How can information systems assist vulnerable communities in their transition toward viability?

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Statement of Contributions

Elham Mohammadi was the sole author of Chapter 1 and Chapter 5 of this thesis, which were written under the supervision of Dr. Simron Singh and Dr. Prateep Nayak and were not intended for publication.

This thesis consists in part of three research manuscripts (Chapters 2–4) prepared for publication. Exceptions to sole authorship of the material in Chapters 2–4 are detailed below:

Chapter 2

Chapter 2 is based on a manuscript co-authored with Dr. Simron Singh, Dr. Prateep Nayak, and Dr. Cameron McCordic. This research was conducted as part of the Vulnerability to Viability (V2V) Global Partnership for Building Strong Small-Scale Fisheries Communities (SSHRC Partnership Grant #895-2020-1021) at the University of Waterloo. Elham Mohammadi was the lead author, conducting the data gathering, analysis, and drafting the manuscript under the supervision of Dr. Singh, Dr. Nayak. Dr. McCordic provided guidance on the methodology and analysis. Dr. Singh, Dr. Nayak. and Dr. McCordic all contributed to the manuscript revisions.

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Citation (Chapter 4): Mohammadi, E., Singh, S. J., Nayak, P. (Forthcoming). *Towards Sustainable and Polycentric Information Systems for Small-Scale Fishers: Lessons from Kumirmari Island, India.* Manuscript in preparation (to be submitted for publication).

Abstract

Information Systems (IS) have the potential to play a crucial role in addressing complex global challenges, from climate change and resource management to social inequality and food insecurity. Despite their widespread applications in numerous sectors, the use of IS to support the sustainability of small-scale fisheries (SSF) remains underexplored. SSF are critical to global food and nutrition security, particularly on islands, where they are essential for local economies and cultural identity. These communities face significant vulnerabilities due to their geographic position, environmental uncertainties, and socio-economic constraints. Existing systems for fisheries are often generic, insufficiently localized, or not tailored to the specific needs of these communities. These gaps limit the ability of the fishers to adapt to changing conditions, optimize resource use, and ensure long-term sustainability. There is a growing need to design and implement IS that are not only accessible but also relevant for SSF. Such systems are crucial for empowering fishing communities, helping them navigate their challenges and fostering a transition toward sustainability.

To address the existing gaps, the main objective of this research is to identify the key principles for designing IS tailored to vulnerable small-scale fishers, supporting their transition toward viability and sustainability. The first part of the study examines SSFs' food systems in island communities, identifying critical factors that influence their vulnerability and viability with regard to food and nutrition security. The second and third parts of the study focus on IS, specifically identifying the requirements of users within these communities and evaluating whether existing systems adequately address these requirements. Finally, the study proposes key design principles for developing IS that can effectively support the sustainability of SSF.

The first part of this thesis focuses on fishers in Small Island Developing States (SIDS), identifying their vulnerabilities and potential viabilities concerning food and nutrition security. The second and third parts of the research focus on fishers in Kumirmari Island, India. Data for the latter sections are collected through surveys and interviews. Interviews are conducted with the members of the information system development team behind the Fisher Friend app. The study introduces the User-Requirements Hierarchy (URH), which is developed based on the Contextual Participatory Design approach. Then, it suggests PUCT Dimensions—including Polycentricity, User-Centricity, Contextuality, and Technicality— as key elements for Information System design for vulnerable communities.

This study contributes to the information system field, particularly in its role in supporting vulnerable communities. It advances the discourse on context-driven design by highlighting the importance of considering both vulnerabilities and viabilities. The study underscores that vulnerability and viability exist on a continuum, and to help communities overcome their vulnerabilities, their long-term decisions as well as viabilities must be recognized and invested in. While community empowerment and agency have emerged in the literature as core principles of technologies for vulnerable populations, their practical application remains unclear. A gap exists between the theoretical understanding and the practical guidance needed to implement it effectively in real-world situations. This research aims to address this gap by introducing the URH and PUCT Dimensions. The study presents design principles that ensure IS align with fisheries' realities and requirements. Drawing from field-based evidence from Kumirmari, the research provides novel insights into designing digital tools, uncovering unrecognized challenges and barriers, and emphasizing the need for polycentric approaches in system development. Practically, this study informs the design of new technologies, ensuring that they are not imposed on communities but are instead developed collaboratively.

The findings of this thesis aim to assist in developing IS that support vulnerable communities in moving toward viability, with a specific focus on food and nutrition security. The findings support creating systems that align with the complex contexts of these communities. The suggested approaches can set the stage for future data collection, knowledge creation, and information system design efforts; helping ensure that the delivered systems are equitable, sustainable, and contextually relevant for vulnerable communities. Ultimately, these systems transform information into actionable knowledge, empowering communities to make informed decisions that drive more sustainable practices.

Keywords: Food and Nutrition Security, Vulnerability, Viability, Information System, Small-Scale Fisheries

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This PhD journey has profoundly changed my life. It has been a time of both academic and personal growth, from engaging with the student community and teaching, to leading initiatives and navigating the challenges of balancing my studies with motherhood. The experience has taught me resilience, perseverance, and the importance of adaptability. As I reflect on this journey, I am grateful for how far I've come, the lessons I’ve learned, and I am thankful to everyone who made this possible.

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A special thank you goes to my supervisor, Professor Simron Singh, whose kindness, guidance, and unwavering support have been pivotal to my growth since I began my Master’s in 2018. His encouragement has been a constant source of inspiration, helping me overcome obstacles and celebrate my successes. Beyond his academic mentorship, he has opened doors for me to explore new professional horizons. His belief in me as a scholar has shaped my journey in profound ways, and I will always be grateful for his support.

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I acknowledge this journey that has shaped me so,
A path of growth where both heart and mind did flow.
A journey long, through trials and grace,
With every step, I found my place.

Through sleepless nights and days of doubt,
I learned what strength was all about.
In classrooms, halls, and hearts I grew,
With lessons learned and friendships true.

A mother, scholar, navigating the tide,
In resilience and love, I did abide.
Grateful for each twist and turn,
For every page, for all I've learned.

This path, though hard, has made me whole,
A journey etched upon my soul.

Dedication

To My Forever Sunshine, Dario!

This thesis is as much yours as it is mine—not only because of your love for shrimp, salmon, and my computer but because your laughter, energy, and joyful spirit have been my greatest source of inspiration. Every smile you shared and every moment of happiness we created together gave me the strength to keep going. You reminded me daily of what truly matters in life, and your love fueled my resilience throughout this journey. This achievement is ours to celebrate, and I am endlessly grateful for the light you bring to my life. And let's be honest—without your occasional naps, this thesis might still be in progress!

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Abbreviations and Acronyms

- Contextual Participatory Design (CPD)
- Decision support system (DSS)
- Food and nutrition security (FNS)
- Food and nutrition insecurity (FNIS)
- Food Security (FS)
- Information systems (IS)
- Participatory Design (PD)
- Research question (RQ)
- Small-scale fisheries (SSF)
- The Food and Agriculture Organization of the United Nations (FAO)
- User-Requirements Hierarchy (URH)
- Vulnerability analysis (VA)
- Vulnerability to viability (V2V)

Clarification of Key Terms

Information System: In this thesis, the term *information system* refers to a single one-stop application that delivers real-time, customized information to users—specifically, small-scale fishers. This system provides essential functionalities, such as weather forecasts and market prices, designed to support users' livelihoods and decision-making while promoting their sustainability.

Viability: Viability denotes the attributes, capacities, and conditions of a system to thrive and sustain its essential functionalities and cohesion over time despite exposure to diverse internal or external stressors, which can be affected by an array of factors (as developed in this thesis).

Vulnerability: "The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards" (UNISDR, 2017).

Preface

This thesis presents research conducted as part of the PhD program in Sustainability Management at the School of Environment, Enterprise, and Development (SEED), within the Faculty of Environment at the University of Waterloo. The study was undertaken under the supervision of Professor Simron Jit Singh and Professor Prateep Nayak. It was carried out within the framework of the research project V2V Global Partnership (https://www.v2vglobalpartnership.org), supported by funding from the Social Sciences and Humanities Research Council of Canada.

This PhD thesis is built upon the research presented in three submitted papers:

Chapter 2: Mohammadi, E., Singh, S. J., Nayak, P., McCordic, C. (Forthcoming). Food and Nutrition Insecurity of Small-Scale Fisheries in Islands: Implications of Machine Learning for a Transition from Vulnerability to Viability.

Chapter 3: Mohammadi, E., Singh, S. J., Nayak, P., Patnaik, P., Mukherjee, J., Kumar Das, A. (Forthcoming). Core Qualities of a User-Centered IS for Small-Scale Fisheries.

Chapter 4: Mohammadi, E., Singh, S. J., Nayak, P. (Forthcoming). Towards Sustainable and Polycentric Information Systems for Small-Scale Fishers: Lessons from Kumirmari Island, India.

In addition, the following research works were conducted during this PhD journey, though they are not included in this thesis:

I. Habib, K., Mohammadi, E., Habib H., Lifetime and Disposal Pathways of Electronics: A Case Study of Canada. Resources, Environment and Sustainability. (Forthcoming)

II. Habib, K., Mohammadi, E., & Withanage, S. V. (2023). A first comprehensive estimate of electronic waste in Canada. Journal of Hazardous Materials, 448, 130865.

III. Mohammadi, E., Singh, S. J., McCordic, C., & Pittman, J. (2022). Food security challenges and options in the Caribbean: insights from a scoping review. Anthropocene Science, 1(1), 91-108.

IV. McCordic, C., Mohammadi, E., & Singh, S. (2022). The priorities and coping strategies of severely food insecure households in Beira in response to Cyclone Idai. International Journal of Disaster Risk Reduction, 83, 103423.

Chapter 1

Introduction

Food and nutrition insecurity (FNIS) remains a pressing global issue, characterized by stagnation in progress and rising disparities. In 2023, between 713 and 757 million people faced hunger globally, representing 8.9 to 9.4 percent of the world population (FAO, IFAD, et al., 2024). Moderate or severe food insecurity affected 2.33 billion people or 28.9 percent of the global population. Projections suggest that by 2030, 582 million people will remain chronically undernourished, marking an increase of 130 million compared to pre-COVID-19 estimates, with over half of those affected residing in Africa. Rural populations experience higher food insecurity rates (31.9 percent) compared to urban areas (25.5 percent), and the affordability of healthy diets remains a challenge *(ibid)*. The goal of ending hunger by 2030 is becoming increasingly far-fetched, underscoring the need for well-designed, innovative strategies to address food and nutrition security (FNS) challenges (*ibid*). This is particularly critical for vulnerable communities that remain at the highest risk.

Small-scale fisheries (SSF) refer to fishing practices that rely on "low-technology, low-capital, and labour-intensive" methods, covering the entire chain of activities—from preparing for fishing (pre-harvesting) and catching the fish (harvesting) to processing and handling the catch (post-harvesting), including subsistence fishing (FAO, Duke University, et al., 2024). SSF are indispensable to global FNS, especially for marginalized populations. SSF contribute approximately 40% of the worldwide fish catch, providing direct employment to over 60.2 million individuals, which accounts for 90% of all fishery employment worldwide (*ibid*). These fisheries also directly support the livelihoods of an estimated 492 million people, demonstrating their broad social impact and importance for economic stability in many regions (*ibid*). Nutritionally, SSF are vital suppliers of micronutrients such as calcium, zinc, and omega-3 fatty acids, which are critical for maintaining human health (FAO et al., 2023). The existing literature explores SSF's value in global FNS through various dimensions, including their nutritional contributions (e.g., Hicks et al., 2019), role in food security (Rice & Garcia, 2011), and importance for food systems (e.g., Charlton et al., 2016), as well as the threats they face, for example, to access enough fish for good nutrition (e.g., Bell et al., 2009). Some studies have looked at the significance of SSF in employment and poverty alleviation (e.g., Belhabib et al., 2015; Béné et al., 2007), or the role of SSF in the context of alleviating FNIS and poverty eradication (e.g., FAO, 2015). Despite the contributions of SSF to the global food system, food security has been identified as one of the most pressing issues confronting SSF.

While SSF provide indispensable contributions to global food security, a critical gap remains: the absence of well-designed information systems (IS) to support their operations. SSF is often underrepresented in existing IS and technological interventions, necessitating increased investment in tailored solutions to address their needs, enhance their visibility, amplify their contributions, and foster sustainable development (Chuenpagdee et al., 2019; Machado et al., 2021). The existing IS for fisheries usually fail to capture the diverse and complex characteristics of the fishers, causing a lack of usable, understandable, and up-to-date data and information (Chuenpagdee et al., 2019). This deficiency can further intensify these communities' marginalization, limiting their representation, recognition, and capacity for empowerment (*ibid*).

Focusing on SSF on islands, the issue is even more acute due to unique geographical, environmental, and socio-economic challenges. Islands often face significant barriers, including limited access to technology and IS, which can exacerbate their vulnerabilities (e.g., Tilley et al., 2024). Limited infrastructure and the high costs associated with implementing digital technologies and data systems can restrict the fisheries' capacity to effectively monitor and manage their resources (Bradley et al., 2019). These limitations highlight the need for tailored solutions that can address the unique needs of SSF, encouraging us to undertake this research.

1.1. Background

Information Systems have been defined in various ways over time, reflecting evolving perspectives on their components and functions. Galliers and Leidner described IS as systems combining hardware, software, and telecommunications networks to enable people to gather, generate, and share valuable data, primarily within organizational contexts. Later, O'Brien and Marakas (2008) expanded this view by emphasizing the organized integration of people, hardware, software, communication networks, and data resources, along with policies and procedures, to store, process, and disseminate information effectively within an organization. More recently, Laudon and Laudon (2022) provided a technical perspective, defining IS as interconnected components designed to collect, process, store, and distribute information to support organizational decision-making and control. These definitions highlight Information Systems' role in leveraging technology, human input, and structured processes to facilitate information management and organizational functionality.

The origins of IS trace back to the mid-20th century, co-occurring with the rise of computing technologies such as IBM's 360 series and the advent of database technology, which emphasized automating routine tasks and managing organizational data (Kadry, 2014). Initially driven by the needs of engineering and accounting departments, IS evolved from simple transaction processing tools to integrated frameworks that centralized data processing, improved efficiency, and facilitated communication and operational alignment across businesses (*ibid*). Over time, IS expanded into a multidisciplinary field, integrating computer science, management, sociology, and psychology principles to address broader societal needs and challenges (Whitworth & Ahmad, 2013).

IS encompasses several common types, each designed for specific functions; Transaction Processing Systems (TPS) manage routine operations such as payroll and order processing, ensuring the smooth functioning of organizational transactions; Management Information Systems (MIS) provide structured reports and insights to managers for effective decision-making; Decision Support

Systems (DSS) aid in non-routine decision-making through the analysis of large datasets; Enterprise Systems integrate core business processes across departments, exemplified by Enterprise Resource Planning (ERP) applications; and Knowledge Management Systems (KMS) facilitate the creation, sharing, and management of organizational knowledge (Whitworth & Ahmad, 2013). Additionally, there is another category about social and collaborative platforms and systems, which can be viewed as IS that facilitate interactions and content sharing, further enriching the information systems landscape (*ibid*).

Over the years, research in IS has undergone substantial transformations. In its early years, research focused primarily on automating tasks and optimizing technical processes (Whitworth & Liu, 2008). As the field progressed, socio-technical perspectives developed, emphasizing that systems designed to address both social and technical needs tend to achieve better social outcomes (Whitworth & Ahmad, 2013). The evolution of IS research has been guided by frameworks such as Actor-Network Theory (Walsham, 1997), Structuration Theory (Jones & Karsten, 2008), and Human-Computer Interaction (HCI) (Whitworth & Liu, 2009), which explore the interplay between human and non-human entities, alongside methods such as participatory design (Cherry & Macredie, 1999) and socio-technical systems theory (Whitworth & Ahmad, 2013), which emphasize user collaboration and the alignment of social and technical needs. These advancements underscore the evolution of IS research from a predominantly technical focus to an interdisciplinary endeavour addressing complex human and societal needs.

Since 1960, there have been ongoing debates on reinforcing the power, agency, and equity in new technologies, including IS. Since the mid-1960s, scholars and activists have explored how technology shapes power, inequality, and justice. The Non-Aligned Movement sought technological independence from dominant powers, while Robert Merton (1968) highlighted how meritocracy ignores systemic barriers. In the 1980s and 1990s, Aníbal Quijano developed the idea of coloniality (Quijano, 1986), later influencing theories of data colonialism. Concerns over bias in technology grew, with Value-Sensitive Design (Friedman, 1996) addressing discrimination in computer systems. Then, legal and social critiques emerged, and movements such as DiscoTech (2009) promoted community-driven tech (as mentioned by Costanza-Chock, 2020). Scholars deepened these critiques, with Danah Boyd and Kate Crawford (2012) questioning big data, Casati (2013) discussing digital colonialism, and Syed Mustafa Ali (2014) arguing that computing is essentially colonial. Later in 2016, Thatcher et al. introduced data colonialism.

Historically, IS for SSF relied on fragmented, manual approaches, making it challenging to integrate the socio-economic and ecological contributions of these fisheries into broader policymaking frameworks (Chuenpagdee et al., 2017). Traditional IS often focus on large-scale, industrial fisheries, leaving SSF even more marginalized in governance and resource allocation (*ibid*). This marginalization is partly due to the diversity and complexity of SSF, which operate in diverse environments with varying fishing practices, making standardized data collection difficult (*ibid*). Recognizing this gap, initiatives such as the FAO's *Voluntary Guidelines for Securing Sustainable SSF* emphasized the need for gender-disaggregated and context-specific data to enhance the visibility of SSF in global fisheries governance (FAO, 2015).

A growing number of studies have started to support SSF in recent years to tackle their challenges with the help of IS. The majority of these efforts are specifically focused on fishing sites (e.g., Zeller et al., 2006), fishing boats (e.g., Johnson et al., 2017), estimating exploitation patterns (e.g., Newton et al., 2007), fleet behaviour (zones/seasons) (e.g., Armenta-Cisneros et al., 2021), and species production (catch and value per species) (e.g., Armenta-Cisneros et al., 2021; Damasio et al., 2015; Zeller et al., 2006). These efforts are still limited, and the SSF sector as a critical system has received little attention.

