Defense Force. It was officially opened by his majesty King Hamad Bin Isa AL Khalifa on 2/2/2012. KHUH is a university hospital primarily serving the Royal College of Surgeons of Ireland, Bahrain branch, which is located at its western border. KHUH has a capacity of 312 beds, with 1731 employees [31]. The project started in 2003 as King Hamad General Hospital to help meet the increasing healthcare needs in Bahrain. KHUH now is a specialized hospital for the delivery of state-of-the-art healthcare, teaching, and research, in addition to fulfilling the national agenda defined in Bahrain Vision 2030 [32]. The site lies in a distinguished area close to all

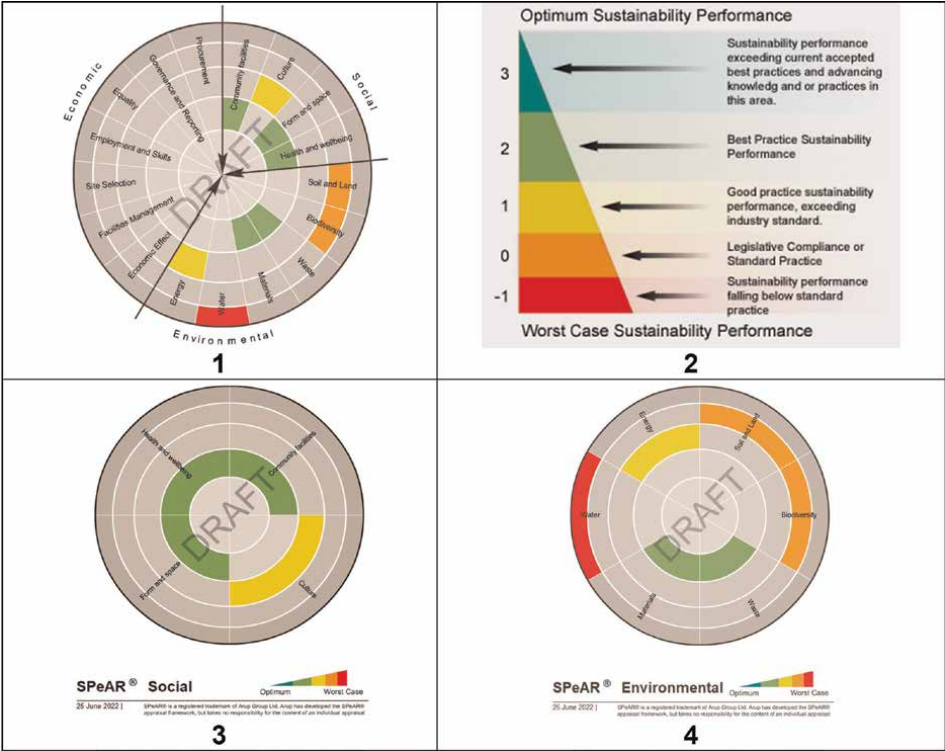


Figure 1. 1. Segment pie chart, 2 performance scale, 3. Social segment pie chart, and 4. environmental segment pie chart.

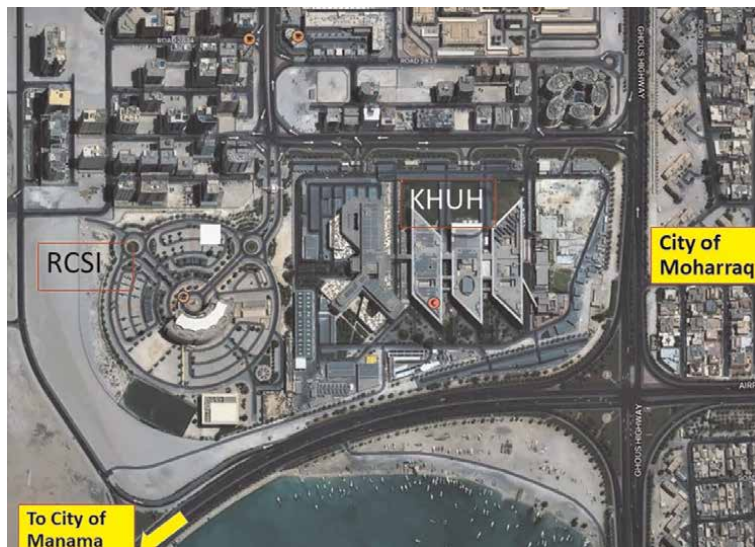


Figure 2.
 KHUH site.

amenities in the cities of Moharraq and Manama (**Figure 2**). The area of the hospital site is 227,000 m², while the total floor area of the buildings is 64,000 m². The building complex is composed of three buildings of three floors all rise above a large podium. The building complex is laid in the center of the site surrounded by huge parking lots on all sides separated from the buildings and from each other with small green areas. A long ramp leads to the main entrance of the hospital in the central building. Although the main entrance exists on the north façade, it is covered with what is believed to be one of the longest canopies in the world [33] (**Figure 3**). Large areas of green grass occupy the area



Figure 3.
 KHUH main buildings with the main entrance in the middle.

in front of the main building entrance, while the approach road to the entrance is defined by rows of trees on both sides. An unshaded visitor's car park with very little green occupies the west side of the building (**Figure 4**). A shaded staff car park was constructed at the northern edge of the site (**Figure 5**).



Figure 4.
KHUD visitor's car park.



Figure 5.
KHUD staff northern car park.

8. Methodology

This research depends on the case study methodology. It uses SPeAR as an SIA tool for the assessment of sustainability levels in the master plan of KHUH in the city of Muharraq, Bahrain. Therefore, it is twofold, the first is to determine what data is available on the master plan of KHUH. And the second is to determine the suitable segments, indicators, and variables or measures of SPeAR to be used for the assessment.

8.1 KHUH data

Unfortunately, no document was found on the master planning of KHUH hospital. The author approached the administration of the hospital seeking information on its planning, design, and construction. The denial of giving any access to any information on the hospital came in an official letter from the lieutenant colonel director of the hospital even though some information was already available on the Internet. The hospital is also open to the public despite being under the administration of the Bahrain Defense Force. The description and analysis of the hospital depended on the personal visits of the author to the hospital and the surrounding areas and on information available on the Internet. No quantitative data are used, and all data used in the assessment are qualitative. Despite the disadvantages of this approach, it represents the first attempt to refer to the severe shortages in the information available on master planning of healthcare facilities, in Bahrain and in the Gulf countries, in general. It is also the first attempt to highlight the importance of sustainability in these hospitals and the need to use SIA procedures for the control and management of its quality in these healthcare facilities.