Over the past decade, IS development for SSF has evolved, mainly driven by advances in digital technologies. Platforms such as the *Information System on Small-Scale Fisheries (ISSF)*, developed under the "Too Big To Ignore" (TBTI) project, represent a significant step toward addressing existing gaps. The ISSF is a publicly accessible, web-based platform designed to facilitate the collection, integration, and sharing of data for SSF. It serves as a resource for stakeholders to both contribute and retrieve valuable information. However, the platform is not specifically designed for direct use by fishers, and it is mainly intended to be used by researchers, policymakers, and practitioners. Similarly, tools such as the PeskAAS system in Timor-Leste integrate GPS tracking and mobile data collection, providing policymakers with real-time data to inform sustainable fisheries management (Tilley & Rossignoli, 2024). While PeskAAS provides open access to aggregated data, the practical barriers, such as low digital literacy and access to technology, hinder fishers from directly utilizing the system (Tilley et al., 2020). An additional case in point is the *Asia–Africa BlueTech Superhighway (AABS)* project, which fosters collaborations to co-design digital monitoring tools tailored to the unique needs of SSF in countries such as Kenya, Mozambique, and Zanzibar (Bevitt & Tilley, 2024). However, the accessibility of the *AABS* for individual fishers is constrained, again by issues such as low digital literacy, unreliable infrastructure, and high costs associated with implementation (Bevitt & Tilley, 2024).

Although recent interventions hold great promise in addressing current gaps, their direct usability for fishers themselves often remains narrow in scope. Limited digital literacy, inadequate infrastructure, and inconsistent government investments hinder the adoption of these systems, particularly in remote or low-income regions (Bevitt & Tilley, 2024; FAO & WorldFish, 2020). Some of these challenges can be addressed by recent advancements, such as open-source software availability, artificial intelligence, and the adoption of participatory design approaches. These developments can support the inclusivity and sustainability of SSF by promoting broader engagement and more effective systems (Bevitt & Tilley, 2024).

1.2. Statement of the Problem

The obvious vulnerability and failure to achieve sustainability [including food and nutrition security] in SSF have intensified criticism of the management approaches commonly used in these fisheries (Castrejon et al., 2014). Some decisions and practices are biased against SSF due to a lack of data (Jacquet & Pauly, 2008) and appropriate IS (Chuenpagdee et al., 2019). These efforts have not resulted in sustainability in related practices and policies, partly because these programmes do not fit these fisheries (*ibid*). Still, one of the serious complications of evaluating and managing SSF, especially when compared to industrial fisheries, is a lack of adequate data and information (Kolding et al., 2014). The significant amounts that have been invested in sustainable seafood activities are not benefitting SSF around the world (Jacquet & Pauly, 2008). Because of their miscellany, dispersion, and social complexity, SSF are frequently underdocumented and underregulated, and many complex management challenges are primarily unaddressed (World Bank, 2012). Failure to address the challenges faced by the SSF threatens the livelihoods of millions of people (World Bank, 2012). Together, these factors highlight the critical role of IS in improving the relevance and effectiveness of solutions for SSF, ensuring that these communities can benefit from more accessible, sustainable, and contextually relevant data, information, and tools for their livelihoods.

1.3. Significance of the Problem and Contribution of the Study

This study is significant because it addresses the critical gaps in the design of IS for vulnerable communities, which are often overlooked in current practices. Despite the growing recognition of the need for inclusive, participatory, and context-aware approaches, many systems still fail to include marginalized users in the design process, often leading to exclusion and reinforcing existing inequalities (Costanza-Chock, 2020; Couldry & Mejias, 2023). This research contributes by providing practical design approaches for information system development that emphasize community empowerment, accessibility, and inclusivity. By focusing on the unique needs and expertise of vulnerable populations, this study highlights the importance of community-led and polycentric approaches. It addresses the challenges of power dynamics, which often hinder equitable system design (as highlighted by Costanza-Chock, 2020; Couldry & Mejias, 2023; Skarlatidou & Haklay, 2021). By providing concrete approaches, this research aims to bridge the gap between theory and practice, ensuring that technology serves the needs of vulnerable communities while respecting contextual, cultural, and social considerations.

1.4. Main Research Objective and Questions

The long-term goal of this study is to establish a research trajectory centred on the vulnerability analysis of small-scale fisheries on islands, providing evidence-based insights to guide information systems in supporting vulnerable communities in their transition from vulnerability to viability. Toward this end, we explored the characteristics, fundamentals, and qualities of a suitable information system needed to support vulnerable communities.

Main objective: To identify the key principles for designing information systems tailored to vulnerable small-scale fishing communities, ensuring equity and transformation to guide them toward food and nutrition security, thereby supporting their transition to viability.

To achieve this objective, this study answered three main questions:

RQ 1) Given the trends, patterns, threats, and opportunities for small-scale fisheries, what indices can be used to track their vulnerability/viability dimensions to food and nutrition insecurity? (Section 2)

RQ 2) What are the core qualities of a participatory information system that can support decision-making in planning for sustainable food systems aimed at the unique needs of vulnerable SSF communities in transitioning from vulnerability to viability? (Section 3)

RQ 3) How should an information system be designed to ensure that power dynamics are egalitarian, allowing all stakeholders to benefit from and contribute to knowledge and to assist vulnerable communities in transitioning from vulnerability to viability? (Section 4)

1.5. Research Design and Methodology Overview

The initial phase of the thesis primarily focused on capturing system or contextual knowledge pertinent to fishers. The subsequent phase investigated the needs and expectations of fishers, referred to as target knowledge. And, the third phase focused on the principal dimensions that should be considered during the design. This phase helps to ensure that the IS are capable of fostering transformative knowledge and ultimately leading to sustainable action in the long term. These steps are informed by the knowledge categorization proposed by ProClim (1997) and Hadorn et al. (2008), in which 'Systems knowledge' is knowledge of the current status; 'target knowledge' is knowledge about a target status; and 'transformation knowledge' is knowledge about how to make the shift from the existing to the desired status (*ibid*).

The first step in this thesis mainly focuses on gathering contextual data to identify the vulnerability and viability factors affecting SSF on islands. To identify these factors, a systematic literature review is conducted following the PRISMA 2009 guidelines (Liberati et al., 2009), ensuring a comprehensive collection of relevant studies. Then, the identified factors are categorized into several domains: economic, environmental, governance, social, technological, and health. Consequently, an exploratory data analysis is performed to understand the trends and patterns over the years. Next, random forest (RF) algorithms (Breiman, 2001) are employed to identify and prioritize the most significant factors, helping to specify key areas where future interventions should be focused to enhance the sustainability and resilience of SSF. RF is selected because it ranks among the most widely used machine learning algorithms, and many available software packages can effectively implement it for identifying feature importance (*ibid*). The data gathered through this process highlights the system knowledge IS should generate to support fishers. This step establishes foundational information applicable to fishers' contexts, facilitating an understanding of the elements impacting the FNS of the SSF.

The next step adopts a user-centric approach to ensure that the IS aligns with the specific needs, perceptions, expectations, and decisions of the SSF. Grounded in participatory design principles (Nygaard, 1987), in this phase, we collected and analyzed data from fishers in Kumirmari Island, India, to understand their requirements from IS. By highlighting the importance of including user-level insights in IS design, this stage underscores the importance of creating systems that resonate with fishers and enable them to implement the provided information effectively in their decisions and activities. The participatory approach promotes a sense of ownership and enhances the applicability of the IS, assuring it satisfies the fishers' requirements and expectations.

Next, building on the findings from previous steps, the research integrates polycentric dimensions (Ostrom, 2010), informed by the Theory of Participation (Reed et al., 2018), emphasizing context, design, power, and scalar fit. This stage involves surveys with SSF to gather insights into their experiences and challenges with existing IS. Additionally, interviews with experts involved in designing the Fisher Friend Mobile Application (FFMA), a decision support system for SSF in India, provide valuable insights into different aspects of the existing IS for SSF. These steps identify the principal dimensions that should be considered for IS. These principles—when integrated into the design of IS for fishers—can do more than merely deliver relevant information. They can enable the acquisition of transformative knowledge, enabling SSF to apply the information effectively in their future actions as well as decision-making processes.

The visual model below outlines the stages of this research (Figure 1). By systematically implementing the approaches outlined in this research, the IS can become more connected platforms, integrating contextually relevant data for SSF. Ackoff's Data-Information-Knowledge-Wisdom (DIKW) hierarchy explains connectedness as relationships among data points that transform data into meaningful information, facilitating the progression to knowledge (Ackoff, 1989). By integrating these steps into the IS design process, the understandability of knowledge acquired from the IS can be significantly improved by aligning it with the specific needs of users, particularly small-scale fishers. This PhD research advocates for the development of scalable and sustainable systems that empower SSF communities, helping them transition from vulnerability to long-term viability.

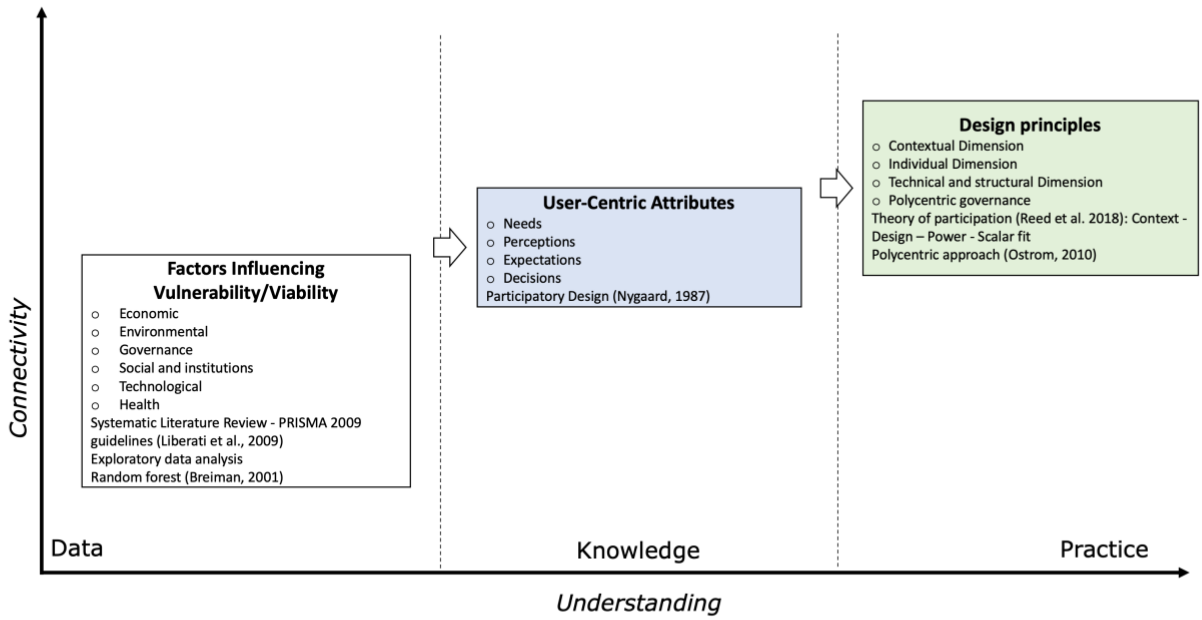

Figure 1. Visual model of this Ph.D. research — This visualization draws inspiration from Ackoff's Data, Information, Knowledge, and Wisdom (DIKW) model (Ackoff, 1989).

1.6. Delimitations of the Study

The first stage of the study focuses on SSF in small island developing states (SIDS). Globally, there are 38 SIDS (see appendix A) facing many similar challenges and threats: (1) limited landmass; (2) small populations; (3) vulnerability to external shocks such as climate change, natural disasters, and economic shocks; (4) reliance on external energy sources; (5) heavy reliance on imported food; (6) distance from global markets; (7) financial deficiencies and narrow economic sources; and (8) food and nutrition insecurity (FAO, 2020; Singh et al., 2022).

The second stage of the study takes a closer look at SSF on islands by exploring the complex food system on Kumirmari Island village, located in Sundarbans, India. Kumirmari is a small island community deeply entwined with its mangrove ecosystem and dependent on fishing. The village is particularly vulnerable to the effects of climate change, including cyclones, tidal surges, and soil salinization, which affect both land and water resources (Mukherjee & Siddique, 2024). The fishing industry, comprising crab collection, prawn seed collection, and SSF are integral to the local economy, with approximately 95% of the population reliant on water-based livelihoods (Das et al., 2022).

However, challenges such as declining fish populations caused by environmental degradation and overfishing have intensified vulnerabilities (Chowdhury et al., 2017). Additionally, fishers face physical risks, including crocodile attacks and tiger encounters, while working in the creeks and mangrove fringes, underscoring the precariousness of their lives (DasGupta, 2024). Also, in this area, adoption to digital tools is hindered by low digital literacy and unreliable connectivity (Mukherjee & Siddique, 2024; Chanchani & Ranjan, 2019). Despite these challenges, Kumirmari's fishers demonstrate remarkable resilience, often leveraging traditional ecological knowledge and participating in emerging sustainable practices such as community-based tourism to diversify incomes (Chanchani & Ranjan, 2019).

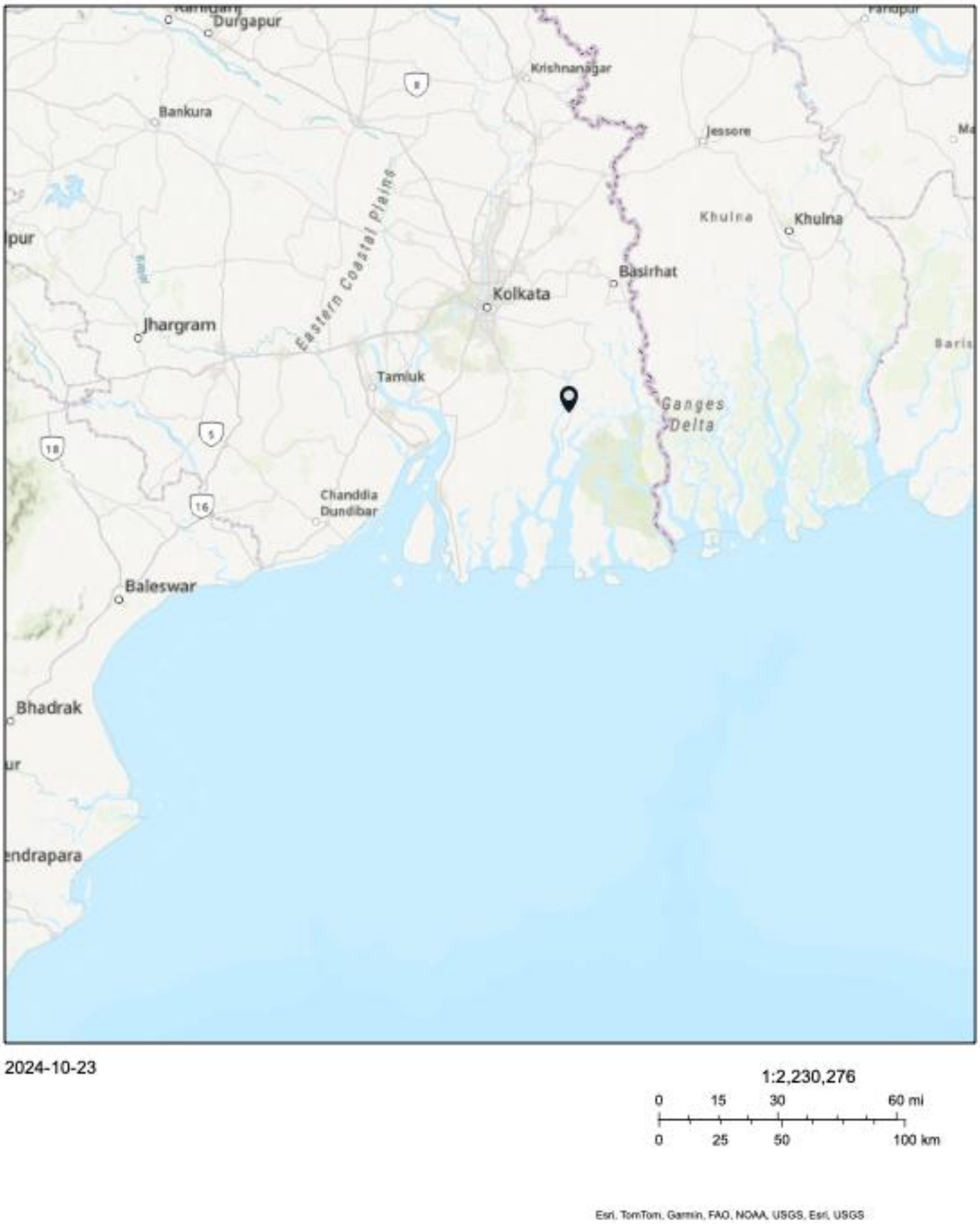

Figure 2. Study area, Kumirmari island, Indian Sundarbans Delta

In Chapter 2, a systematic literature review at the global level was conducted to examine vulnerability and viability factors contributing to FNIS across various island typologies—spanning territorial islands, territory islands, SIDS, and others. This wide lens enabled the identification of core vulnerability and viability factors. Subsequently, the relationship among these factors was evaluated within SIDS, due to the comparative abundance of data available for these islands. Drawing on insights from the literature review, the vulnerability and viability factors were then used as a benchmark to examine whether existing information systems in Kumirmari island village, a river island in India are adequately addressing the identified risks. This progression—moving from a broad global perspective to a more concentrated focus on SIDS and then a river island—enabled us to gain a broader perspective. Also, by shifting the focus to Kumirmari Island, the research addresses a critical gap in the literature on the river islands.

SIDS are developing countries characterized by small land areas, limited natural resources, and geographic isolation that make them especially vulnerable to environmental hazards and economic shocks (United Nations, 2024). These states are typically marked by challenges such as limited economic diversification, high dependency on imported goods, susceptibility to natural disasters, and the impacts of climate change, all of which complicate their sustainable development efforts (*ibid*).

In comparing the characteristics of SIDS with those of river islands, distinct yet overlapping dynamics emerge that underscore both environmental vulnerability and divergent governance frameworks. SIDS and river islands share inherent isolation and limited resource bases, factors that intensify their vulnerability to climate change and natural disasters (Baruah et al., 2025; Thomas et al., 2020). For example, while some SIDS contend with challenges related to sea-level rise and extreme weather events (Pelling & Uitto, 2001), some of the river islands exhibit vulnerabilities such as rapid fluvial dynamics, sedimentation and erosion (Sarker et al., 2019; Talukdar et al., 2021). Also, key differences are evident: SIDS operate as sovereign nations actively shaping international policy and evolving toward a hybrid model of sovereignty (Mitra & and Sanghi, 2023), whereas river islands, as sub-national territories, are embedded within larger administrative systems and depend on national governance structures for vulnerability management and disaster risk management. Furthermore, river islands are continually reshaped by fluctuating water flows and sediment levels due to upstream hydrological modifications and land-use changes, creating dynamic landscapes (Sarker et al., 2019) that may differ from oceanic islands. These differences challenge us to rethink how different technologies may help to build resilience in diverse island environments.

1.7. Limitations of the Study

Island nations vary widely in their socioeconomic structures, cultural contexts, as well as geographic and environmental conditions. Because of this diversity, it is difficult to apply universal conclusions that fully capture the distinct challenges each island faces. Instead, the findings and perspectives discussed here should be tailored to the specific needs and circumstances of each island nation or community, ensuring they align with local realities and priorities.