8.2 SPeAR for KHUH

This research used KHUH qualitative data on the sustainability segments, indicators, and sub-indicators of the Evaluation Version of ARUP SPeAR V. 11.1.4.02013, Oasys Ltd.

The economic segment of SPeAR was ignored for the lack of information. For the same reason, not all the indicators and sub-indicators in the social and environmental segments were used nor all the questions were considered. Some of the questions were also altered to suit the ability of judgment on the issue.

9. Results and analysis

After entering the data in SPeAR according to the chosen segments, indicators, sub-indicators, and questions, it gives the results in detailed reports in rtf and excel file format. These reports show the evaluation scale, the segments pie chart, and the total average evaluation scores of the indicators (**Figure 1**). This is in addition to long text tables containing the details of the evaluations.

Table 1 shows the results brief of the environmental segment with the justifications for the scores used. Four indicators were used with a total of ten sub-indicators in all of them. The average score of each indicator is the sum of the scores of the sub-indicators divided by their number. Similarly, the average score of the segment is the score of the indicators divided by their number. The indicators of soil, land, and

Environmental segment				
Indicators	Sub indicator score		Score	Av. score
Soil and land	Soil quality	The project although provided some protection of soil profiles and improved soil quality, no documentation was available on-site management, storm water management or landscape management.	0	0
	Drainage systems	Although the different treatment of the master plan and its landscaping show concern towards drainage issues, no sustainable drainage system has been applied.	0	
Biodiversity	Protected species and habitats	Although KHUH enhances the natural life and biodiversity in the site, there is still a need to prepare and disseminate ecology and biodiversity management plans. On the other side, the performance was better in.	0	0
	Conserving and improving local biodiversity	The landscaping of the project will be contributing to the conservation and improvement of the biodiversity in the site but there is still a need to compensate for the disturbance in the natural environment due to the development of the project.	0	
	Habitat connectivity	The project represents an important hub for connection between different natural elements in the context but there is a need for more in-depth studies and plans to mitigate the effect of the continuous movement in the site due to its function.	0	
Waste	Waste in operation	KHUH represents a benchmark in the planning and management of waste since this is one of the most serious problems in hospitals. The details of the management plans in operation need to be disseminated for monitoring and feedback.	2	2
	Hazardous/special waste	KHUH also pays a great attention to the safety measures in the treatment of hazardous waste and the discharge of its containers.	1	
Materials	Materials efficiency	Materials used in the development of KHUH have been chosen according to high standards either in the buildings and the outdoor spaces without any clear sign of waste or neglect.	2	2
	Environmental and sustainability impacts of materials	Although there is apparent harm to the environment from the materials used in the project, there is a need for a detailed and in-depth study and analysis of the sustainability impact of these materials.	1	
	Healthy materials	Health measures are clearly applied in the materials used in the hospital.	2	
Overall segment average score			1	

Table 1.
Indicators and sub-indicators of the environmental segment and their scores.

biodiversity got “0” score, which means they are at standard practice level fulfilling minimum requirements. In contrast, the indicators of waste and materials got “2” score, which means they are at the level of best practices. This indicates that the development of the project concentrated more on the buildings, while less concentration was directed on the outdoor spaces and their natural components.

The overall performance of the environmental segment got “1” score, which means good practice level. This very general result shows that it was possible to achieve some good levels of sustainability in the environmental sectors of KHUH master plan. Still, there is a lot to be done to improve them including all the indicators and sub-indicators of SPeAR.

Table 2 shows the results brief of the social segment with the justifications for the scores used. Four indicators were used with a total of 19 sub-indicators in all of them. The social segment overall performance showed the best practice level. This is due to the

Indicators	Sub indicator	Justification	Score	Av. score
Community facilities	Education	KHUH is now considered the university hospital of RCSI-Bahrain. It is the newest and modernist medical education institution in the country. KHUH has its own educational spaces within its premises that are used by its staff, students, and outside guests.	2	2
	Healthcare	KHUH provides state of the art health care services for all people of Bahrain. It is equipped with all the necessary modern equipment and a qualified staff is available in all the medical services of the hospital. All medical services are offered free of charge for Bahraini citizens regardless of age, gender, ethnic group, or religion.	2	
	Recreation	Although KHUH is not an open public space, it provides excellent indoor and outdoor leisure facilities and green spaces that can be easily used by the staff, visitors, the patients, and the students of RCSI.	2	
	Retail	KHUH provides modern retail services to serve the staff, visitors, patients, and students of RCSI for the whole length of their stay in the hospital. These include small shops, a coffee shop, and a restaurant.	1	
Culture	Respecting socio-cultural identity	KHUH represents with its modern design the dynamism of Bahraini culture that is open, livable, and developing. At the same time, it is preserving its roots and principles as an Arabic multi-ethnic multi-religion culture.	2	1
	Cultural and religious facilities	All cultural groups have equal access to all parts of the complex without any kind of barrier or discrimination.	2	
	Use of environment	The site of KHUH was a vacant urban site. The project's master plan transformed the site into a monumental landmark with wide and diversified green elements.	2	
	Intergenerational and gender practice	KHUH respects the fact that most of the people of Bahrain are Arab Moslems. The freedom of dress, behave and worship is guaranteed for all including other religious groups.	2	

Indicators	Sub indicator	Justification	Score	Av. score
	Art	Unfortunately, public art has not been considered in KHUH despite the high quality of its urban design and architectural design.	-1	
Form and space	Density, scale, height and massing	KHUH fits well within its context and provides distinguished masses of buildings in a very prominent site. These building masses are surrounded by green spaces that serve all parts of the hospital. The scale of the buildings' masses of the hospital is distinguished within its context providing a monumental gate for the city of Muharraq.	2	2
	Public-private relationship	KHUH provides clear separation between private and public spaces. Visitor parking is separate from those of the employees. The routes and entrances of the employees are separate from those of the patients and visitors. The zoning and spatial definition of the master plan is simple and clear and areas around buildings are wide and transparent.	1	
	Landscaping	It is clear from the master plan of KHUH that landscaping was a main concern. It was treated to aid the environmental, visual, and social needs of the hospital. It was integrated with the buildings and the open spaces between and around them. It aids the sustainable drainage system by aiding the infiltration of rainwater and the prevention of flooding. At the same time, it naturally helps the development of habitat life in the site.	2	
	Landscape, townscape, and visual impact	KHUH complements the general green structure of the area at the meeting border between the two cities of Manama and Muharraq. It is a continuation of the green structure on the roads to its south and east. As such, the project adds to the urban visual character of Bahrain and enhance the green culture of the community. KHUH provides good spatial openness and visual transparency of the spaces around the buildings and in the public open spaces of the site. Public and private spaces are clearly defined, and suitable lighting is provided for the public areas like parking lots and green spaces without affecting the buildings of the hospital. Surrounding residential areas to the north of the hospital are far enough to be affected.	1	
	Security	KHUH provides good spatial openness and visual transparency of the spaces around the buildings and in the public open spaces of the site. Public and private spaces are clearly defined, and suitable lighting is provided for the public areas like parking lots and green spaces without affecting the buildings of the hospital. Surrounding residential areas to the north of the hospital are far enough to be affected.	2	
	Connectivity	Within the nice natural environment and well-designed beautiful buildings and spaces, KHUH	1	

Indicators	Sub indicator	Justification	Score	Av. score
		provides both the employees, patients, and visitors with a splendid chance of meeting, communication and cooperation in a lively and vibrant environment.		
Health and wellbeing	Access to green space	KHUH added great value to the surrounding areas by transforming the vacant site into a monumental landmark with wide areas of greenery. It has enhanced the overall urban image of the area.	2	2
	Community cohesion	KHUH has been providing an excellent opportunity for the integration between the different groups of users without any discrimination based on color, gender, religion, or ethnic group. KHUH is the second largest healthcare facility in the country, and it has considered the future population growth of the citizens and expatriates. At the same time, KHUH has a wide range of services that respond to the different needs of the community.	2	
	Institutions and social networks	KHUH is a government hospital working under the umbrella of the Ministry of Health. The users of the hospital with all their classes are subjected to the government healthcare system in general and to the special high standards of the hospital. At the same time.	3	
	Social vibrancy	KHUH provides enough open public spaces where people can meet like the clean well paved roads and parking lots. Nice, beautiful green spaces are also available for meeting and suitable social activities.	1	
Overall segment average score			2	

Table 2.
Indicators and sub-indicators of the cultural segment and their scores.

strong institutional, educational, and healthcare structure of KHUH. All the sub-indicators got “1” score and above which means they all came in the good practices and best practices range. Art sub-indicator of culture indicator came below the standard level. There is a lack of public artworks in the outdoor spaces that would enhance the positive aesthetical experience of the users and their appreciation of the quality of the project. Also, there is a lack of space and landscape furniture that would be used for art activities in the project. In contrast, institutions and social network sub-indicator of health and wellbeing indicators got “3” score making it exceptional and exceeding the best practice level. This is because KHUH is a government hospital providing its services to its users regardless of their social class or ethnic origins. This result shows again that it was possible to achieve good levels of sustainability in the cultural sectors of KHUH master plan, but hard work is still needed to cover all the cultural indicators and sub-indicators and all the questions and issues that need to be comprehensively considered.

10. Conclusion

Nothing could compensate for the official document of the master plan for this very distinguished hospital that is considered a masterpiece of architectural and urban

design in Bahrain and the region. It is here worthy to make an appeal to the hospital administrations in Bahrain to help disseminate information on the project because this practice is a sustainable conduct that is desperately needed for raising public awareness toward these important issues. The declared interest in sustainability from the decision makers can be hindered by the lack of information. It is no longer acceptable that other countries consider sustainability in the master plans of their hospitals since the eighties of the twentieth century and Bahrain and other Gulf Countries lag far behind this level in the twenty-first century. It is hoped that this research would find a way to be extended for a detailed and in-depth study for KHUH soon. On the side of SPeAR, it has been found helpful in giving general qualitative ideas on sustainability issues of the project. It is also flexible and user-friendly, and indicators, sub-indicators, and questions can be easily adapted to the needs of the user and the project under consideration. Yet, although it covers a wide range of sustainability issues, it is too broad and descriptive, which also leaves a wide gap for the subjective judgment of the sustainability practitioner. Many sustainability issues can be quantitatively measured and can have numerical ranges for the accepted levels. It is hoped that future research will be conducted on the development of SPeAR to provide more accurate and generalized quantitative models for sustainability impact assessment.

Conflict of interest

The author declares no conflict of interest.

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International Cooperation as a Tool to Mitigate and Prevent Risks in Informal and Consolidated Human Settlements in the Tumbaco Zone Administration of the DMQ

Christian Fernando Vicente Correa and Rui Alexandre Castanho

Abstract

This study analyzes risk management and sustainable urban development in the context of Ecuador, specifically in the Metropolitan District of Quito, which has been affected by various natural disasters, and the Informal and Consolidated Human Settlements approved within the jurisdiction of the Tumbaco Zone Administration. The importance of the New Urban Agenda and the Sustainable Development Goals as fundamental tools for promoting sustainable urban development and risk management is highlighted. Additionally, the importance of international cooperation in improving local capacity and addressing challenges related to risk management and sustainable urban development is addressed, presenting examples of good practices in international cooperation in this field. The objective is to promote knowledge exchange and strengthen local capacity in risk management through international cooperation.

Keywords: urban development, risk management, sustainable development goals, international cooperation, disaster resilience

1. Introduction

In recent decades, Ecuador has been the scene of multiple natural disasters that have significantly affected its territory and population. The Metropolitan District of Quito, the capital of Ecuador, has experienced several seismic, volcanic, and landslide events that have highlighted the need to improve the risk management of public institutions and make it more efficient to protect the lives and assets of its inhabitants. In turn, within the jurisdiction of the Tumbaco Zone Administration, dozens of ordinances have been approved that approve Informal and Consolidated Human Settlements, where the challenge of addressing the problem of leaving people who inhabit them vulnerable is faced.

In this context, the Sustainable Development Goals (SDGs) and the New Urban Agenda are presented as essential tools to promote sustainable and resilient urban

development, which guarantees the protection of the population and the conservation of the environment and heritage. Thus, the SDGs establish a global framework for poverty eradication, environmental protection, and sustainable development, and the New Urban Agenda establishes the principles and commitments that guide urban and territorial planning in the 21st century.

It is here where international cooperation emerges as a key factor in strengthening local capacities and addressing the challenges related to risk management and sustainable urban development, by providing technical and financial resources and sharing experiences and knowledge that enable improving the quality of life of the population and building safer and more sustainable cities.