Another major limitation was the inability to interview government agencies due to contextual constraints. To work around this, we focused on two key groups: vulnerable fishers who rely on IS and experts involved in IS design. Additionally, since these fishers engage in various alternative livelihoods, their perspectives provided valuable insights into the views of other stakeholders, including fish traders, aquaculturists, and forest resource collectors (e.g., collecting honey, wood, or other forest products). Surveys with fishers provided direct insight into their needs and experiences with IS. The fisher's perspectives were essential in understanding how current IS functions. On the other hand, expert interviews helped us explore the design and implementation processes, revealing both strengths and weaknesses. By combining these two perspectives, we sought to balance the practical implications and the technical complications, ensuring a more comprehensive understanding.

1.8. Thesis Structure

This thesis adopts a manuscript-based format, presenting three interconnected, original research articles that collectively contribute to developing a guide for information system design to address the unique vulnerabilities of small-scale fishing communities.

Chapter 1: Introduction

Chapter 2/Manuscript #1: Food and Nutrition Insecurity of Small-Scale Fisheries in Islands: Implications of Machine Learning for a Transition from Vulnerability to Viability.

Chapter 3/Manuscript #2: Core Qualities of a User-Centred IS for Small-Scale Fisheries.

Chapter 4/Manuscript #3: Towards Sustainable and Polycentric Information Systems for Small-Scale Fishers: Lessons from Kumirmari Island, India

Chapter 5: Conclusion

Chapter 2

Food and Nutrition Insecurity of Small-Scale Fisheries in Islands: Implications of Machine Learning for a Transition from Vulnerability to Viability

Small-scale fisheries are essential to provide food and nutritional security to millions of people, especially in developing and island communities. In addition to providing essential nutrients for local populations, fisheries are often a significant source of income and livelihood for communities in island nations and coastal areas. Despite their importance, these fisheries face numerous challenges, including food and nutrition insecurity. To help address these challenges, researchers should be turning to advanced analytical techniques to better understand the complex underlying factors. By uncovering the root causes and dynamics behind these issues, these methods offer valuable insights that can guide more effective solutions and policy interventions. This research delves into the dynamics of the island fishers' food systems by adopting an approach that combines vulnerability and viability analysis, using a systematic literature review, exploratory data analysis, and the Random Forest algorithm. The initial step is conducted across all islands, while the second and third steps focus on Small-Island Developing States. Through a systematic literature review, the key factors influencing food and nutrition security among island fishers are identified and categorized into seven areas, including food system, environment, economy, social aspects, and governance. Through exploratory data analysis, this research identified patterns and trends spanning over 40 years, highlighting vulnerability and viability factors discussed in the literature. The results highlighted a substantial surge in the exportation of marine food from the islands, as well as a significant increase in access to the internet, the Gross National Income, and aquaculture production. Subsequently, the integration of Random Forest analysis enhanced our capacity to distinguish non-linear relationships and dependencies among the identified factors. The Random Forest analysis demonstrated the significance of various factors, including the (1) food trade balance, (2) access to education, and (3) agriculture's value added to GDP, among others, in determining the vulnerability or viabilities of fishers to food and nutrition insecurity. The analysis was conducted at global, regional, and national levels, highlighting why "scale" matters. The insights from the analyses provided in this research can empower decision-makers to navigate system complexities, design targeted interventions, and contribute to the overall well-being of SSF and communities dependent on them.

Keywords: Food and Nutrition Security, Vulnerability, Viability, Machine Learning, Random Forest, Small-scale fisheries

2.1. Introduction

Food and nutrition insecurity (FNIS) is a long-standing global concern. The world's food systems have been grappling with a slew of interconnected economic, social, and environmental issues (Prosperi et al., 2016). The global goal of ending hunger by 2030 is not on track anymore; the number of undernourished individuals in the world has increased since 2014, and healthy-affordable diets are out of reach for around 3 billion people (UN, 2021). The growing likelihood that FNIS in vulnerable areas will increase in the coming years is a serious concern (Bell et al., 2009), especially when we consider the implications for island communities with their specific characteristics (FAO, 2021). In small island states, malnutrition affects around 15.2 percent of the population, which is 1.8 times greater than the global average (*ibid*). According to recent statistics, overweight in children, obesity in adults, and anemia in women are all on the rise in these communities (*ibid*). Moreover, many islands are among the first to be affected by climate change and global warming, which further threatens their food security (Mbow et al., 2019).

Small-scale fisheries (SSF) in islands are extremely vulnerable to FNIS, facing tremendous challenges due to various natural circumstances and anthropogenic stressors (Amparo et al., 2017). SSF are vital to the FNS and economic well-being of island communities. However, studies suggest that these fisheries are vulnerable to multiple challenges, including overfishing, climate change, and environmental degradation (Belhabib et al., 2020; Morrison et al., 2020; Teh et al., 2016). Rising sea levels and water temperatures—due to climate change—can cause changes in the distribution and abundance of fish species (Belhabib et al., 2020; Béné et al., 2016). This can impact the availability of seafood and lead to food insecurity (Béné et al., 2016; Rudd et al., 2019). In addition, overfishing and destructive fishing practices can deplete fish stocks and negatively impact the resilience of these fisheries (Liu et al., 2020; Osterblom et al., 2017). The economic impacts of health crises such as the COVID-19 pandemic can also impact these fishers, exacerbating food insecurity (Fabinyi et al., 2021), resulting in disruptions in supply chains, reduced market demand, and decreased income for fishers (Béné et al., 2020). FNIS, due to the vulnerability of SSF in island communities, can have long-lasting effects on the health and social well-being of local populations, particularly children and pregnant women (Morrison et al., 2020). Studies signify a crucial need for adaptive and integrated management approaches that consider the socio-economic, ecological, and cultural aspects of SSF in island communities (Cinner et al., 2018; Fabinyi et al., 2018).

Ensuring food and nutritional security for millions of individuals is a fundamental aspect of small-scale fishing (Belhabib et al., 2020; Morrison et al., 2020; Teh et al., 2016), achieved through various means, including generating employment opportunities and poverty alleviation (e.g., Belhabib et al., 2015; Béné et al., 2007). There has been an increase in global efforts to draw the attention of policymakers and decision-makers to the importance of SSF, as well as to motivate the necessary engagement toward sustainable fisheries (World Bank, 2012). It has been highlighted that SSF require knowledge in decision-making, especially because they face numerous challenges, such as decreasing fish stocks, degradation of marine habitat, resource depletion, natural hazards, and climate change impacts, as well as additional issues caused by their specific characteristics (Agapito et al., 2019). However, large-scale fisheries have been the main focus of prior efforts because of their highly concentrated and urban-based contributions, as well as their recognition as a significant source of foreign exchange (World Bank, 2012). While significant progress has been made in recent years in recognizing the importance of SSF and the challenges they face, there is still a need for increased attention and engagement by researchers, policymakers and decision-makers to address these issues and promote sustainable fisheries practices in these communities.

The obvious vulnerability and failure to achieve sustainability [including food and nutrition security] in SSF have intensified criticism of the assessment and management approaches commonly used in these fisheries (Castrejon et al., 2014). Some decisions and practices are biased against SSF due to the challenges associated with data-poor fisheries (Jacquet & Pauly, 2008). Existing efforts have not resulted in faster sustainability in related policies, partly because these programmes do not fit data-poor fisheries (*ibid*). Still, one of the serious complications of evaluating and managing SSF, especially when compared to industrial fisheries, is a lack of adequate data and information (Kolding et al., 2014). Also, the significant amounts that have been invested in sustainable seafood activities are not benefitting SSF around the world (Jacquet & Pauly, 2008). Because of their miscellany, dispersion, and social complexity, SSF are frequently under-documented and underregulated, and many complex management challenges are primarily unaddressed (World Bank, 2012). Failure to address the challenges faced by the SSF jeopardizes the livelihoods of millions of people (World Bank, 2012).

Analyzing the root causes of FNIS of SSF in island communities is crucial and can be achieved by employing new methodologies that can consider the distinct socio-economic, cultural, and environmental aspects that influence these fisheries. To analyze FNS status, machine learning and deep learning algorithms are becoming more popular. In this domain, algorithms and models such as Random Forest (RF), k-Nearest Neighbor (kNN), Support Vector Machine (SVM), Naive Bayes (NB), Multi-Layer Perceptron (MLP) and Neural Networks have been applied (Browne et al., 2021; Nigus & Shashirekha, 2022). RFs are machine learning methods that combine multiple decision trees to improve prediction accuracy (Breiman, 2001). They are widely used across diverse fields, including bioinformatics, medical sciences, finance, remote sensing, weather forecasting, and computational biology, due to their robustness in handling complex, high-dimensional datasets (Ziegler & König, 2014). They are powerful and flexible methods offering good accuracy, and robustness to noise (*ibid*). RFs are among the most commonly used machine learning algorithms and can be implemented using various widely available software packages in many programming languages (Browne et al., 2021).

RFs provide a way to assess the importance of each variable, helping to identify which features contribute most to predictions (Breiman, 2001).

This research seeks to address the research question: What are the critical vulnerability and viability factors affecting food security in SSF within island communities, and how can data analysis methods, such as RF, help uncover and prioritize these factors to inform sustainable interventions? The research investigates the key factors influencing the vulnerability and viability of SSF in island communities and explores the utility of incomplete data and a machine learning technique for analyzing these factors to enhance food and nutrition security. This research question and objective aim to fill a gap in the literature by employing the potential of machine learning methods, which are infrequently used in socio-ecological contexts, for addressing the complex and interconnected factors that contribute to the vulnerability and viability of SSF. By focusing on island communities, which are often vulnerable to food and nutrition insecurity, this study scrutinizes their challenges and offers a systems view.

This study consists of three interconnected steps. In the first step, a systematic literature review is conducted to identify and synthesize the factors that contribute to the vulnerability and viability of SSF on islands to FNIS. This step provided a multi-dimensional understanding of the current state of knowledge about the subject and served as the basis for subsequent steps of this thesis. The second step involved exploratory data analysis and examined patterns and trends across the various dimensions identified in the literature review. Finally, in the third step, the underlying factors were further analyzed using RF to prioritize the strength of their impact on FNIS, signifying the most important factors. This step was particularly critical, as it has the potential to inform the development of effective interventions and policies to reduce FNIS for SSF. Overall, this research offers a systematic approach to understanding and addressing challenges related to food and nutrition insecurity in SSF on islands and beyond.

2.2. State of the Art: Transition from Vulnerability to Viability (V2V)

The concepts of vulnerability and viability are mutually dependent, and recognizing their reciprocal relationship is fundamental to any vulnerability study.

Over time, scholars have provided various definitions for vulnerability. One of the first formal definitions of vulnerability can be found in the literature on sustainability science: "Vulnerability is the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, a perturbation of stress/stressor" (White, 1973). This definition equates vulnerability with exposure. Chambers (1989) highlighted that vulnerability comprises two aspects: an external facet involving risks, shocks, and stressors faced by individuals or households and an internal facet involving defenselessness, which denotes a lack of resources to cope without experiencing detrimental losses. Later, in 2001, a more popular definition in the glossary of the IPCC Assessment Report (McCarthy et al., 2001) defined vulnerability [to climate change] as follows: “The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity”. Later, Adger (2006) defined vulnerability as a condition characterized by the susceptibility to harm resulting from exposure to environmental and social changes, along with the absence of adequate capacity to adapt. In 2017, the United Nations Office for Disaster Risk Reduction highlighted that vulnerability pertains to the circumstances influenced by physical, social, economic, and environmental factors or processes that elevate “the susceptibility of individuals, communities, assets, or systems to the impacts of hazards” (UNISDR, 2016).

In certain definitions, such as those put forth by the IPCC and Adger, the reciprocal relationship between vulnerability and viability is emphasized as integral to the evaluation of a system’s vulnerability. In these definitions, viability is implicitly addressed through the emphasis on adaptive capacity. Research by Nayak and Berkes (2019) highlighted how overcoming vulnerabilities and leveraging current and acquired strengths can contribute to viability. Despite the importance of the viability concept, there is limited consensus among scholars regarding the definition of viability, as still few distinct definitions have been put forth. FAO defines viability as the ability of a system or population to maintain its functioning and integrity over time, despite facing various stressors or hazards (FAO, 2013). According to the Webster 2nd edition 20th Century Dictionary, viability is: “the state or quality of being viable (i.e. able to live) and the state of being able to survive under conditions of wide geographical distribution, as species of animals and plants” (Schuhbauer & Sumaila, 2016). In this study, we define viability as the attributes, capacities, and conditions of a system or community that enable it to thrive and maintain its functionality and cohesion over time despite exposure to various stressors, including hazards and disasters.

We argue that a concurrent understanding of both vulnerabilities and viabilities of a system is imperative for the development of effective strategies and interventions. Merely analyzing vulnerability alone is insufficient; equal attention should be given to the trajectory toward viability. Therefore, Vulnerability to Viability (V2V) analysis is essential to evaluate the dynamic and continuous process of moving from a state of susceptibility, fragility, or exposure to various stressors towards a state of robustness, adaptability, and long-term sustainability. This acknowledges that vulnerability and viability exist on a continuum without distinct thresholds. The factors influencing vulnerability are also the foundation for enhancing viability. The transition toward viability requires the reduction of vulnerabilities and the development of resilience, enabling the system to thrive and persist in changing conditions and challenges. A solitary vulnerability analysis may mainly focus on traditionally perceived negative factors, while a viability analysis may overlook potential vulnerabilities. Therefore, simultaneous assessment of vulnerability and viability is essential for recognizing instances where a factor, initially contributing to viability, may evolve into long-term vulnerability and vice versa. It is crucial to recognize that the transition from V2V is a continual process that necessitates constant monitoring, assessment, and adaptation.

2.3. Random Forest: Application in Sustainability and Food-related Studies

Random Forests (RFs) were first introduced by Leo Breiman in 2001 as a robust and multipurpose method for classification and regression tasks (Breiman, 2001). RF builds multiple decision trees by utilizing a bootstrap aggregating technique, commonly known as "bagging," which reduces variance and enhances predictive accuracy by averaging the outputs of numerous trees (Ziegler & König, 2014). Initially, RF was seen as a solution to overcome the instability of individual decision trees, which were highly sensitive to small variations in the data (Breiman, 2001). Over the years, it has evolved, with researchers extending its applications to more complex tasks, such as probability estimation, and high-dimensional data exploration (Cutler et al., 2007). Notably, RF's ability to handle missing data, capture feature interactions, and deliver high prediction accuracy, even with correlated variables, has been further refined by extensions of the RF algorithm such as conditional inference forests and survival random forests (Ishwaran et al., 2008; Ziegler & König, 2014). The flexibility and robustness of RF, combined with its ease of use and interpretability, continue to make it a useful tool in contemporary machine learning and data science (Cutler et al., 2007; Ziegler & König, 2014).

RF is considered a transformative machine learning tool in environmental and sustainability studies due to its capacity for handling complex, nonlinear relationships between variables and its applicability in diverse modelling scenarios. In the realm of feature importance detection, RF has been instrumental in discerning the most significant environmental factors influencing ecological outcomes, such as climate variables impacting biodiversity and public health (Cappelli et al., 2024). This method's ability to effectively rank predictors makes it highly suitable for identifying which variables should be prioritized in future strategies (*ibid*). Furthermore, RF performs well in anomaly detection data. It can reveal abnormalities in ecological systems—such as unusual shifts in species distributions or extreme weather events—enabling early warning systems for ecosystem monitoring (Strobl et al., 2007). Moreover, RF has proven effective in imputing missing data (Kim & Loh, 2001), which is critical in environmental research where data gaps are common due to the challenges of long-term data collection. Its capacity for data imputation not only enhances the quality of analysis but also supports more reliable long-term trend analysis, as demonstrated in climate change impact studies (Kim & Loh, 2001). Beyond these applications, RF has been leveraged in optimization problems, particularly in resource management and sustainable planning (Durairaj et al., 2022). Overall, RF's flexibility and accuracy in dealing with diverse types of data make it a crucial tool in performing analysis in sustainability research, offering predictive and optimization insights (Sandri & Zuccolotto, 2006).

The application of RF in food-related studies has gained significant attention due to its ability to tackle complex challenges. Prediction, feature importance detection, classification, and mapping are some of the prominent applications of RF in this domain as explained below. RFs can be instrumental tool for identifying feature importance, enabling researchers to determine the key variables that drive specific outcomes (e.g., Dhillon et al., 2023; Wang et al., 2022; Eştürk, 2022). It is also widely employed for prediction tasks such as forecasting crop yields, predicting climatic factors impacting agriculture, or anticipating food insecurity in vulnerable populations *(ibid)*. Moreover, RF is commonly used for classification and mapping, such as identification of land cover types, croplands, and irrigation areas, as well as detecting plant diseases (Tariq et al., 2023; Tikuye et al., 2023). Despite its wide range of applicability, some gaps remain in the incorporation of RF. The utilization of RF in vulnerability analyses in coupled human and natural systems is still infrequent, and only a small number of applications can be observed in specific domains. Moreover, the majority of the previous RF analyses were conducted solely using data from a single region or country, whereas studies encompassing multiple nations remain relatively scarce.

2.4. Delimitations of the Study

In the initial stage of this research—or the systematic literature review—the primary objective is to identify any relevant factors related to vulnerability and viability to FNIS that have been previously examined for island regions globally. The island regions under consideration in this study encompass a diverse range of geographic and political classifications, including those that are (1) part of a larger country, (2) Small Island Developing States (SIDS), (3) island countries and (4) overseas territory islands. The focus of this stage is to synthesize and build upon the existing literature to identify common themes and patterns across these island regions.

The subsequent stages of the research focus on SSF in SIDS. Globally there are 38 SIDS (see appendix A) facing many similar challenges and threats: (1) limited landmass; (2) small populations; (3) vulnerability to external shocks such as climate change, natural disasters, and economic shocks; (4) reliance on external energy sources; (5) heavy reliance on imported food; (6) distance from global markets; (7) financial deficiencies and a narrow economic sources; and (8) food and nutrition insecurity (FAO, 2020; Singh et al., 2022). Given the relatively greater availability of data for SIDS compared to other categories of islands, the quantitative part of this study concentrated on these islands. Although the data availability is still limited for SIDS, their bounded international geographies render quantitative analysis more feasible. It is important to acknowledge that further efforts are essential to collect more data for SIDS to augment the precision of future analysis.