In this chapter, the problem of natural disasters in Ecuador will be addressed, with emphasis on the Metropolitan District of Quito and the Tumbaco Zone Administration. Additionally, the importance of the New Urban Agenda and the SDGs to address this issue will be analyzed, as well as the forms of international cooperation that can contribute to mitigating risks and promoting sustainable and resilient urban development, presenting experiences of good practices of international cooperation in this field, with the aim of promoting knowledge exchange and strengthening local capacities.

1.1 Part I: “...sleep peacefully in the midst of crunching volcanoes...”

Since the beginning of humanity, it has faced various natural threats, confronting atmospheric phenomena (hurricanes, hailstorms, fires, among others), hydrological phenomena (floods, desertification, salinization, erosion, among others), geological phenomena, especially seismic (earthquakes, faults, liquefaction, among others) and volcanic (ashes, lava flows, pyroclastic flows, gases, among others), in addition to others that result from the combination of the previous ones (landslides, subsidence, expansive soils, among others)¹.

Natural phenomena per se do not cause harm to society, but rather, the lack of adequate planning and territorial management leads to exposure to risks and hence to vulnerability. The absence of prevention, mitigation, and preparation measures, as well as the presence of human settlements in high-risk areas, contribute to the magnitude of the damage caused by natural phenomena. Therefore, it is crucial to address disaster risk and territorial management in an integrated manner, considering technical, social, economic, and environmental aspects, to reduce the vulnerability of communities and build more resilient cities and territories.

Considering that these threats occur in different magnitudes and temporalities depending on the location of the planet, each population has known how to adapt to the natural phenomena specific to the region. However, in some cases, the periodicity with which they occur causes the community to neglect prevention measures, and unfortunately, once the disaster occurs, the authorities begin to adopt measures, which initially focus on emergency response, victim care, reconstruction, and finally presenting a prevention plan, which after some time is neglected again.

Alexander von Humboldt, a German scientist and researcher, explored the territory of what years later would become the Republic of Ecuador in 1802, with the permission of King Carlos IV, and in his travels, he was able to describe Ecuadorians by saying “...they sleep peacefully in the midst of crunching volcanoes, live poor in the midst of incomparable wealth, and rejoice in sad music” [2].

¹ Natural threats are understood as “those elements of the environment that are dangerous to humans and are caused by forces external to them” [1].

Throughout the recorded history of the Republic of Ecuador, various natural events that have resulted in disasters have occurred, leaving thousands of victims who lost their belongings and even their lives. Among the most significant natural events, in terms of the damage they caused, are the following (**Table 1**).

As can be seen, Ecuador is susceptible to natural disasters leaving serious consequences in populations, reporting thousands of human casualties, material damage and in some cases rebuilding entire cities².

In the last decade, the event that has had the greatest impact on Ecuador was the earthquake in Manabi, from which several populations on the Ecuadorian coast are still in recovery, even receiving assistance from countries such as Venezuela, Colombia, Peru, Mexico, Cuba, Bolivia, Chile, China, Switzerland and Spain, as well as international organizations including the United Nations High Commissioner for

Date	Location	Event	Effects
September 3, 1587	Metropolitan District of Quito	Earthquake	• Collapse of houses and churches • Numerous deaths • Large number of injured
March 15, 1645	Riobamba	Earthquake	• Damage to constructions • Large number of deaths
February 22, 1757	Latacunga	Earthquake	• Destruction of houses and churches, even in surrounding villages • Over 4000 deaths
February 4, 1797	Riobamba	Earthquake	• The most destructive earthquake in Ecuadorian history • 12,833 deaths recorded Hundreds of aftershocks for several months
March 22, 1859	Metropolitan District of Quito	Earthquake	• Serious damage to houses, churches, and public buildings • Large number of deaths in Machachi, Chilligallo, and other populated centers • The church of La Merced was heavily affected
Several months of 1982	Ecuadorian coast	El Niño phenomenon	• Strong rains and floods • 307 deaths • 700,000 affected • Destroyed roads
March 5, 1987	Metropolitan District of Quito	Volcanic eruption - El Reventador	• Earthquakes of 6.9° and 6.1° on the Richter scale • Destruction of buildings • Around 1000 deaths • Material damages for over \$1 billion

² The case of Ambato (1949) and Manta (2016) is an example, as they had to be rebuilt and some settlements even relocated after strong earthquakes.

Date	Location	Event	Effects
Several months of 1993	La Josefina	Landslide and collapse	• 75,000 affected • Estimated damages of \$500 million
Several months of 1997	and 1998, Ecuadorian coast	El Niño phenomenon	• Strong rains and floods • 35,000 affected • Estimated damages of \$271 million
July 14, 2006	Tungurahua	Volcanic eruption	• Thousands affected in different parts of the national territory • Loss of hundreds of houses
January to April 2008	Provinces of the Ecuadorian coast and Sierra	Floods	• 90,297 affected families • Destroyed roads • Dozens of deaths and disappearances
April 16, 2016	Manabí	Earthquake	• 7.8° Richter scale earthquake • Widespread destruction of homes, roads, and other buildings • 671 deaths • 12 missing

Table 1.
Natural events that have resulted in disasters in Ecuador [3–9].

Refugees (UNHCR) and the Pan American Health Organization [10]. On the other hand, it should be noted that the landslide in January 2022, which occurred in the city of Quito, also represented an event that left dead, injured and damage to buildings and businesses. Although several institutions offered assistance, many of these offers did not arrive, including those made by the municipal government, without any positive or negative responses, and even failing to provide for the orphans to whom the municipality offered protection [11].

1.2 Part II: de Facto and consolidated human settlements

In recent history, the current Constitution of the Republic of Ecuador was approved by the Constituent National Assembly in 2008, being a promulgated Constitution that was elaborated with citizen participation and approved by a Constituent Assembly elected for that purpose.

In this legal framework, the importance of protecting citizens from natural events is recognized, thus in its article 389 it is stated:

“The State shall protect individuals, communities and nature from the negative effects of disasters of natural or anthropic origin through risk prevention, disaster mitigation, recovery and improvement of social, economic and environmental conditions, with the objective of minimizing vulnerability.

The decentralized national risk management system is composed of risk management units of all public and private institutions at the local, regional and national levels. The State shall exercise leadership through the technical agency established by law. Its main functions shall include, among others:

1. Identify existing and potential risks, internal and external, affecting Ecuadorian territory.
2. Generate, democratize access to, and disseminate sufficient and timely information to properly manage risk.
3. Ensure that all public and private institutions mandatorily and transversally incorporate risk management into their planning and management.
4. Strengthen capacities in citizens and public and private entities to identify risks inherent in their respective areas of action, report on them, and incorporate actions aimed at reducing them.
5. Coordinate institutions to coordinate actions to prevent and mitigate risks, as well as to face them, recover and improve conditions prior to the occurrence of an emergency or disaster.
6. Carry out and coordinate necessary actions to reduce vulnerabilities and prevent, mitigate, respond to and recover from eventual negative effects derived from disasters or emergencies in national territory.
7. Ensure sufficient and timely financing for the operation of the System, and coordinate international cooperation aimed at risk management.” [12].