To further discuss the V2V factors among SIDS, we focused on three countries representing diverse economic and geographic profiles: (1) The Bahamas, (2) Fiji, and (3) São Tomé and Príncipe. The Bahamas, with a population of approximately 407,906 and a GDP per capita of $34,750, can be considered a developed economy that benefits from its proximity to the United States. Fiji, home to about 896,445 people and a GDP per capita of $6,200 (World Bank Open Data, n.d.-a), has a diversified economy; however, its relative remoteness poses challenges for trade logistics. São Tomé and Príncipe, with a population near 231,856 and a GDP per capita of $2,602 (World Bank Open Data, n.d.-b), faces developmental challenges due to its small land area and distance from mainland Africa. Examining the V2V dimensions for these SIDS provides insights into how contextual factors, such as population size, can influence the analysis.

2.5. Methods

2.5.1. Systematic Literature Review

A systematic literature review is a comprehensive and rigorous approach to identifying, evaluating, and synthesizing existing research evidence and ignorance on a specific research topic (Petticrew & Roberts, 2005, p. 2). Guidelines for reporting, such as the PRISMA, offer researchers a structure to disclose their systematic review comprehensively and transparently (Moher et al., 2009). Researchers commonly use systematic reviews in vulnerability analysis studies to investigate various subjects, such as agriculture's vulnerability to pandemics (Štreimikienė et al., 2022), climate change adaptation (Hafezi et al., 2018), or climate change and food security (Thompson et al., 2010). The result of systematic reviews can serve as a valuable tool for decision-making where evidence-based approaches are critical.

To commence the initial phase of this research, a systematic literature review was conducted to offer a synthesis of the existing knowledge pertaining to the factors influencing the vulnerability of SSF to FNIS in island contexts. A systematic literature review is used following PRISMA 2009 guidelines (Liberati et al., 2009) to provide a reliable and unbiased summary of the state of knowledge. The screening process of the review was conducted using Rayyan, a web-based research tool (Ouzzani et al., 2016) used for handling and screening large volumes of academic literature during the systematic review. The information for the review were obtained from scientific journals, conference proceedings, and books—mainly from Web of Science and Scopus. A total of 1,824 unique entries were extracted and imported into Rayyan. Rayyan is then used to detect duplicates and make inclusion and exclusion decisions. Entries that did not meet inclusion criteria, such as not being related to SSF, not focusing on food security, or not being relevant to islands, were identified and excluded. Afterwards, duplicate entries were removed. In the next stage of the review, the data extraction process involved a selection of 322 studies. Afterwards, 216 studies were found to meet the eligibility criteria for the study.

During the data extraction process, relevant information about the study, such as the population, study area, employed research methods, and factors that contributed to vulnerability or viability to FNIS, were carefully extracted and documented. The data extracted from the reviewed literature was classified into discrete categories. These categories encompass a spectrum of factors relevant to food systems, comprising direct influences on food systems and broader considerations related to environmental, health, economic, social, governance, and tools, methods, and technologies. This procedure entailed an examination and organization of available information, aiming to establish an understanding of the multifaceted factors influencing the FNS of the islanders.

2.5.2. Exploratory Data Analysis

To identify the critical vulnerability and viability factors, it is necessary to extract the requisite data and distinguish the corresponding patterns. By analyzing available data on factors identified in the systematic literature review, patterns and trends were identified to inform future targeted interventions to address food insecurity. Available data was collected from various sources, and then data estimation, normalization, and integration were performed to ensure that the data was in a suitable format for an exploratory pattern and trend analysis, as well as RF. A total of 34 indicators were obtained from 11 distinct global databases, namely Sea Around Us, the World Bank, the International Disasters Database, the World Health Organization, and FishStatJ, among others. For a complete list of indicators, units of analysis, sources, and definitions, please refer to Appendix C. Out of these 38 islands, 18 of them had significant gaps in their data; therefore, to enhance the accuracy of the analysis, those 18 islands were excluded, resulting in a final dataset that consists of 20 SIDS.

The identified data gap underscores the fact that SIDS encounter significant challenges related to inadequate storage and accessibility of data, insufficient digitization, and complexities in both generating and accessing cross-sectoral data (UN DESA & UNDRR, 2022). The substantial data gap of SIDS can be attributed to various factors. These factors encompass challenges in cross-sectoral data collection, limited storage and access to data, a lack of digitization, a project-based culture leading to disparate information pools, non-standardized data, a shortage of skilled human capital, outdated and insufficiently shared lessons learned, and less usable portals and databases (*ibid*). The impact of these factors can differ across islands, significantly influencing the accessibility and reliability of data for analytical and research pursuits. Due to the substantial data gap and the limited availability of data in the context of SIDS, data estimation becomes mandatory and vital, employing statistical and computational models.

In this research, data gaps are addressed through the utilization of backcasting, forecasting, and imputation techniques. This hybrid three-step approach was implemented, which was selected based on its appropriateness for the available data, data trends, and analysis at hand. Firstly, the data were aggregated from 20 SIDS to analyze the evolving trends and patterns across 34 variables during the period spanning from 1980 to 2023. For backcasting purposes, the growth rate was utilized. Backcasting involves estimating historical values based on known future values and is particularly useful when assessing trends over time. This method allows for the reconstruction of missing data points by extrapolating backward from available information. Then, the Exponential Smoothing (ETS) method for interpolation and extrapolation was utilized, where a substantial portion of the data was available. ETS is a widely used forecasting technique for time series that considers historical patterns and trends to project future values (Hyndman et al., 2008). Lastly, for the missing points where data values were predominantly absent, the RandomForestRegressor algorithm was employed for imputation. The appropriateness of this regressor for imputation is demonstrated by several studies, such as Browne et al. (2021) on open-access food security data. When predicting missing values, RF takes into account multiple instances in the database, utilizing the collective knowledge captured by the ensemble of decision trees (*ibid*).

The efficacy of the hybrid method was tested to evaluate its performance in the given context. Various techniques, including Multiple Imputation by Chained Equations (MICE), Bayesian approaches, and K-Nearest Neighbours (KNN), were initially considered. To choose the most appropriate imputation method, we compared the results from different methods. The goal was to ensure the results from the chosen method aligned with the expected data ranges. After evaluation, the hybrid method was chosen as it captured existing trends effectively.

2.5.3. Random Forest Analysis

This study implemented RF using Python to find the hidden relationships between response variables based on a set of predictor variables in a dataset. Splitting the data into predictor and response is generally required for RF. This is because RFs are trained using a set of inputs (predictors) and corresponding outputs (responses) to learn the underlying relationship between them. The analysis included a range of predictor and response variables to evaluate vulnerability and viability. The identification of these proxy variables influencing the vulnerability and viability of sampled SIDS to FNIS is drawn from the systematic literature review and the availability of the data in the most current global databases. The analysis describes the included SIDS to contextualize the environment in which the SSF in these islands operate. It is important to note that the list of indicators may not be comprehensive, as certain factors may not have been thoroughly explored or measured yet. For a more comprehensive compilation of factors contributing to the vulnerability and viability of SSF—beyond the FNS—reference is made to recent research conducted by Dias et al. (2023).

In this analysis, the input indicators are the predictor variables labelled 1 to 29 in the dataset. The predictor variables cover various domains, including social, environmental, economic, health, technology, and political factors, as identified in the literature review. Potential overlaps between predictors were assessed through correlation analysis. The results indicated no significant multicollinearity, suggesting that each variable captures distinct information in the model. The response variables correspond to indicators numbered 30 to 34 in the dataset, which are (1) marine food production/harvest per capita, (2) catches by artisanal and subsistence fishing sectors, (3) prevalence of nutritional deficiencies, (4) marine food supply per capita, and (5) total food supply per capita. These response variables relate to the four dimensions of FNS—availability, accessibility, utilization, and stability. Availability is related to total marine food production/harvest per capita (1) and supply per capita (4). Accessibility is mainly associated with catches by artisanal and subsistence fishing sectors (2). Utilization pertains to the prevalence of nutritional deficiencies (3). For a complete list of indicators, units, sources, and definitions, please refer to Appendix C. Finally, stability encompasses all five response variables as it emphasizes maintaining food security over the long term. Each of these dimensions can also be connected to other aspects of FNS.

Upon preprocessing the raw data to identify the predictor and response variables, a normalization procedure was applied, rescaling the data to a range of -1 to +1. Normalizing data was required to bring different variables onto a comparable scale. Then, the dataset was split into training, validation, and testing sets. The analysis utilizes a RandomForestRegressor from the Scikit-learn library. The RandomForestRegressor is an ensemble of Decision Trees, where each tree in the forest is trained on a subset of the data, selected through bagging and with a random subset of features at each split. This approach helps reduce variance, improve prediction accuracy, and mitigate overfitting, which is a common issue with individual Decision Trees (Breiman, 2001). The random forest in this code employed 100 estimators (trees), ensuring the reproducibility of results. The proportion used for the splits of the data was 80% for training and validation (60% for training and 20% for validation) and 20% for the test set. This proportion was chosen based on the evaluation of the model on different ratios.

The model was trained on the dataset with lagged, rolling, and expanding features that capture time dependencies. These techniques are often employed to optimize the performance of the models by allowing them to capture both short-term fluctuations and long-term patterns, aiming to improve predictive performance by considering temporal correlations within the data (Galli, 2022; Gupta et al., 2022; Polyzos & Siriopoulos, 2022). The predictions were evaluated using metrics such as Mean

Absolute Error (MAE) and Mean Squared Error (MSE), which provided insights into the accuracy and performance of the model. Subsequently, given the resulting model and using SHapley Additive exPlanations (SHAP), the top predictor variables were identified for the model and each response variable. SHAP ascribes an importance value to each individual predictor variable by attributing importance values to them based on their respective contributions toward the predicted outcomes (Lundberg & Lee, 2017).

To evaluate whether the choice of RF combined with lagged, rolling, and expanding features was optimal, we compared its performance against two other models: a Decision Tree (DT) and a Neural Network with LSTM layers. DT and the Neural Network with LSTM were evaluated to understand how these models perform when given the same data, where DT uses a single decision tree and the LSTM neural network employs sequential data handling capabilities suited for time series (Hochreiter & Schmidhuber, 1997; Quinlan, 1986). The models were compared using metrics such as Mean Absolute Error (MAE) and Mean Squared Error (MSE) to determine the accuracy and robustness of each approach. The results were then included in the sensitivity analysis to show how each model responds, making it possible to compare their performance.

2.6. Results

The results from the systematic literature review, exploratory data analysis, and RF are detailed below in separate sections.

2.6.1. Results from the Systematic Literature Review

The results of the systematic literature review show that scholarly works on the vulnerability and viability of small-scale fishers to FNIS have been conducted in various islands. Figure 3.1 shows the global distribution of these studies across various regions. These studies span multiple nations, including Indonesia, the Philippines, Solomon Islands, Tanzania, the United States, Timor Leste, Fiji, and Palau. The countries shown in Figure 3-2 were identified as the main focus of the previous studies. Moreover, the distribution of studies conducted across continents revealed that Oceania and Asia had the highest percentages at 38% and 36%, respectively, while Antarctica had the lowest representation at 0.5% (Figure 3-3).

Previous studies conducted on the subject were primarily focused on SIDS, which comprised the largest proportion of these studies at 39% (See the frequency graph in Appendix D-1). Territorial islands (Islands under the jurisdiction or control of a particular country) constituted 33% of the studies, indicating a significant but slightly lower representation and dependent territory islands had the lowest representation, accounting for only 2% of the studies conducted. Dependent territory islands refer to islands that are politically linked to and governed by another country; these islands often have a degree of autonomy. Also, according to the literature review, 90% of the prior studies focus on island communities in developing economies, with only 8% centring on islands in developed economies (See the frequency graph in Appendix D-2).

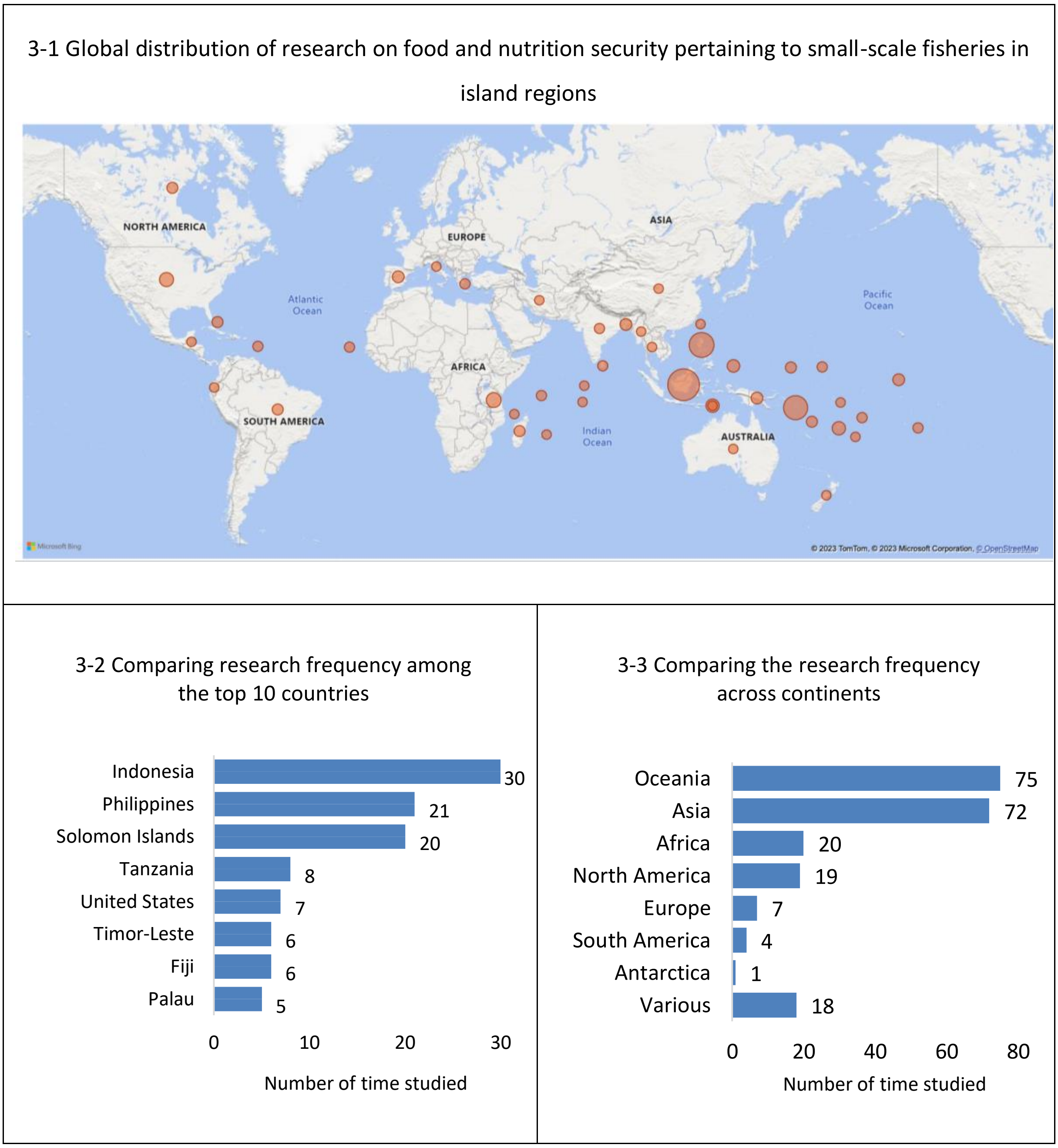

Figure 3. Geographic distribution of research on food and nutrition security pertaining to small-scale fisheries in island regions across

Examining the existing literature, vulnerability and viability domains pertaining to FNIS of SSF in island regions were identified (as illustrated in Table 1). The existing domains of vulnerability and viability were classified into distinct categories encompassing (1) food system, (2) environmental, (3) health, (4) economic, (5) social, (6) governance and institutional, and (7) tools, methods, and technologies. The food system category specifically encompasses direct impact domains within the food system, such as food availability. Other categories capture vulnerability and viability factors that intersect with the food system and have indirect effects on its functioning. The classification of vulnerability and viability domains in this study is based on the authors' perspective and deemed most suitable for the research. Certain dimensions of vulnerability and viability may intersect across multiple categories; however, in the context of this study, we have allocated them to a single category.

Table 1. Key areas investigated in previous studies regarding the vulnerability and viability of small-scale fisheries in relation to food and nutrition security in island communities, as explored in the systematic literature review

Food System	Environmental	Health	Economic	Social	Governance & Institutional	Tools, Methods, & Technologies
Availability Accessibility Utilization Stability	Biodiversity Climate Change Environmental Risks and Hazards Land Use Patterns	Epidemics	Economic Development Market System Fiscal Status	Social Perception Social Justice Social Cohesion Social Knowledge	Institutional Framework Legal System Power Dynamics	Sustainable Innovation

Among the domains, governance and institutional domain, received the highest occurrence across continents, with Asia and Oceania each accounting for 33% of the studies, followed by Africa and North America at 14% each. In the environmental domain, Oceania had the highest occurrence at 40%, followed by Asia at 31%. For the economic domain, Asia had the highest occurrence at 47%, followed by Oceania at 34%. In the social domain, Asia had the highest occurrence at 39%, followed by Oceania at 33%. Within the food system domain, Oceania had the highest occurrence at 38%, while Asia had 29%. In the health domain, Asia had the highest occurrence at 45%. Lastly, in the tools, methods, and technologies domain, Oceania had the highest occurrence at 64%, followed by North America at 27%.