Since 2010, Ecuador has had the Organic Code of Territorial Organization, Autonomy and Decentralization (COOTAD), which is an Ecuadorian law that establishes the basis for territorial planning, autonomy, and decentralization in the country. It has become a fundamental tool for territorial organization and sustainable development in Ecuador, allowing for the coordination of different levels of government and citizen participation in decision-making.

Through the COOTAD, human settlements are recognized as existing throughout the national territory and must be managed to avoid uncontrolled population growth. Article 596 of the COOTAD establishes special expropriation for the regularization of human settlements of social interest in urban and urban expansion land, as follows:

In order to regularize human settlements of fact on urban and urban expansion land of private owners, metropolitan or municipal decentralized autonomous governments, by resolution of the legislative body, may declare these properties of public utility and social interest in order to provide them with basic services and define the legal situation of the possessors, assigning them the corresponding lots.

Each municipal or metropolitan decentralized autonomous government shall establish, by ordinance, the criteria for considering a human settlement as consolidated or any other definition that is required to legalize human settlements of social interest in their territorial jurisdictions, taking into account their own realities.

In this sense, the COOTAD establishes the need to develop territorial planning plans to prevent and regularize informal settlements, as well as to guarantee the quality of life and safety of the population, especially in areas where the population is at risk. Additionally, the COOTAD promotes citizen participation in the management of

informal settlements in order to ensure sustainable and equitable territorial planning that promotes human and social development in Ecuador.

The Metropolitan District of Quito, capital of the Republic of Ecuador, has a population that exceeded 2'781,641 inhabitants as of 2020 [13], settled in a territory that is administratively divided into 5 urban zonal administrations, 4 rural zonal administrations and 2 rural delegations [14], within which Informal and Consolidated Human Settlements (AHHYC, by its acronym in Spanish) have been registered since 2010. For the purposes of this chapter, we will take as an example those settlements recognized within the jurisdiction of the Tumbaco Zonal Administration, for which over 55 metropolitan ordinances have been issued from 2010 to 2022 recognizing and modifying the following (**Table 2**).

Based on the presented table, it can be observed that from 2010 to 2020, the Metropolitan District Council of Quito has issued more than 50 ordinances within

#	Year	AHHYC	Ordinance	Parish	Observation
1	2010	Luis Alberto Maigua y Otros	3858	Checa	No green area No risk study
2	2011	Barrio Los Jazmines	9	Tumbaco	2 green areas No risk study
3	2011	Comité Promejoras Altamira	44	El Quinche	No green area No risk study
4	2011	Comité Promejoras del barrio "Brisas del Valle"	62	Pifo	2 green areas No risk study
5	2011	Comité Promejoras del barrio "Las Marías"	128	Tumbaco	Green area No risk study
6	2012	El Jardín de Yaruquí	204	Yaruquí	Green area No risk study
7	2012	La Victoria	205	Yaruquí	2 green areas No risk study
8	2012	Mirador Yaruqueño	206	Yaruquí	Green area No risk study
9	2012	Jesús del Gran Poder	207	El Quinche	Green area No risk study
10	2012	Mi Terrenito	214	Yaruquí	2 green areas No risk study
11	2012	La Victoria de Yaruquí	314	Yaruquí	No green area No risk study
12	2012	Nuevo Amanecer I etapa	315	El Quinche	Green area No risk study
13	2012	La Victoria II	326	Yaruquí	Green area No risk study
14	2012	Nuevo Amanecer II etapa	331	El Quinche	Green area No risk study
15	2013	La Cruz	348	El Quinche	Green area No risk study
16	2013	Herederos Aña Toapanta	359	Tumbaco	No green area No risk study

#	Year	AHHYC	Ordinance	Parish	Observation
17	2013	Comité pro mejoras “Nuevo Amanecer” (sector el Chamizal) III etapa	421	El Quinche	Green area No risk study
18	2013	Comité pro mejoras Los Pinos de Santa Rosa de Tumbaco”	423	Tumbaco	4 green areas No risk study
19	2013	Comité pro mejoras Los Laureles	424	Pifo	Green area No risk study
20	2014	Reforma de ordenanza comité pro mejoras del barrio el Belén	482	Pifo	13 green areas 11 protection strips No risk study
21	2014	Comité pro mejoras Luz y Vida	486	Yaruquí	Green area No risk study
22	2014	Comité pro mejoras “Los Cipreses”	487	Yaruquí	No green area No risk study
23	2014	Barrio Chaupimolino II”	488	Pifo	Green area No risk study
24	2014	Las Orquídeas	515	El Quinche	No green area No risk study
25	2014	Barrio “Chaupimolino I”	513	Pifo	Green area No risk study
26	2014	La Cruz del Quinche	514	El Quinche	3 green areas No risk study
27	2014	Nuevo Amanecer IV etapa	516	El Quinche	Green area No risk study
28	2016	El Inga Bajo	100	Pifo	48 green areas No risk study
29	2018	Reforma de ordenanza comité pro mejoras Balcón Yaruqueño y la Buena Esperanza	272	Yaruquí	2 green areas No risk study
30	2019	La Isla sector Unicornio	25	Yaruquí	2 green areas Risk study
31	2019	La Delicia sector Vista Hermosa	280	Checa	No green area Risk study
32	2019	La Villa Vega	281	Tumbaco	No green area Risk study
33	2019	Triangulo de Yaruquí	303	Yaruquí	3 green areas 2 protection areas Risk study
34	2019	San Francisco de la Tola Grande II etapa	308	Tumbaco	No green area No risk study
35	2019	Los Pinos del Chamizal	313	Tumbaco	2 green areas Risk study
36	2019	Molinos de Yaruquí	314	Yaruquí	Green area Risk study
37	2019	Churuloma pasaje Machala	317	Tumbaco	No green area Risk study