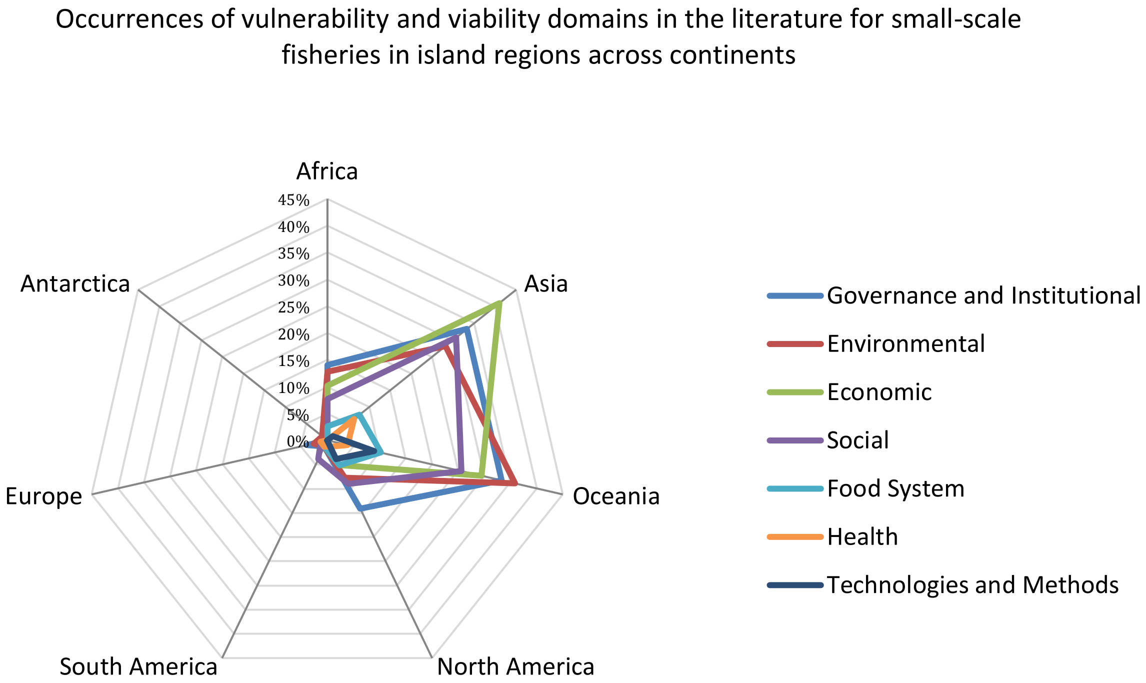

Figure 4. Occurrences of vulnerability and viability domains in the literature for small-scale fisheries in island regions across continents

Vulnerability and viability factors across aspects of food systems: Some studies in the field of FNS have directly evaluated aspects such as food availability, accessibility, utilization, and stability, providing valuable insights into the multifaceted nature of this topic among SSF in the context of islands. The literature emphasizes the importance of maintaining the level of fish consumption for good nutrition (Bell et al., 2018). However, it is highlighted that coastal fisheries alone may not provide sufficient fish to meet nutritional requirements (Bell et al., 2015). Coral reef fisheries are recognized as a source that can contribute substantially to the food security of coastal communities (Cabral & Geronimo, 2018), and interventions to recover degraded coral reef ecosystems are suggested to capture the growth potential in nearshore fisheries (Cabral & Geronimo, 2018). The literature emphasizes the need for research and institutional reforms to improve the utilization of different sources of fish protein, including tuna (Dorta & Martin-Sosa, 2022; Wabnitz et al., 2018), pelagic (Dorta & Martin-Sosa, 2022; Wabnitz et al., 2018), and demersal, and aquaculture (Dorta &

Martin-Sosa, 2022). The changing fish consumption patterns influenced by tourism and development are considered a potential concern as they may contribute to food insecurity (Yadav et al., 2021). These changing fish consumption patterns might have multifaceted implications for individual health, environmental sustainability, food system resilience, cultural practices, and economic dynamics. The role of fisheries as natural insurance against shocks is further discussed in the literature, highlighting the resilience response of fishing activities during crises (Higgs, 2021). It is mentioned that local food production practices and food sharing during the COVID-19 pandemic conferred resilience (Ferguson et al., 2022).

Vulnerability and viability factors across environmental aspects: Based on the literature review, studies show that environmental factors play a crucial role in impacting the vulnerability of SSF to FNIS on islands. In the environmental domain, factors such as climate change, biodiversity, environmental risks, and land use have been identified as significant importance. Climate change poses significant challenges to food supply, particularly in regions already facing food insecurity (Hodgson et al., 2022; Robinson et al., 2022). Climate change-related impacts such as rising sea temperatures, declining dissolved oxygen, and reduced net primary productivity can result in local species extinctions, decreased catch potential, and income loss (R. Asch et al., 2018). Furthermore, the potential implications of ocean warming and acidification on fishing industries further highlight the complex challenges faced by these communities (Bell et al., 2013; Jones et al., 2022; Nicol et al., 2022; Wilson et al., 2022). On the other hand, natural calamities and extreme events negatively impact marine ecosystems and fishing activities (Kiruba-Sankar et al., 2021), leading to reduced catch and income for fishers, which in turn affects FNS (A. S. Thomas et al., 2019). Compound climate risks also threaten aquatic food systems, including fisheries and aquaculture, while climate-driven coral bleaching events reduce the productivity of coral reef fish and fisheries. Unsustainable fishing practices, habitat degradation, and overexploitation of fish stocks exacerbate food insecurity in regions such as Palau and Kiribati, where marine resource reliance is high (Brewer et al., 2013; Cabral et al., 2013; Golden et al., 2022; Higgs, 2021; Muller-Karanassos et al., 2021). Land use can also impact food security by affecting coastal ecosystems (Crumpler & Bernoux, 2020, p. 1), which play a crucial role in supporting fisheries and aquaculture.

Vulnerability and viability factors across health aspects: Health-related factors were recognized as having varied effects on the assurance of FNS in SSF located on islands. The COVID-19 pandemic, as observed by many scholars, had direct and indirect impacts on FNS (Ferguson et al., 2022; Golden et al., 2022; Higgs, 2021; Mejia et al., 2022). The importance of local food production, such as seafood, was acknowledged during the pandemic due to limited mobility and supply chain disruptions (Ferguson et al., 2022; Manlosa et al., 2021; Mejia et al., 2022). The closure of hotels and restaurants and reduced tourism posed income losses and implications for fish resources, affecting the food security of SSF (Guerra-Marrero et al., 2021). The pandemic significantly impacted fishers' livelihoods and emphasized the need for alternative livelihood opportunities and support mechanisms (Uddin et al., 2022). It disrupted the food systems, and the importation of foods (Ferguson et al., 2022). However, amidst these challenges, the resilience of local food production practices and food sharing was demonstrated *(ibid)*. Innovative strategies emerged, such as partnerships between chefs and fishers and the rise of barter economies (Mejia et al., 2022). Additionally, fishing activity initially increased as a reliable source of traditional food in some islands, such as the Bahamas, during the early stages of the pandemic (Higgs, 2021). However, it subsequently declined with the partial resumption of other economic activities (Higgs, 2021), emphasizing the complex relationships within the food system.

Vulnerability and viability factors across economic aspects: Literature suggests that SSF experience vulnerability and viability issues in terms of economic development, market systems, and fiscal analysis, which influence their FNS. SSF contribute significantly to employment income, food security, and national GDP, particularly in developing countries (McClennen, 2012). However, multidimensional poverty is one of the most important factors impacting food security among these communities (Cahyadinata et al., 2019; Fabinyi, 2018; Stanford et al., 2013), and fishers with limited income sources and scarce productive physical capital have higher vulnerability and lower adaptive ability (Chen et al., 2020). This can be caused by several factors, including declining fish stocks, the presence of foreign industrial vessels, interference from international entities, and intermittent access to essential resources such as fuel and food (Dancette, 2019). Furthermore, the way resources are allocated, competition is managed, and spatial configuration is organized within these communities can significantly impact their livelihoods (Setiadi, 2020). Factors such as operational costs (Purcell et al., 2016) and fleet income impact the availability of small-scale fishing trips, which in turn affects the supply of fish as a source of nutrition (Picaulima et al., 2021). Other economic dynamics such as export orientation and commercialization (Vianna et al., 2020), income distribution dynamics in seafood value chains (Rodrigues & Villasante, 2016), as well as demand, market conditions, and profitability (Thyresson et al., 2013; Zeller et al., 2021) can have complex implications for FNS in the context of small-scale fishing. Moreover, industrial fishing and transshipping have shown a negative impact on SSFs' employment, catches, fresh fish availability, and incomes (James et al., 2018; White et al., 2018). Due to these factors, the increasing global dependency on marine fish supplies can lead to intense competition, fishery conflicts, and unsustainable fishing practices, resulting in the depletion of marine fishery resources (Kiruba-Sankar et al., 2021). The impact of excessive fishing in SSF, as observed in Madagascar, poses significant risks to the income, food security, and overall welfare of vulnerable communities (Gough et al., 2020).

Livelihood diversification is an effective economic approach recognized for enhancing FNS among small-scale fishers (André et al., 2022; Andriesse, 2018; Eriksson et al., 2020; Paulus et al., 2019; Sulu et al., 2015), particularly as a means of adapting and managing crises (Uddin et al., 2022). Promoting aquaculture (Funk et al., 2022; K. Hicks & Murashige, 2018; Manlosa et al., 2021; Syukur et al., 2021), sea cucumber fishing for export to Asia (Hair et al., 2019; Purcell et al., 2016), seaweed farming (Steenbergen et al., 2019), marine snail fishery, and tourism industry (Añasco et al., 2021; Cusack et al., 2021; Lopes et al., 2017; Uddin et al., 2021; Wood et al., 2013) among others have been recognized as alternative livelihoods for island fishers in different parts of the world. Moreover, the type of livelihood activities households engage in greatly influences their food security, with certain activities offering better access to food resources and income (Eriksson et al., 2020). The distribution of benefits from livelihood diversification strategies can vary across different market systems (O'Neill et al., 2018). Therefore, these projects need to consider the balance, variety, and disparity of livelihood strategies. Cash transfer programs (Nasrudin et al., 2020), capital assistance systems (Ridwan & In'am, 2021), support from patrons (Ferrol-Schulte et al., 2014), participating in insurance (Suharno, 2022), as well as support of social organizations (Steenbergen et al., 2019) and social capital (Dacks et al., 2020; Diedrich et al., 2019) can also help fishers mitigate uncertainty and manage risks associated with their business activities. Adopting systemic approaches is crucial for avoiding undesirable consequences; for instance, while offering financial support such as subsidies to fisheries may seem beneficial, it can have adverse effects such as overfishing, underscoring the importance of reducing harmful subsidies to mitigate this issue in SIDS (Sumaila et al., 2013).

Vulnerability and viability factors across social aspects: Social factors, including societal perception, social knowledge, social cohesion, and social justice, have significant implications for the sustainability, resilience, and equitable management of fisheries as explained below. Studies highlight the significance of women's contributions to food security, emphasizing the need for their inclusion in fisheries management to ensure sustainability and challenge traditional gender norms (e.g., Rabbitt et al., 2019; Thomas et al., 2021). Gender dynamics, social conflicts, and inequalities are identified as social justice issues in the fisheries sector (Kiruba-Sankar et al., 2021; Stacey et al., 2019). Adaptive capacity domains, including flexibility, social organization, learning, and agency, are identified as important for recognizing and responding to change effectively (Turner et al., 2020). Collaborative and cooperative governance efforts are observed to build resilience in fisheries, highlighting the importance of coordination and cooperation at multiple levels (Syddall et al., 2022). Trust building and collective actions contribute to social cohesion, adaptive capacity, and the effective implementation of fisheries-related regulations (Albasri & Sammut, 2022; De la Cruz-Modino et al., 2022). Social capital, social networks, and traditional knowledge are crucial for sustainable livelihoods, resilience, and coping with change (Galappaththi et al., 2020; Wongbusarakum et al., 2021). Cultural heritage, social practices, and values play important roles in sustainable fishing policies and interventions (Alonso Población, 2013; Miñarro et al., 2016).

Vulnerability and viability factors across governance and institutional aspects: The literature review indicates that the legal system, encompassing traditional systems of rights, governance/management tools, legal instruments, and gender-specific strategies, can play a crucial role in supporting FNS among SSF. Effective governance solutions and policy measures for SSF should consider catering to specific characteristics and recognizing the heterogeneity of fisheries within an island (Falsone et al., 2020; Galappaththi et al., 2020; Silas et al., 2020; Smallhorn-West et al., 2022). Participatory approaches that incorporate local communities, customary knowledge, and community-based adaptations are required to contribute to sustainable fisheries management and enhance adaptive capacity, and viability (J. D. Bell et al., 2018; Rahman et al., 2021; Schemmel et al., 2016; R. A. M. Silvano et al., 2017). Just fisheries management, which involves addressing trade inequities, considering the power dynamics among stakeholders, and promoting socio-economic goals, can support enhancing sustainability and the well-being of fishing communities (N. Roberts et al., 2022). Gender-specific strategies should be integrated into fisheries governance to enable the self-organization and adaptive capacity of fisherfolk, ensuring their food security (McConney et al., 2015). The significance of governance and policy cannot be overlooked when it comes to providing support to SSF by ensuring their access to credit and financial resources (Dancette, 2019; Rahman et al., 2021). Strengthening associations and cooperatives among fishers and traders and addressing scientific capacity gaps along with effective monitoring and regulations can help protect local fishery resources, address income inequality, and enhance governance and policy effectiveness in managing small fisheries (Rodrigues & Villasante, 2016; Sekadende et al., 2020). Data and information play a crucial role in informing policy and management strategies, and there is a need for improved data reporting, integrating data into governance decisions, addressing data deficiencies, considering scientific capacity and monitoring programs, and understanding the complex nature of fisheries in small islands (Dunstan et al., 2018; Evans et al., 2018; Falsone et al., 2020; Greer et al., 2014; Greer K., 2014; McConney et al., 2015; Rahman et al., 2021; Sekadende et al., 2020; Smallhorn-West et al., 2022; Taylor et al., 2021).

Vulnerability and viability factors across technological aspects: The literature emphasizes the importance of sustainable tools, methods, and technologies to improve FNS in SSF. Fish Aggregating Devices (FADs) have been proven effective in intensifying fishing efforts and achieving sustainable yields, particularly for small pelagic species (Bell et al., 2015; Roeger et al., 2016). Also, the strategic implementation of lights on FADs increases fish catch rates and improves catch assemblage (Tilley et al., 2019). In Pacific Island nations, for example, the use of lights on FADs contributes to improved access and food security, emphasizing the importance of building capacity for harvesting pelagic fish

(Filous et al., 2020). Furthermore, understanding movement patterns is crucial for effective fisheries planning and data collection (Itano & Holland, 2000). In the Caribbean, moored fish aggregating devices (MFADs) equipped with data collection capabilities have demonstrated their potential to enhance resilience in fisheries (Wilson et al., 2022). Quantitative seascape ethnoecology (QSE) is being used in Arctic coastal regions to improve food security (Watts et al., 2017). Integrated policy responses and resource allocation are advocated for maximizing the food security benefits of using different tools, such as artisanal FADs with data collection features, in different islands, such as Pacific Island countries (Campbell et al., 2016). Finally, nearshore FADs and data capabilities have proven beneficial for fish supply and fisheries management in the Solomon Islands despite associated trade-offs and risks (Albert et al., 2014).

This review highlights key findings and identifies gaps in current research. There is a lack of studies focused on different aspects of food and FNS for SSF on islands. Critical dimensions such as availability, accessibility, utilization, and stability remain underexplored. Another major gap is the lack of research on how health shocks, such as pandemics, affect FNS dynamics. The impact of new sustainable technologies and methods on the food system is also largely neglected. Addressing these gaps can provide a deeper understanding of these food systems' complex challenges and opportunities.

2.6.2. Results of the Exploratory Data Analysis

First, we provide an overview of capture and aquaculture fish and seafood production, import, export, and supply in samples SIDS from 1961 onwards, highlighting some key trends and shifts over time. This trend provides an overview of the context in which SSF operate on these islands. Figure 5 illustrates these trends. Between the years 1961 and 2017, the overall quantity of marine food production/harvest has experienced a significant increase from 133,030 tonnes (live weight) to 1,749,790.19 tonnes (live weight), demonstrating a growth of over 13 times. Concurrently, the total marine food supply to the inhabitants of these islands has risen from 291,690 tonnes (live weight) to 1,128,960 tonnes (live weight), indicating a comparatively modest increase of 3.9 times. Conversely, the total importation of marine food to the islands has shown a rise from 254,248 tonnes (live weight) to 1,054,748 tonnes (live weight), representing an increase of 4.1 times. The exportation of marine food from the islands has displayed a substantial surge, escalating from 85,788 tonnes (live weight) to 1,023,909 tonnes (live weight), revealing a growth of approximately 12 times.

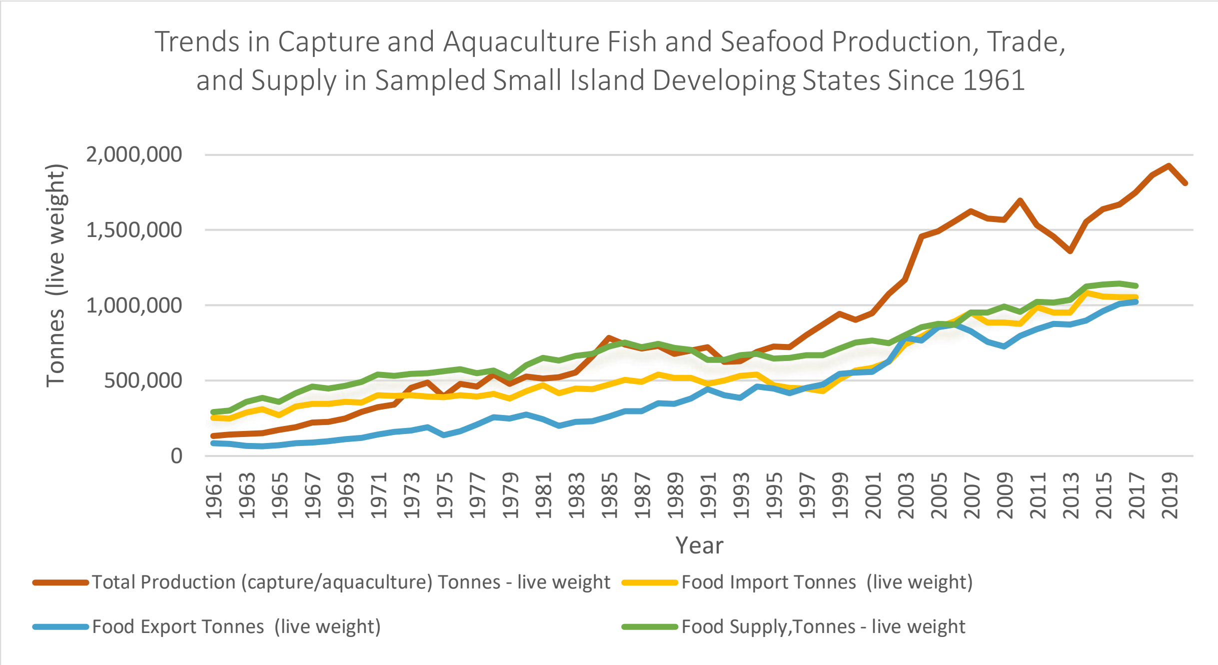

Figure 5. An overview of trends in capture and aquaculture fish and seafood production, as well as import, export, and supply in Sampled Small Island Developing States from 1961 onwards.

The vulnerability and viability roots of FNS extend beyond the scope of food production and supply, encompassing additional factors such as policies, economics, and social dynamics. Thus, a critical evaluation of the prevailing trend becomes imperative to address the multifaceted challenges and enhance the overall resilience and sustainability of FNS systems. Using the findings of a literature review, the following analysis presents historical trends from 1980 to 2022 for variables associated with those identified in the review. This analysis can provide a more inclusive comprehension of the likely vulnerability causes and their respective significance.

The analysis of variables corresponding to the vulnerability and viability factors of SSF in SIDS to FNIS over a span of 43 years, from 1980 to 2022, reveals noteworthy patterns of change. Among the variables exhibiting the biggest changes, the percentage of the population using internet shows a remarkable increase of 99 times, reflecting a substantial growth in internet connectivity and usage within these regions. Furthermore, GNI per capita experiences a significant rise of around 17 times, indicating improved economic conditions and higher income levels for islanders. It is noteworthy that the global GNI per capita has only multiplied by 4.86 over the same 43-year timeframe (World Bank, n.d.). The Food Trade Balance variable demonstrates a considerable change of 5.19 times, signifying a shift in the balance between food exports and exports in the SIDS under examination. This indicates that there has been a notable growth in the value of food exports or a reduction in the value of food imports, resulting in an improved trade balance in the marine food sector. Additionally, Aquaculture

Production per capita and Universal Health Coverage (UHC) Service Coverage Sub-index on Infectious Diseases both exhibit substantial increases of 5.15 times and 4.63 times, respectively, indicating growth in aquaculture production and improved healthcare service coverage.

Conversely, certain variables experience negative changes, such as Marine Trophic Index (MTI) (-0.01 times), Marine Food Supply Per Capita (-0.02 times), and Overall Ocean Health Index Score (-0.02 times), implying declines in these specific aspects. The Fragile States Index (FSI) variable demonstrates a decrease of -0.23 times, indicating an improvement in state stability. The Prevalence of Nutritional Deficiencies also shows a decrease of -0.25 times, indicating that there has been a slight improvement in addressing and reducing the occurrence of inadequate nutrition in these SIDS. The variable Renewable Energy Consumption experiences a decrease of -0.43 times, indicating a reduction in reliance on renewable energy sources. Finally, the variable "Agriculture, Forestry, and Fishing Value Added (% of GDP)" shows a notable decrease of -0.44 times. This implies a reduction in the contribution and economic output generated by agriculture, forestry, and fishing activities.

Figure 6. Changes in vulnerability and viability factors associated with food and nutrition insecurity in sampled Small Island Developing States, over a span of 43 years, from 1980 to 2022.

(For a complete list of indicators, units, and sources, please refer to Appendix C)

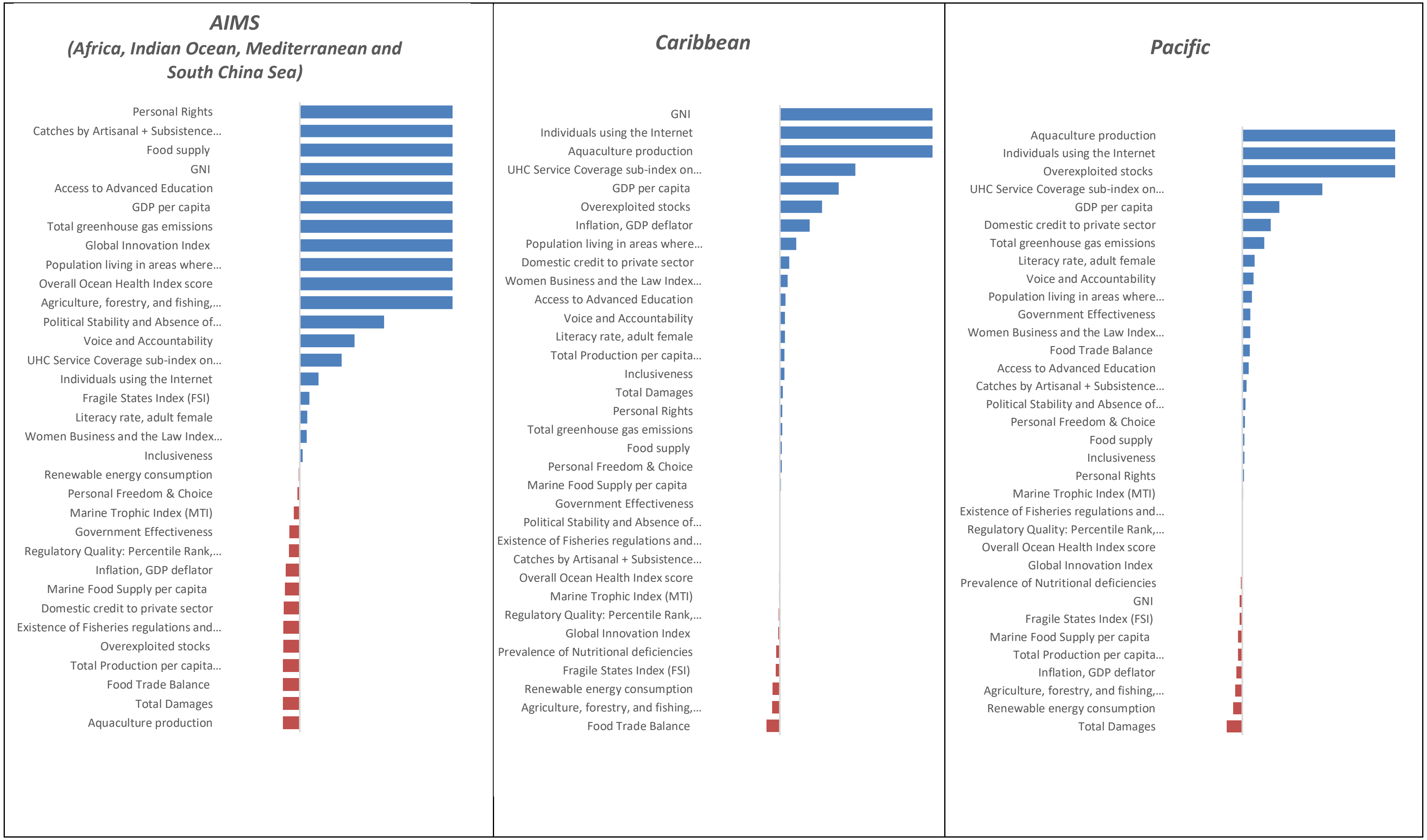
AIMS
(Africa, Indian Ocean, Mediterranean and South China Sea)
Personal Rights
Catches by Artisanal + Subsistence...
Food supply
GNI
Access to Advanced Education
GDP per capita
Total greenhouse gas emissions
Global Innovation Index
Population living in areas where...
Overall Ocean Health Index score
Agriculture, forestry, and fishing,...
Political Stability and Absence of...
Voice and Accountability
UHC Service Coverage sub-index on...
Individuals using the Internet
Fragile States Index (FSI)
Literacy rate, adult female
Women Business and the Law Index...
Inclusiveness
Renewable energy consumption
Personal Freedom & Choice
Marine Trophic Index (MTI)
Government Effectiveness
Regulatory Quality: Percentile Rank,...
Inflation, GDP deflator
Marine Food Supply per capita
Domestic credit to private sector
Existence of Fisheries regulations and...
Overexploited stocks
Total Production per capita...
Food Trade Balance
Total Damages
Aquaculture production
Caribbean
GNI
Individuals using the Internet
Aquaculture production
UHC Service Coverage sub-index on...
GDP per capita
Overexploited stocks
Inflation, GDP deflator
Population living in areas where...
Domestic credit to private sector
Women Business and the Law Index...
Access to Advanced Education
Voice and Accountability
Literacy rate, adult female
Total Production per capita...
Inclusiveness
Total Damages
Personal Rights
Total greenhouse gas emissions
Food supply
Personal Freedom & Choice
Marine Food Supply per capita
Government Effectiveness
Political Stability and Absence of...
Existence of Fisheries regulations and...
Catches by Artisanal + Subsistence...
Overall Ocean Health Index score
Marine Trophic Index (MTI)
Regulatory Quality: Percentile Rank,...
Global Innovation Index
Prevalence of Nutritional deficiencies
Fragile States Index (FSI)
Renewable energy consumption
Agriculture, forestry, and fishing,...
Food Trade Balance
Pacific
Aquaculture production
Individuals using the Internet
Overexploited stocks
UHC Service Coverage sub-index on...
GDP per capita
Domestic credit to private sector
Total greenhouse gas emissions
Literacy rate, adult female
Voice and Accountability
Population living in areas where...
Government Effectiveness
Women Business and the Law Index...
Food Trade Balance
Access to Advanced Education
Catches by Artisanal + Subsistence...
Political Stability and Absence of...
Personal Freedom & Choice
Food supply
Inclusiveness
Personal Rights
Marine Trophic Index (MTI)
Existence of Fisheries regulations and...
Regulatory Quality: Percentile Rank,...
Overall Ocean Health Index score
Global Innovation Index
Prevalence of Nutritional deficiencies
GNI
Fragile States Index (FSI)
Marine Food Supply per capita
Total Production per capita...
Inflation, GDP deflator
Agriculture, forestry, and fishing,...
Renewable energy consumption
Total Damages

Figure 7. Changes in vulnerability and viability factors associated with food and nutrition insecurity in sampled Small Island Developing States in the AIMS (Africa, Indian Ocean, Mediterranean and South China Sea), Caribbean, and the Pacific, over a Span of 43 Years, from 1980 to 2022. The axis values represent percentage changes ranging from -99.99% to +900% and beyond. Percentage changes exceeding +900% are not fully displayed due to spatial constraints.

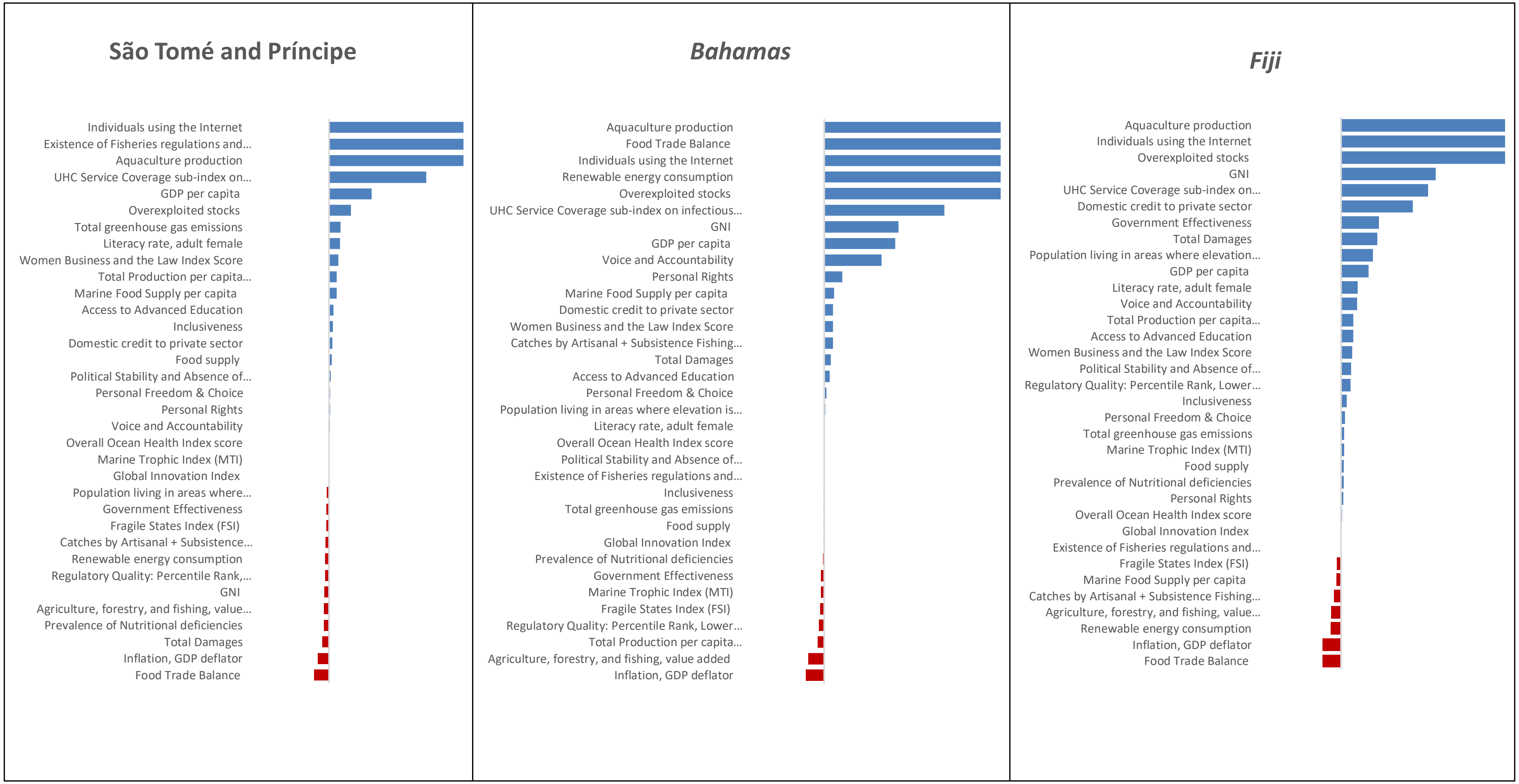

Figure 8. Changes in vulnerability and viability factors associated with food and nutrition insecurity in São Tomé and Príncipe, Bahamas, and Fiji over a Span of 43 Years, from 1980 to 2022. *The axis values represent percentage changes ranging from -99.99% to +900% and beyond. Percentage changes exceeding +900% are not fully displayed due to spatial constraints.*

The trends across SIDS in different regions (Figure 7) highlight a nuanced picture of progress and challenges. The Caribbean shows the highest number of positive trends (23) relative to negative ones (10), suggesting development in areas such as economic growth, technological advancement, and social indicators. The Pacific follows closely with 21 positive and 12 negative trends, reflecting substantial gains in sectors such as aquaculture and internet access, but also indicating persistent challenges in sustainability and resource management. In contrast, the AIMS group exhibits a more balanced yet concerning distribution with 19 positive and 15 negative trends, indicating significant volatility. Despite remarkable growth in certain indicators, such as personal rights and food supply, AIMS experienced steep declines in critical areas such as fisheries production, nutritional sufficiency, and governance quality.

Regional trends have shifted significantly over time. Some indicators, such as aquaculture production, internet usage, and GDP per capita, have experienced substantial growth, which highlight economic progress and greater access to technology. For example, the Pacific demonstrated a 1020% increase in aquaculture production, with the Caribbean and AIMS also showing growth in this area, though less dramatic. Similarly, internet usage rose significantly in all regions, marking a shared technological transformation. However, several critical areas showed consistent declines. Renewable energy consumption decreased substantially, particularly in the Caribbean (-42%) and Pacific (-55%), pointing to challenges in sustainable energy transitions. Food trade balance, agriculture value-added, and nutritional sufficiency also saw declines across regions, with the AIMS region experiencing some of the steepest drops, such as a near-total collapse in aquaculture production and nutritional deficiencies (-100%). These trends highlight a complex mix of progress and setbacks across various domains, shaped by the unique socio-economic and environmental contexts of SIDS.

The Bahamas, Fiji, and São Tomé and Príncipe (Figure 8) illustrate distinct patterns of progress and challenges related to FNS that do not entirely align with broader regional trends.
The Bahamas shows significant economic growth (GNI: 378%, GDP per capita: 361%) and improved governance (Voice and Accountability: 292%), but its extreme rise in overexploited stocks (3210%) and also a decline in agriculture value-added (-81%) diverge from the Caribbean's moderate trends in these areas. In the Pacific, Fiji demonstrates notable increases in domestic credit access (392%) and government effectiveness (208%), which exceed regional averages. However, Fiji's dramatic increase in overexploited stocks (21125%) indicates a more severe challenge compared to the broader Pacific trend (1008%). Meanwhile, São Tomé and Príncipe shows dramatic growth in aquaculture production (7700%) and UHC service coverage (651%), standing out from the overall volatility seen in the AIMS region, yet its complete collapse in food trade balance (-100%) and decline

in agriculture value-added (-34%) further highlight the vulnerabilities. These three cases suggest that while regional trends provide a broad context, each island's unique socio-economic, environmental, and governance dynamics shape their food systems in distinct ways.

2.6.3. Results from the Random Forest Analysis

Figure 9 illustrates the result of the RF and helps delve deeper into understanding the intricate relationships between different vulnerability and viability factors and their impact on FNS in SIDS. The top 10 predictor variables, using SHAP (SHapley Additive exPlanations) values, which have a significant impact on the five response variables, are depicted. The SHAP values can provide a "unified measure" for assessing the importance of features (Lundberg & Lee, 2017). Here, these SHAP values facilitate an understanding of the individual impact of features on the RF model. The relationship between these vulnerability and viability factors and FNIS are measured among the sampled SIDS.

The analysis indicates that multiple factors from social, political, environmental, and economic domains significantly contribute to the vulnerability and viability of SSF to FNIS. The top three predictors include Food Trade Balance (with a SHAP value of 3.3), Access to Advanced Education (1.6), and Agriculture, Forestry, and Fishing, value added (1.5). A higher SHAP value here suggests a stronger impact on the model, either positively or negatively, depending on the context. Factors such as Inclusiveness (1.3), Overall Ocean Health Index Score (1.0), Marine Trophic Index (MTI) (0.7), and variables related to geographic and environmental vulnerability, such as Population living in areas where elevation is below 5 meters (0.5), also have significant contributions. Additional determinants such as Total greenhouse gas emissions, Literacy rate, adult female, and Women Business and the Law Index Score further reflect the multifaceted nature of FNS vulnerabilities faced by SIDS.

Based on this analysis, economic factors, particularly the Food Trade Balance and the Value added by agriculture, forestry, and fishing to the economy, are crucial in supporting FNS of SSF. Social factors, including Access to advanced education, Inclusiveness, Literacy rate of adult females, and Women's rights as indicated by the Women Business and the Law Index Score, emerge as critical influencers in enhancing resilience and food security. These factors highlight the importance of social equity and educational opportunities in strengthening SSF. Environmental factors also play a vital role, with indicators such as the Overall Ocean Health Index score, MTI, population residing in low-lying coastal areas, and total greenhouse gas emissions impacting the FNS of SSF.