#	Year	AHHYC	Ordinance	Parish	Observation
38	2019	San Javier	032	Pifo	6 green areas Risk study
39	2019	Portal Vega Troya	051	Tumbaco	No green area Risk study
40	2019	San Francisco de la Tola Grande	047	Tumbaco	No green area Risk study
41	2019	El Chiche sector Mendoza	060	Puembo	No green area Risk study
42	2019	San Vicente	061	Yaruquí	No green area Risk study
43	2020	Chaupi Molino III	066	Pifo	No green area Risk study
44	2020	Comité Pro mejoras del barrio Vista Hermosa de Checa	070	Checa	5 green areas Risk study
45	2020	El Vergel	082	Tababela	No green area Risk study
46	2020	Comité pro mejoras del barrio Brisas del Quinche	086	El Quinche	Green area Risk study
47	2020	Bellavista del Quinche	100	El Quinche	No green area Risk study
48	2021	La Cruz de Puembo	113	Puembo	No green area Risk study
49	2021	Villa Vega III	149	Tumbaco	No green area Risk study
50	2021	Franklin de la Torre	150	El Quinche	No green area Risk study
51	2021	Los Jazmines - reforma a la ordenanza 271-2012	151	Tumbaco	No green area Risk study
52	2021	La Delicia, sector calle Quito	163	Checa	No green area Risk study
53	2021	La Tola de Checa	164	Checa	No green area Risk study
54	2021	La Tola Chica	176	Tumbaco	No green area Risk study
55	2022	Santa Inés pasaje Carrera	181	Cumbayá	No green area Risk study

Table 2.
Informal and consolidated human settlements on the Tumbaco zonal administration [15–67].

the territory of the Tumbaco Zonal Administration, which recognize and approve the subdivision of plots of land to legally establish consolidated informal settlements, benefiting hundreds of families. The following moments can be appreciated:

From 2010 to 2016, in the majority of settlements, the delivery of green areas to the municipality was approved, where even certain community works, such as courts, community houses, and children's games, were required.

From 2016, the number of settlements that had to deliver green areas decreased considerably, even being exempted from them within the same ordinances, under the pretext of “being considered a settlement declared of Social Interest³” [15–67].

Since 2019, prior to approving any ordinance on consolidated informal settlements, the Metropolitan Directorate of Risk Management requested technical reports to determine the risks that exist in each of the plots to be subdivided, with emphasis on their geomorphological conditions and possible natural disasters. In some ordinances, beneficiaries are even requested to present a technical report on risk mitigation, and if necessary, present a valued schedule of works to mitigate possible disasters, with these works being assumed by the owners of the subdivided plots⁴.

1.3 Part III: safe sites?

In general terms, a safe site is a space that is considered secure in the event of a natural disaster, a similar adverse event, or for emergency situations. In the context of risk management planning, these locations are important for evacuating people who are in vulnerable or dangerous areas, and/or who have been affected by a disaster, whether it be natural or man-made. The number and location of safe sites may vary depending on the specific needs of each community and its exposure to different types of risks.

During the mayoralty of Dr. Augusto Barrera (2009–2014), the Safe Sites project was created with the aim of reducing the vulnerability of the inhabitants of the city of Quito to natural disasters. The idea behind these sites is to provide temporary shelter and safety to the affected population in case of a natural disaster or emergency.

The Safe Sites strategy is based on the identification and enablement of safe spaces in different areas of the city, such as public buildings, schools, parks, and other places that meet certain safety requirements, which allows for wide coverage in case of emergency.

This Safe Sites initiative was developed in collaboration with several international and local organizations, which allowed for the mobilization of resources and the implementation of best practices in the identification and enablement of these sites. Initially, 30 of these sites were planned to accommodate up to 700,000 people [68]. In addition, the community was involved in the process, which ensured that the selected sites were relevant and acceptable to the local population.

Currently, the Metropolitan District of Quito, through the Secretariat of Security and Governance of the Municipality of Quito, has released “a table and a map of the 79 points where the Safe Sites are located, with the aim of making it easy for citizens to locate them” [69], the locations of the Safe Sites are detailed below (**Table 3**).

The following map was also released (**Figure 1**).

As can be seen, none of the Safe Sites indicated by the Municipality of Quito are located in the informal settlements approved in the Tumbaco Zonal Administration,

³ This phrase became common in the approval of Human Settlements ordinances of Fact and Consolidated since 2016.

⁴ An example of this is ordinance 2019–303, which recognizes and approves the subdivision of property no. 5148320, where the consolidated and de facto human settlement of social interest called “Triángulo de Yaruquí”

N°.	Safe sites	Ubication
South		
1	Southern Metropolitan Park	El Troje, Av. Simón Bolívar
2	Quitumbe Square	Av. Quitumbe s/n and Condor Ñan
3	UTAQ Park	Leonidas Dubles E5B
4	Nueva Aurora Park	Manuel Guamaní and Principal
5	Solanda Ecological Park	José Abarcas y J. Alemán
6	Las Cuadras Park	Av. Rumichaca and Av. Morán Valverde
7	Solanda S4 Park	Calle Manuel Monteros y José Pontón
8	Solanda Neighborhood League	José Alemán And Ajaví
9	Solanda S2 Park	Calle Francisco Rueda and Simón Guerra
10	Cardinal de la Torre Park	Av. Cardenal de la Torre, between Ajaví and Tnte. Ortiz
11	Combatientes del 41 Park	Angamarca and Río Cristal
12	National Ball Complex	Calle Ecuador y Chugchilán
13	Chimborazo Battalion Park	Calle Punta Arenas
14	December 4th Park	Felicísimo López y Chilibulo
15	Concepción Sur Park and League	Calle Egusquiza and Benito Flores
16	Yaguachi Park	Gral. Pintag y Tnte. García
17	Metro Park	Jacinto Collaguazo and R. Chávez
18	Skate Park	Calle Princesa Toa and Cori Duchicela
19	January 14th Cooperative Park	Chicaña y Paquisha
20	La Raya Park	San Luis and Tnte. Hugo Ortiz
21	Puengasí Treatment Plant	Av. Simón Bolívar junto P. Metropolitano
22	Factory Theme Park	Av. Maldonado and Pujilí
23	Eplicachima Barracks	Av. Maldonado and Joaquín Gutiérrez
24	Liga Oriental Stadium	Abelardo Andrade and Hermandad Ferroviaria
25	July 17th Park	Lorenzo de Garaicoa and Maridueña
26	Chimbacalle Stadium	Juan de Alcázar and Andrés Pérez
27	Caupicho Park	Leonidas Dubles E5B
Center		
28	San Francisco de Quito (Obrero Independiente) courts	Constantino Fernández and Ricardo Izurieta del Castillo Street
29	San Francisco Square	Cuenca and Sucre
30	Santo Domingo Square	Flores, between Bolivar and Rocafuerte
31	Plaza Grande	Between Venezuela and García Moreno
32	Chica Square	Espejo Passage between Guayaquil and Venezuela
33	San Blas Square	Pichincha Ave. and Francisco de Caldas
34	Itchimbía Park	Itchimbía and Fray Jodoco Ricke
35	El Arbolito Park	12 de Octubre Ave. and Tarqui