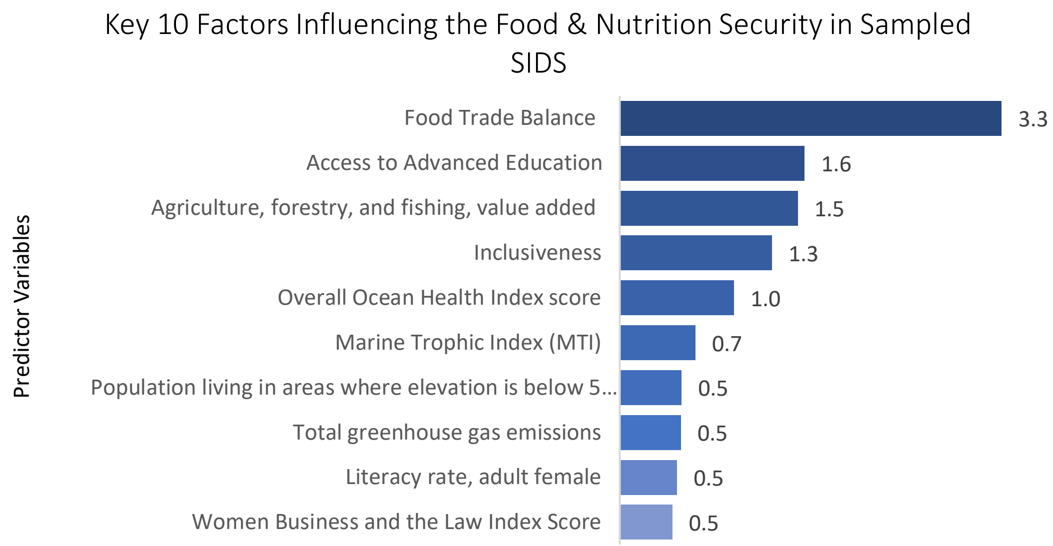

Figure 9. The key ten factors on the vulnerability and viability to food and nutrition insecurity in sampled Small Island Developing States, as determined via examining a Random Forest. The axis values represent mean SHAP values (Average impact on the model).

It is important to note that the significance of predictor variables vary across different response variables (Appendix E-1), promoting a shift toward goal-oriented approaches. The analysis of the factors across SIDS— in the Pacific, AIMS, and Caribbean regions— reveals both commonalities and regional distinctions, highlighting new insights from different perspectives (Figure 10). Consistent factors influencing FNS across all three regions include population living in areas where elevation is below 5 meters, access to advanced education, and food trade balance. However, differences emerge in the magnitude and focus of impacts. In the Pacific, the most prominent indicators are the population living in areas below 5 meters, food trade balance, and aquaculture production. In AIMS, access to advanced education, population living in low-elevation areas, and food trade balance rank highly. The Caribbean region is more significantly influenced by greenhouse gas emissions, domestic credit to the private sector, and food trade balance.

Another picture emerges by looking at the findings from individual islands. The results highlight how each island's unique characteristics and challenges can reflect or deviate from broader regional trends. For example, Fiji's performance within the Pacific region reveals both alignment and divergence. Indicators such as population living in areas below 5 meters and access to advanced education are consistent with the region's trends, while the higher impact of the Fragile States Index

(index for assessing the vulnerability of nations to conflict or collapse) and Marine Trophic Index scores highlight more specific vulnerabilities. The three islands—Fiji, Bahamas, and São Tomé and Príncipe—do not fully align with regional trends.

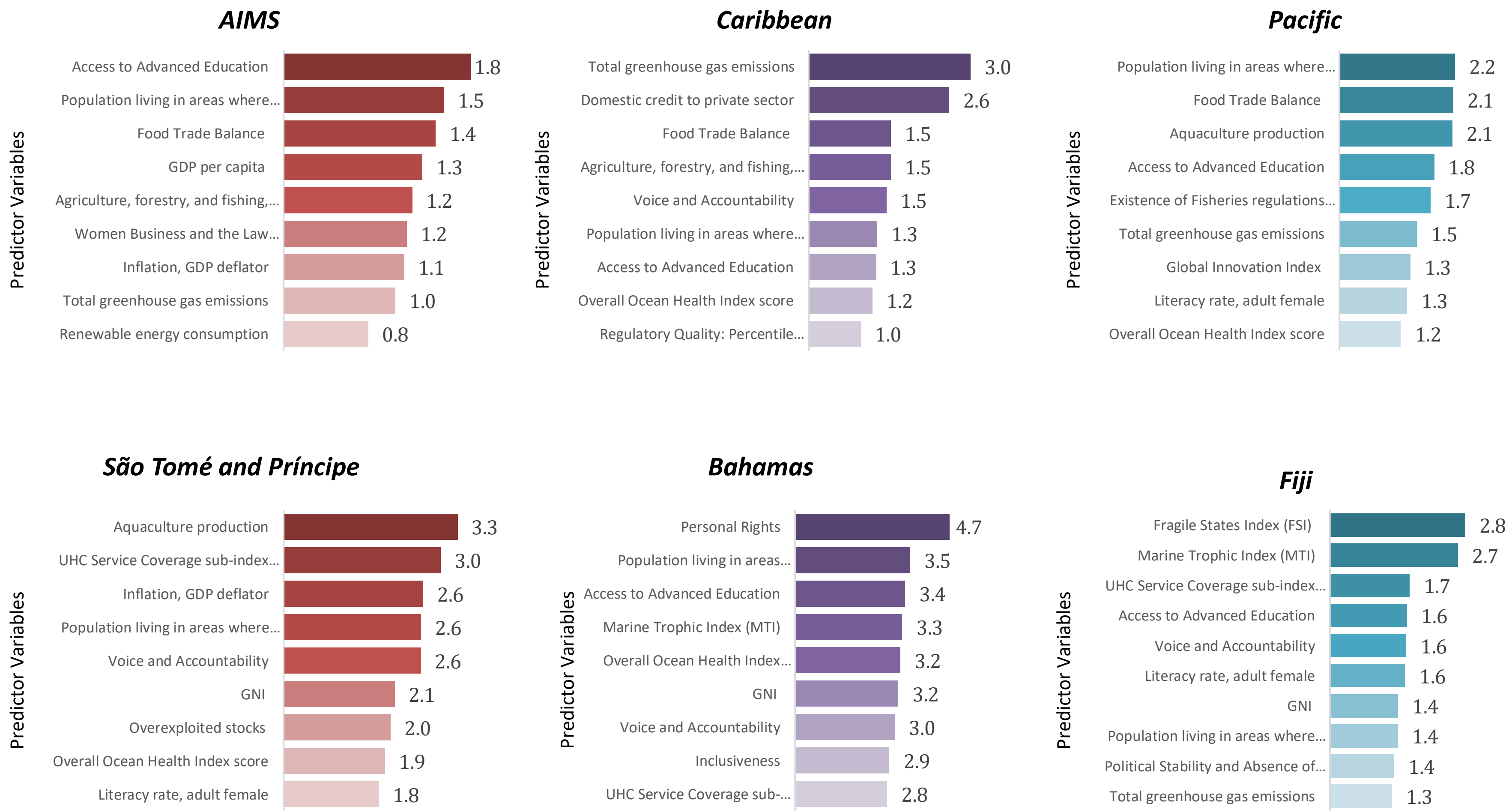

Figure 10. Key 10 Vulnerability and Viability Factors Impacting Food and Nutrition Insecurity in sampled Small Island Developing States in the AIMS

(Africa, Indian Ocean, Mediterranean and South China Sea), Caribbean, Pacific, including São Tomé and Príncipe, Bahamas, and Fiji over a Span of 43 Years, from 1980 to 2022. The axis values represent mean SHAP values (Average impact on the model).

2.6.4. Sensitivity Analysis: Performance Comparison of Random Forest, Decision Tree, and Neural Network Models

The sensitivity analysis results demonstrate that the RF model exhibits significantly higher accuracy compared to DT and LSTM models (Figure 11). Both the MAE and MSE were substantially lower for RF across the five response variables, indicating higher performance. In contrast, the LSTM model displayed the lowest accuracy, with notably higher MAE and MSE values. Moreover, the ranking and importance of predicted features fluctuated with each iteration in the LSTM model, suggesting that it lacks robustness and is unsuitable for this type of data analysis. The model performance analysis, using Actual vs. The stability and reliability of the RF model across repeated trials make it the preferred method for analyzing the given dataset, aligning with existing literature that underscores the model's robustness in handling both categorical and continuous variables (Breiman, 2001; Liaw & Wiener, 2001). Moreover, predicted Values as shown in Appendix E-2 further supports the observation that the RF model performs quite well compared to both the Decision Tree and LSTM models.

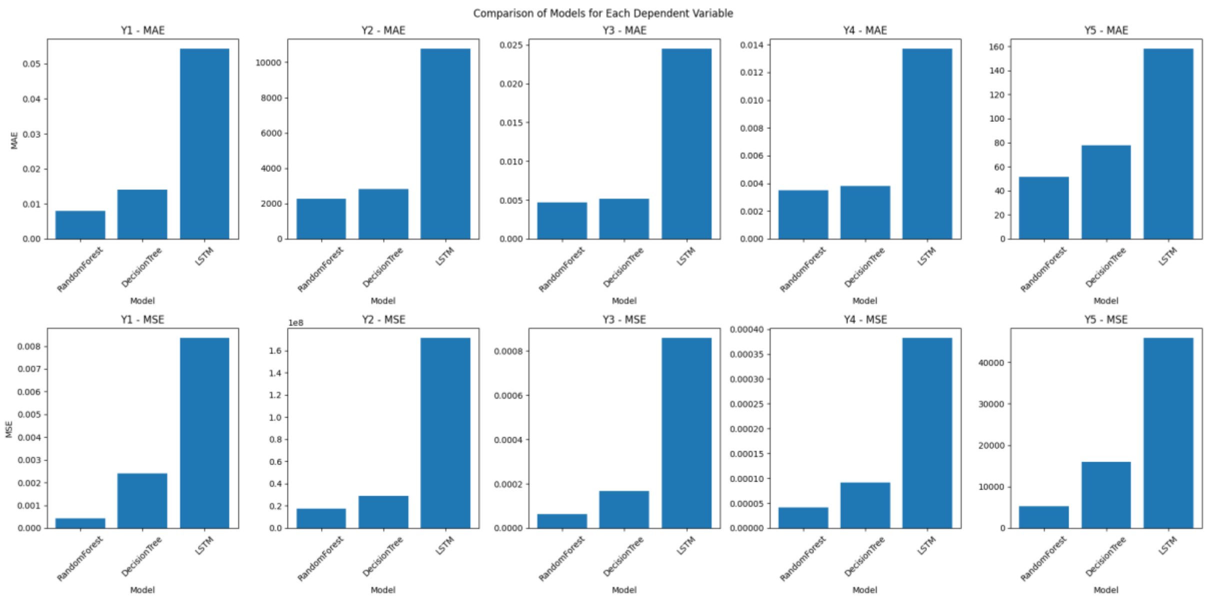

Figure 11. Comparison of the Random Forest, Decision Tree, and Long Short-Term Memory, using Mean Absolute Error (MAE), Mean Squared Error (MSE)

2.7. Discussion

This research claims that merely examining aspects of vulnerability is inadequate when performing a vulnerability analysis. It is imperative to expand the viewpoint and include the entire range from vulnerability to viability. This highlights the interconnected nature of vulnerability and viability, emphasizing that the further a system moves away from vulnerability, the closer it gets to achieving a state of viability. This approach emphasizes that vulnerability and viability are not binary states but rather exist on a continuum, requiring a nuanced understanding and a continual effort to reduce vulnerabilities and increase cultivated viabilities. Taking a "contextual vulnerability" perspective (Adger, 2006), this research identified vulnerability and viability factors related to the FNS of SSF in islands. The analyses performed in this research entailed considering not only the elements that contribute to the vulnerability of the SSF to FNIS but also those that foster viability.

The systematic literature review revealed the complex and dynamic nature of island food systems, which are shaped by a multitude of factors. Based on the result of our literature review, the Multidimensional Vulnerability Index (MVI) for islands proposed by Sachs et al. (2021), including economic vulnerabilities, structural development limitations, and environmental vulnerabilities, could be broadened. The broadened perspective should include (1) governance and institutions, (2) environmental, (3) social and cultural, (4) health, and (5) technology dimensions. The V2V conceptual model (Figure 11) illustrates the interconnectedness among these five system dimensions in which changes or developments in one dimension can have cascading effects on others.

The identified factors influencing FNIS in SIDS can have both direct and indirect impacts, and some of the dynamics can be explained through the Pressure and Release or PAR model. The PAR model explains how root causes, dynamic pressures, and unsafe conditions interact with hazards to create vulnerabilities, emphasizing the need to address these factors to reduce risks (Liu et al., 2007). In SIDS, root causes such as dependency on external markets and weak governance structures, identified through the literature review, can lead to dynamic pressures, including overfishing driven by inadequate regulation enforcement and the impacts of climate change, such as rising sea levels. These pressures subsequently result in unsafe conditions, such as the depletion of fish stocks, the fragility of coastal infrastructure, and limited access to marine resources. When hazards (e.g., tropical cyclones, sea-level rise) occur, these vulnerabilities can be further exacerbated, resulting in severe disasters and FNIS for small-scale fishers and communities. The FNIS can occur due to systemic vulnerabilities, rooted in historical, economic, and governance factors, creating conditions where local food systems are inherently fragile and unsustainable. Addressing these vulnerabilities through sustainable resource management, governance reforms, and economic diversification is essential to improving FNS in

SIDS (FAO, 2020a; UN DESA & UNDRR, 2022). While the PAR model offered a foundational view by tracing vulnerability back to root causes, more recent frameworks from the IPCC and UNDRR incorporate dynamic risk, adaptive capacity, and systemic interdependencies (IPCC, 2022; UNDRR,2019), which can be further analyzed.

The literature review highlighted a concentration of existing studies in specific countries or regions. In particular, extensive research has been conducted on the vulnerability of small-scale fishers to FNIS in Indonesia, the Philippines, and the Solomon Islands. This is mainly due to the reason that SSF in these countries face FNIS due to their high dependence on fisheries for livelihoods and nutrition (Béné et al., 2016), vulnerability to climate change and environmental degradation (Connell, 2015), socioeconomic and institutional challenges such as weak governance and financial instability (Kronen et al., 2010), and the global research focus on these biodiversity-rich regions for improving fisheries sustainability (FAO, 2020a; FAO, 2020b).

The V2V dimensions can both influence and be influenced by (1) identity, encompassing values, beliefs, and norms; (2) competency, involving knowledge and skills; and (3) infrastructure, comprising both physical and technological elements. Values and beliefs function as reflective surfaces, mirroring present and future dynamics within SSF, offering guidance for sustainability across the broader social-ecological system (Berenji et al., 2021). Competencies, encompassing both knowledge and skills, are essential for instigating change across all dimensions of the system (Shove et al., 2012). Access to infrastructure, technology, and innovative tools can aid the development of sustainable fishing practices (Belhabib et al., 2021; Song et al., 2020). Our argument lies in the idea that identities, competencies, and infrastructures wield the potential to influence transformative actions. The emergence of these transformative changes can result from the actions and interventions of various actors (de Haan & Rotmans, 2018).

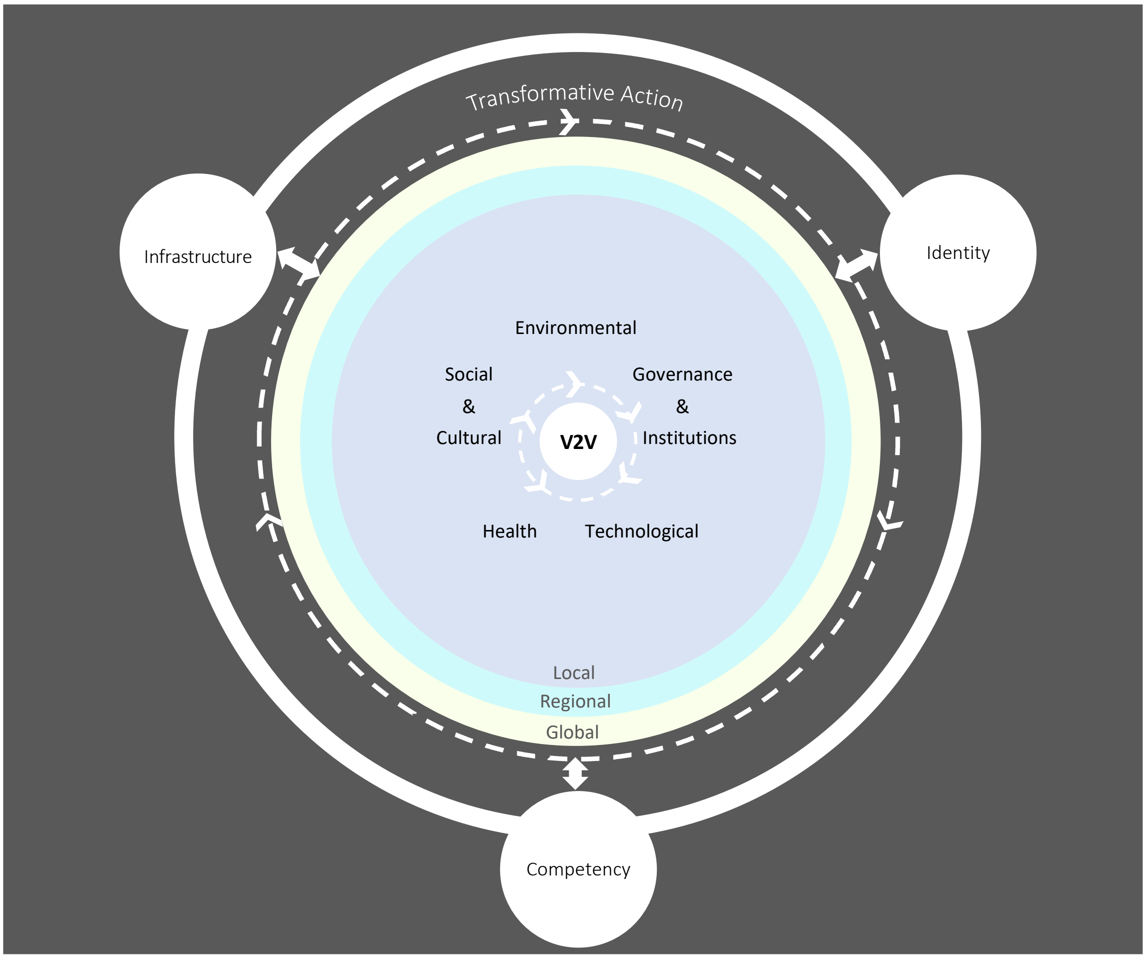

Figure 12. The conceptual model for a transition from a vulnerability to viability (V2V), framed in accordance with findings from a systematic literature review.

Our exploratory data analysis highlighted that the targeted 20 islands collectively produced around 45.8 million tonnes of marine food between 1961 and 2017 (Figure 13). A total of 32.1 million tonnes of marine food was imported to these islands, resulting in a combined input of 77.9 million tonnes over the 57-year period. Approximately 30% of this input, equivalent to around 24.3 million tonnes, was exported outside the islands, while only about 50% was utilized domestically as marine food. Furthermore, an estimated 18% of the input was allocated for non-human purposes, classified as waste or lost along the supply chain.