N°.	Safe sites	Ubication
36	La Alameda Park	10 de Agosto Ave. and Gran Colombia
37	El Ejido Park	Tarqui Ave. and 10 de Agosto Ave.
38	La Vicentina “Vacas Galindo” Park	Godín Street
39	La Vicentina Neighborhood League	Godín and Condamine Street
North		
40	Women’s Park	Av. Mariana de Jesús and Diego Martín de Utreras
41	Burgeois Park	Burgeois and Teresa de Cepeda
42	El Heraldo Park	El Heraldo and El Día
43	Gualgüiltagua Metropolitan Park	Gualgüiltagua and Diego Noboa
44	La Carolina Park	Av. Eloy Alfaro and República
45	Seymour Island Park	Isla Seymour and Isla Floreana
46	Sixto María Durán Park	Duarte and Brasil
47	Emblematic Park	Jorge Piedra and Calle 10
48	La Luz Park	Diógenes Paredes and Rafael Ramos
49	Bicentennial Park	Av. Amazonas and De La Prensa
50	English Park	General Vicente Aguirre and Machala
51	La Victoria Park	Pío Jaramillo and Isaac Barrera
52	Matovelle Park	Juan Alzuro and Calle K Barrera
53	Einstein Park	Roberto Andrade and Alberto Einstein
54	Carcelén Park	G. Duarte and Alejandro Ponce
55	Carapungo Recreational Area	José Velasco Ibarra and Juan de Dios Martínez
56	Calderón Pampa	Independencia, between Giovanni Calles and 9 de Agosto
57	C and D Park	Galo Plaza Lasso and Juan de Dios Martínez
58	Municipal Educational Unit Esplanade	Amalia Eriguen and Agustín Guerrero
59	Los Nardos Communal Area	Jacaranda and Fidel Martínez
60	Ecuador Neighborhood Sports Field	Eloy Alfaro and Alta Tensión Street
61	San José de Morán Urbanization Park	Carlos Mantilla and Eloy Alfaro
62	La Bombonerita Sports Field, next to the CDC of Llano Chico	17 de diciembre and La Delicia
63	March 18 Sports Field	3 de mayo and Río Amazonas
64	San Miguel Commune Central Park	Atahualpa and España
65	Oyacoto Central Park	Atahualpa and 4 de octubre
66	Llano Grande Market	García Moreno next to the UPC, Ingahuayco Neighborhood
67	Bicentennial Green Area	Eloy Alfaro and extension of Av. Simón Bolívar
Valleys		
68	Bretaña Park	El Beaterio and A Street, Conocoto
69	Armenia Park	Sebastián de Benalcázar Street, La Armenia way
70	La Moya Park	Julio Moreno and Mideros Street, Conocoto

N°.	Safe sites	Ubication
71	Intergenerational Park	Azuay and Santa Isabel Street
72	Cuendina Neighborhood Sports Club	Los Capulíes Street
73	Central Neighborhood Sports Club	Antisana and Sucre Street
74	Tonlontag Stadium	Main Avenue
75	La Hospitalaria Stadium	Manuela Cañizares and Francisco Olearys Street
76	Ministry of Sports Recreation Center, Ushimana	Río Ushimana and Puerto Rico Street
77	Central Neighborhood Stadium	Atahualpa Street
78	Tumbaco Central Park	Francisco de Orellana and Eugenio Espejo Street
79	Electric Company Complex	Cumbayá Reservoir

Table 3.
Secure sites on the Metropolitan District of Quito [69].

and in the event of a disaster, the populations of these settlements would have to move several kilometers⁵.

Upon reviewing the Annual Procurement Plan of the Decentralized Autonomous Government of the Metropolitan District of Quito [70] from 2019 to the present, no contracts related to Safe Sites have been awarded. Therefore, the information provided is simply to disclose parks and areas designated as meeting points, which for the most part are not suitable or equipped to deal with emergency situations.

1.4 Part IV: habitat III, the new urban agenda, and human settlements

In 2016, Quito hosted Habitat III, the United Nations Conference on Housing and Sustainable Urban Development, which brought together world leaders, urban development experts, international cooperation professionals, academia, civil society representatives, and other relevant actors to discuss and define a new global agenda for sustainable urban development.

This conference adopted the New Urban Agenda, a document that establishes a common vision to achieve more sustainable, inclusive, and resilient cities. The agenda addresses key issues such as access to housing, sustainable mobility, urban planning, risk management, and citizen participation.

Regarding human settlements, the New Urban Agenda recognizes the importance of improving the living conditions of inhabitants in informal settlements, as well as the need to promote social inclusion in urban planning processes. Additionally, it emphasizes the need to adopt an integrated approach to disaster risk management, including disaster risk reduction, emergency preparedness, and early recovery of populations.

The New Urban Agenda highlights the need to strengthen cities' resilience capacity against risks and disasters, as well as integrate risk management into urban planning processes and decision-making, considering that risk management is a critical issue for achieving more sustainable and inclusive cities [71].

The Sustainable Development Goals (SDGs) were proposed for the purpose of achieving more sustainable and inclusive cities, which the New Urban Agenda

⁵ For example, the Human Settlement of Fact and Consolidated Jesús del Gran Poder, located in the parish of El Quinche, is more than 28 km away from the nearest Safe Site, located in the center of Tumbaco.

recognizes as important. There is emphasis on the need to align urban policies and practices with the SDGs and integrate the objectives and targets of the SDGs into urban planning and decision-making processes.

It can be concluded that Habitat III and the New Urban Agenda adopted therein are a key milestone in the pursuit of more inclusive, sustainable, and resilient cities. However, achieving sustainable and equitable urban development, with populations prepared to face disasters, requires close collaboration among local governments, civil society, the private sector, and the international community.

Regarding human settlements and risk management, these aspects are addressed in several SDGs of the United Nations' 2030 Agenda [72], including the following objectives:

- SDG 1: Eradication of poverty, which aims to ensure that all people, especially the most vulnerable, have access to basic resources such as adequate and dignified housing, clean water, sanitation, basic services, and community facilities [73].
- SDG 11: Sustainable cities and communities, which seeks to improve city planning and management, including reducing the vulnerability of people to natural disasters, and promoting inclusive, safe, sustainable, and resilient human settlements [74].
- SDG 13: Climate action, which aims to reduce the vulnerability and increase the resilience of communities to climate change, including promoting risk management policies and practices [75].
- SDG 17: Partnerships for the goals, which seeks to strengthen partnerships among governments, civil society, and the private sector to promote sustainable development, including technology and knowledge transfer and international cooperation [76].

It is important to highlight that these objectives are interrelated and mutually reinforcing, making it necessary to address them comprehensively to achieve sustainable and resilient development in human settlements, both informal and consolidated.

1.5 Part V: international cooperation as a mechanism for disaster management

International cooperation has evolved over the last few decades into a fundamental tool for achieving development goals. It is now indispensable for addressing the global challenges that humanity faces, especially in the context of risk management and resilience to natural disasters. In the case of Ecuador, as we have seen, a country highly vulnerable to extreme climate events, international cooperation has been key to the implementation of projects and programs aimed at preventing and mitigating the effects of these events on the population and infrastructure. Furthermore, international cooperation has enabled the strengthening of local capacities, the transfer of knowledge and technologies, and the promotion of collaboration between different actors, both nationally and internationally, to achieve sustainable and resilient development.

Due to the numerous natural and anthropogenic events, there are many examples of international cooperation projects and good practices that have helped populations affected by natural disasters worldwide. For the purposes of this chapter, two examples of international cooperation carried out by the United Nations Development Programme at the international and Ecuadorian level are presented.

1.6 Part VI: international Cooperation as a mechanism to address disasters

International cooperation has evolved in recent decades as a fundamental tool for achieving development objectives, to the point that it is now indispensable for tackling the global challenges facing humanity, particularly in the field of risk management and resilience to natural disasters. In the context of Ecuador, which, as we have seen, is a highly vulnerable country to extreme climate events, international cooperation has been key to the implementation of projects and programs aimed at preventing and mitigating the effects of these events on the population and infrastructure. In addition, international cooperation has allowed for the strengthening of local capacities, the transfer of knowledge and technologies, and the promotion of collaboration among different actors, both at the national and international levels, in order to achieve sustainable and resilient development.

Due to the multiple natural and anthropogenic events, there are many examples of international cooperation projects and good practices that have helped populations affected by natural disasters worldwide, of which two examples of international cooperation projects implemented by the United Nations Development Programme (UNDP) at the international level and in Ecuador are presented for the purpose of this chapter's exposition.

The Philippines Development Plan (PDP) developed by the United Nations Development Programme (UNDP) in coordination with the Philippine government focuses on reducing disaster risk in vulnerable communities through improved infrastructure, strengthening the capacity of local governments, and community education in risk management. This project has proven to be successful in increasing communities' capacity to face and recover from natural disasters [77].

In Ecuador, an example of good practice in international cooperation is the project "Resilience of the population in vulnerable situations and at risk in Ecuador (RPVE)," implemented by UNDP in partnership with the Municipality of Chillanes, Central Ecuadorian Foundation for Agricultural Services "CESA," Foundation for Economic and Ecological Habitat Development "ECOSUR ECUADOR," Bolivar Prefecture, Municipality of San Miguel, Chillanes Fire Department, National Service for Risk Management and Emergencies - Provincial Directorate of Bolivar, and the Ministry of Public Health - District Directorate of Chillanes, District Directorate of Guaranda, and Hospital of Guaranda. Rural communities in the Bolivar province have been reducing the risk of COVID-19 transmission through prevention actions implemented by the project, as well as having Community Emergency Committees and first response brigades for emergencies [78].

Furthermore, this strategies of cooperation involves collaboration and support from various countries, international organizations, and non-governmental entities to address the unique challenges faced by these settlements. As some examples of methods and models, we can highlight the following:

- a. **Data Sharing and Analysis:** International organizations and countries can collaborate to gather and share data on disaster risks and vulnerabilities in the Tumbaco Zone Administration. In fact, this data can help identify high-risk areas and prioritize interventions;
- b. **Capacity Building:** International cooperation can provide resources, expertise, and training to strengthen the capacity of local authorities and communities

- j. Advocacy and Awareness: International cooperation can support advocacy campaigns to raise awareness about the importance of disaster risk reduction and its relevance in informal and consolidated human settlements.

2. Conclusion

With this background, it is evident that Ecuador, despite having a long history of natural disasters, has not been able to implement effective plans for risk prevention and mitigation, and in the case of the Metropolitan District of Quito, despite being the venue for Habitat III, this has not been the exception.

It is clear that in recent years, instead of investing in risk mitigation programs or adopting policies that promote risk prevention, the Municipality of the Metropolitan District of Quito has been reducing the number of green areas in informal and consolidated settlements, leaving them without spaces where equipment or safe sites can be implemented. This means that, at some point when a natural disaster occurs, the population will not have spaces to take refuge, carry out first aid tasks, triage, and carry out activities that lead to a dignified resilience process.

International cooperation is an important tool for preventing and mitigating risks associated with natural disasters and promoting resilience in affected populations. It is crucial that the Central Government, decentralized autonomous governments at all levels, manage resources and technical cooperation to generate preventive and palliative programs for the various scenarios that will occur in the national territory. All this must be done hand in hand with the Sustainable Development Goals, the New Urban Agenda, and based on the inclusion and participation of the community in the generation of policies and development of activities.

In sum, it is essential to recognize that the needs and challenges of each community within the Tumbaco Zone Administration may vary. Therefore, international cooperation should be sensitive to local contexts, cultures, and existing capacities while effectively providing support and resources to address disaster risks. Collaboration between stakeholders, including local governments, international organizations, NGOs, and affected communities, will be vital to achieving meaningful and sustainable results.

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Ebba Ossiannilsson, Rui Alexandre Castanho
and Luís Loures*

In a rapidly changing world, the need for sustainable development has never been more urgent. This volume explores the critical challenges of balancing economic growth with environmental responsibility, emphasizing the importance of global cooperation and innovative solutions. Through a multidisciplinary approach, it examines strategies for efficiently managing resources, fostering social equity and wellbeing, and building resilient systems for future generations through knowledge and education. Featuring insights from leading experts, this book provides valuable perspectives on how businesses, governments, organizations, and communities can drive meaningful change. It is an essential resource for those committed to creating a more sustainable and equitable world.

*Usha Iyer-Raniga,
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Published in London, UK

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