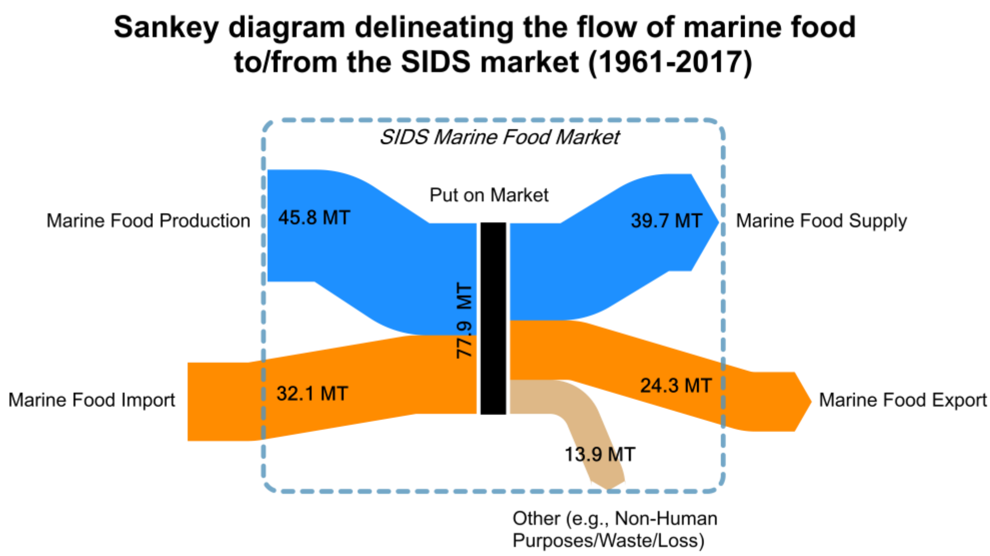

Figure 13. A Sankey diagram delineating the input and flow of capture and aquaculture fish and seafood to the island's market has been illustrated in millions of tonnes, with the time period spanning from 1961 to 2017.

The diagram has been classified into four categories of marine food production/harvest: import, export, supply, and others (fish and seafood used for non-human purposes and the amount of waste or loss along the supply chain).

The increase in exports can offer significant economic advantages to SIDS, including contributions to GDP growth, foreign exchange earnings, job creation, and government revenue through tax and licensing (Jaunky, 2011). However, such growth carries ecological and social risks. Overfishing, unsustainable practices, and weak resource governance threaten long-term sustainability (*ibid*). Also, without careful management, the drive for short-term gains may deplete marine resources and undermine the very economic benefits these exports are meant to support (*ibid*). As global demand rises, local fishers may become trapped in exploitative patron–client relationships, where they depend on traders for credit and market access (Crona et al., 2015). This often leads to growing debt and limits their autonomy. Moreover, profits from exports are frequently captured by wealthier intermediaries, leaving fishers with low incomes. It can also lead to other social and economic challenges, such as mounting conflicts among fisheries actors, and wealth accumulation by elites, especially in the absence of strong institutions and when vulnerable species are targeted for high-demand international markets (*ibid*). As more fish is directed to export markets, local food security can decline, especially in communities that rely on fish as a staple protein source (*ibid*). These dynamics can undermine both social equity and long-term economic resilience in coastal areas.

The exploration of the data spanning 43 years reveals the longitudinal patterns in the indicators. On a global scale, positive shifts, such as the significant increase in Internet Usage, rise in GNI per Capita, growth in Aquaculture Production, and advancements in Healthcare Service Coverage, show technological, economic, and health improvements. This aligns with a recent FAO report, which highlights significant improvements in aquaculture production and global seafood consumption, as well as technological advances in the sector (FAO, 2024). Conversely, negative trends, including declines in marine tropic levels, marine food supply, and overall ocean health, highlight environmental and sustainability challenges. These challenges indicate the need for better management practices, innovative solutions, and the implementation of the Blue Transformation Roadmap (FAO, 2024).

The trends across different regions reflect a combination of progress and challenges, with improvements in indicators such as aquaculture production, GDP, and internet access, as well as declines in critical areas such as renewable energy consumption, agricultural value-added, and food security. The AIMS region faces significant challenges, including a decline in aquaculture production and increasing nutritional deficiencies which can be understood through an analysis of local aspects. Several countries in the AIMS region have seen a substantial decrease in aquaculture production, such as Malawi (FAO, 2024). Aquaculture in the region is hampered due to several factors, including disease, limited availability of land and feed, water scarcity, and environmental factors *(ibid)*. Also, sub-Saharan Africa is experiencing a decline in per capita consumption of aquatic foods. This is concerning because aquatic foods are a key source of animal proteins and micronutrients in this region *(ibid)*.

The cases of The Bahamas, Fiji, and São Tomé and Príncipe further highlight the complex interplay of progress and challenges faced by fishers in each country. While some show economic growth and governance improvements, they also experience severe environmental issues, such as overexploited fish stocks and collapsing agricultural sectors. The Bahamas—Aquaculture production, Food Trade Balance, Individuals using the Internet, Renewable Energy Consumption, and Overexploited Stocks—experienced the highest increase from 1980 to 2022. The dramatic increases are due to different factors including the strategic focus on sustainable aquaculture, rising seafood demand such as those from the tourism industry, and growing pressure on marine stocks from intensified fishing . Similarly, in Fiji, aquaculture production has increased due to government and private sector investments aiming to meet growing demand, while overexploited stocks have become a concern due to intensified fishing pressure and inadequate management (FAO, n.d.). São Tomé and Príncipe has experienced a significant improvement in fisheries regulations and aquaculture due to increased awareness of sustainability, government and international collaborations, historical regulatory efforts, a co-management approach involving local communities, decentralization of resource management, control over fishing efforts, and the need to address overexploitation (Zacarias et al., 2022). Moreover, aquaculture has been increasingly utilized, as seen in Fiji and the Bahamas, primarily to ensure livelihoods and promote long-term economic growth (*ibid*).

São Tomé and Príncipe, Fiji, and the Bahamas have all experienced negative trends. São Tomé and Príncipe's decrease in total damages by disasters can be linked to improved disaster management, although climate change continues to affect its marine ecosystem (Zacarias et al., 2022). Inflation has been driven by different factors, such as significant fuel shortages and the pandemic's economic impact, while the country's food trade balance suffers from underutilized fisheries, overexploitation, and illegal fishing (*ibid*). In Fiji, a decline in the food trade balance is likely influenced by fluctuations in marine resources such as sea cucumber fisheries and low pearl oyster stock densities (FAO, n.d.). The Bahamas has faced reduced fisheries production per capita, with declines in spiny lobster and conch exports, due to reliance on tourism and finance over agriculture (Moultrie et al., 2016).

The RF was used to identify and rank the most influential factors that affect FNS. While economic factors were discussed earlier, social and political factors are also of significant importance. Social and political factors, such as access to advanced education, women's literacy, and inclusiveness, are crucial for securing FNS on sampled small islands in several ways. For instance, access to advanced education boosts skills and innovation in fisheries (Levine et al., 2011). Women's literacy enhances resource management and supports family nutrition (Kleiber et al., 2015). Inclusiveness also promotes equitable resource distribution and strengthens resilience (Pretty, 2003). The RF result highlighted that environmental considerations are fundamental for ensuring the FNS on SIDS. Healthy marine ecosystems support consistent fish availability and maintain the ecosystem's balance (Pauly et al., 1998), while the vulnerability of low-elevation coastal populations to climate change threatens access to fishing grounds, emphasizing the need for resilience strategies (Cinner et al., 2012; Nicholls & Cazenave, 2010). These prioritized factors offer a strategic framework for intervention, making them potential leverage points in improving FNS and sustainability in island contexts.

The results of the RF analysis suggest that while global and regional trends in FNIS provide useful insights, they may not fully capture the unique conditions of individual countries within SIDS. Food and nutrition security in the broader Caribbean is influenced by large-scale economic and environmental factors, including greenhouse gas emissions driving climate change, limited access to financial resources for agricultural and fisheries development, and a reliance on food imports that creates trade imbalances and vulnerability to external factors (FAO, 2024; Mohammadi et al., 2022; Rahman et al., 2022). In contrast, The Bahamas faces distinct challenges where food security is more closely tied to secure tenure and resource access for fishers (Moultrie et al., 2016), the heightened risk of natural disasters in low-lying coastal areas (*ibid*), and the need for better education and training (*ibid*) to support economic stability and adaptive capacity within fishing communities. In the Pacific, while reliance on fisheries is a regional trend (Asch et al., 2018), countries such as Fiji experience compounded challenges from political vulnerabilities, which are linked to the quality of governance (Gong & Rao, 2016; Roberts et al., 2011). Also, the health and balance of Fiji's marine ecosystem are crucial for food and nutrition security, as the country relies heavily on fisheries for both economic stability and local diets, with factors such as overfishing, ecosystem degradation, and climate change threatening fish stocks and livelihoods—making tools such as the marine trophic index valuable for monitoring and managing these risks (FAO, n.d., 2024; Jentoft & Eide, 2011). The differences in FNS drivers between the AIMS region and São Tomé and Príncipe arise from context-specific geographic, economic, and institutional factors. While the AIMS region emphasizes structural and long-term development factors such as trade, education, and climate resilience, São Tomé and Príncipe prioritizes immediate food security concerns related to fisheries, inflation, and healthcare. São Tomé and Príncipe's food security vulnerabilities can be mainly linked to its reliance on fisheries, economic instability, and healthcare quality. A shift to aquaculture aims to supplement wild-caught fish and reduce dependence on imports, addressing challenges such as overfishing and limited local food production (Zacarias et al., 2022). Also, the islands high dependency on imported food (*ibid*) makes it vulnerable to global market price fluctuations, while inflation worsens the affordability of essential goods (*ibid*), and the country's limited healthcare infrastructure (*ibid*) further hampers efforts to combat malnutrition and public health challenges, complicating the achievement of food and nutrition security.

The comparison of findings across global, regional, and national scales underscores the important role of "scale" in comprehending and addressing vulnerabilities. Understanding scale can play a key role in the effectiveness of sustainability actions (Wilbanks, 2007). There is a need for a multi-scale approach to address resource mismatches, adapt to local contexts, and refine strategies (*ibid*). Using methodologies, such as multi-scale approaches and systems thinking, can help integrate insights across scales (Loorbach, 2008). They can enable the alignment of ecological integrity with economic well-being, ensuring that solutions are both sustainable and equitable across scales (*ibid*). The diverse and context-specific drivers of FNS across SIDS underscore the need for a systems thinking approach in both analysis and policy formulation. While regional trends offer valuable insights, they often mask localized interactions among environmental, economic, institutional, and socio-cultural factors that shape FNS outcomes. Systems thinking enables a holistic understanding of these complex, interdependent dynamics by recognizing feedback loops, non-linear relationships, and cross-scale interactions that conventional sectoral analyses may overlook.

Using RF, we came to close proximity to introduce an index for V2V analysis but deliberately chose not to introduce a singular measure. A single index can oversimplify complex systems, making interpretation less reliable across different settings. Additionally, as systems evolve, a fixed index may fail to capture ongoing changes. Therefore, this research highlights the need for a dynamic approach to assessing vulnerability and viability, acknowledging that risks shift over time and across locations.

This study recommends a flexible and adaptive approach to vulnerability and viability assessments, wherein the methodology is customized to account for unique considerations of communities. Couplings between human and natural systems exhibit spatial, temporal, and organizational variations, necessitating an analysis incorporating nonlinear dynamics encompassing thresholds, reciprocal feedback loops, time delays, resilience, heterogeneity, and unexpected events (Liu et al., 2007). Brown et al. (2015) emphasize the importance of assessing stakeholder dynamics, power relationships, and perceptions of influence over decision-makers. The convergence of the results from computational techniques with participatory approaches can help to incorporate these dynamics and enrich the depth of the results. Also, in our data-gathering stage, we identified that SIDS and SSF struggle with significant data gaps, limiting a deep and detailed understanding of their specific and complex challenges. Closing these gaps is essential for developing evidence-based strategies that enhance resilience and ensure equitable resource allocation.

The V2V approach suggested in this study resonates profoundly with the principles underpinning the blue economy, blue growth, and blue justice, as it accounts for the intricate interplay of ecological, economic, social, governance, and technological dimensions that shape the sustainability and resilience of marine-based systems (Adger, 2006; Bennett et al., 2021; OECD, 2016; Silver et al., 2015). By moving beyond a narrow vulnerability lens and integrating viability considerations, this approach aligns with blue economy visions that seek both ecological stewardship and economic development, as well as blue growth agendas that champion innovation and enhanced resource efficiency (Belhabib et al., 2021; de Haan & Rotmans, 2018; Shove et al., 2012). Critically, the notion of blue justice, emphasizing fairness and equity, is advanced by this perspective through the recognition that the identities, competencies, and infrastructures of local communities—especially small-scale fishers—must be empowered to achieve long-term sustainability and equitable resource access (Allison et al., 2012; Berenji et al., 2021; Ostrom, 2009). The rigorous integration of exploratory data analysis (EDA) and advanced machine learning techniques, such as random forest (RF), serves to illuminate complex patterns and trade-offs within island food systems, providing a high-resolution understanding of how economic vulnerabilities, environmental stresses, and socio-cultural dimensions interact to influence FNS (Burstein & Holsapple, 2008; Cinner et al., 2012; FAO, 2020; Najafabadi et al., 2015; Sachs et al., 2021; Stephen & Downing, 2001). By harnessing the insights derived from these analytical endeavours, policy interventions can be more strategically aligned with blue economy principles to optimize marine resource use, improve governance frameworks, and foster greater inclusivity, while technological and infrastructural innovations—ranging from artificial intelligence-driven monitoring to participatory decision-making platforms—become conduits for transformative change that harmonizes local values, institutional arrangements, and ecological imperatives (Bennett et al., 2021; Bertot & Choi, 2013; Liu et al., 2007; Miller, 2007; Song et al., 2020; Steenberg et al., 2019).

The findings emphasize the need for systemic, context-sensitive approaches to better inform decision-making. Applying a systems lens, this study has shown that island food systems are embedded within dynamic ecological, political, economic, and social systems that interact in non-linear ways. Based on the LR FNIS on islands is a chronic, complex, and fragmented problem, with stakeholders pursuing partial, sometimes conflicting solutions that can hinder long-term coordinated action toward FNS. Therefore, systems thinking, defined as 'a way of understanding reality that emphasizes the relationships among a system's parts, rather than the parts themselves' (Meadows, 2008, p. 6), can deepen understanding of system behaviour and support the development of context-specific, actionable solutions. The results of our LR enhanced understanding of the food system on islands and offered preliminary insights into its underlying dynamics. Moving forward, the findings can inform further analysis at local and national levels to identify potential leverage points for targeted interventions, ' where a small shift in one thing can produce big changes in everything' *(Meadows, 1999, p. 1).* Further analysis will help to understand how feedback loops, time delays, and interdependencies can shape the food system behaviour, making it particularly valuable in analyzing the complex drivers of FNIS on islands. For example, integrated modelling in Pacific SIDS highlights that climate change, governance capacity, and market access act together to shape the food system, revealing leverage points not visible in other assessments (Barnett et al., 2020, p. 4). These insights demonstrate how systems thinking can enable more effective policies and interventions by accounting for relevant interactions across environmental, institutional, and social domains.

2.8. Conclusion

This part of the thesis, we examined island fishers' food systems vulnerability and viability dynamics through a systematic literature review, exploratory data analysis, and an RF model with lagged, rolling, and expanding features to capture time dependencies. The literature review, conducted globally across islands, identified key factors influencing food and nutrition security among sampled islands, categorizing them into seven domains. Quantitative analyses focused on SIDS, where exploratory data analysis revealed trends such as a sharp rise in marine food exports, increased internet access, higher Gross National Income, and aquaculture growth. The RF model highlighted key determinants of vulnerability and viability to food and nutrition security, including food trade balance, education access, agriculture's contribution to GDP, and inclusive policies. We argued that instead of merely focusing on vulnerabilities, incorporating Vulnerability to Viability or V2V analysis offers a more comprehensive approach.

The exploratory data analysis and random forest modelling were conducted to better understand the vulnerabilities and viabilities in relation to the FNS on SIDS at global, regional, and national levels. The results demonstrated how the scale of analysis significantly impacts results. These differences in scale, scope and context significantly affected the results and their broader implications. Moreover, integrating V2V analysis employed in this study enhanced our understanding of the complex food systems. This approach—combining assessments of vulnerability and viability dimensions, data estimation, exploration of trends and patterns, as well as machine learning methods—emphasized the importance of using advanced methods to understand the challenges faced by vulnerable systems in a rapidly changing world.

Chapter 3

Core Qualities of a User-Centred Information System for Small-Scale Fisheries

Information systems are an important yet underexplored tool that can help vulnerable communities, such as small-scale fisheries (SSF), improve their livelihood and food security. Recent studies have increasingly emphasized the importance of addressing challenges faced by SSF because of their economic and social significance. One of the major issues identified is the inadequate utilization of IS within these communities primarily due to the systems' failure to consider their specific needs. Effective IS for SSF encompasses a broad range of functions, including data collection, communication, decision support, and platforms for resource management and knowledge dissemination. Despite this broad potential, efforts have predominantly concentrated on data gathering—specifically on fishing sites, boats, exploitation patterns, fleet behaviour, and species production. These efforts, however, remain limited, resulting in SSF receiving far less attention compared to large-scale fisheries, leaving SSF to suffer from a lack of appropriate IS. This research highlights the critical role of a multi-level, context-sensitive Participatory Design (PD) approach in formulating and developing IS for small-scale fishers, fostering critical transitions from vulnerability to viability. Through an analysis involving literature and user surveys in Kumirmari Village Island of the Indian Sundarbans Delta, the paper identifies key attributes of effective PD for an efficient and user-friendly IS. It discusses how integrating context-specific data with active user participation, focused on the hierarchy of needs, perceptions, expectations, and decisions, can empower SSF to navigate various challenges, offering transformative and insightful solutions. The proposed hierarchy highlights the broader implications of this approach for designing global sustainability initiatives, particularly in creating information systems and technologies that are specifically designed to support vulnerable communities. This has significant potential for both enhancing academic understanding and offering practical solutions for sustainable development.

Keywords: Participatory Design, small-scale fisheries, Information system, Food security, Sundarbans, Kumirmari

3.1. Introduction

Fish represents a significant share of the global population's animal protein intake, with per capita consumption rising from 9.0 kg in 1961 to 20.5 kg in 2018, highlighting its growing importance in the global food supply (FAO, 2020b). Small-scale fisheries (SSF) are indispensable to global food and nutrition security (FNS), contributing significantly to the global fish supply, which provides a vital source of protein, essential fatty acids, vitamins, and minerals to millions worldwide (Béné et al., 2016). In many developing countries, SSF are vital for the livelihoods of coastal and rural communities, supporting FNS both directly, through fish supply and indirectly through income generation (Béné et al., 2016; FAO, 2020b; HLPE, 2014). Despite their importance, SSF encounter diverse challenges across environmental, economic, social, and regulatory dimensions, such as overfishing, economic volatility, social inequities, and fragile governance (Allison et al., 2009; Béné, 2006; Chuenpagdee, 2011). Recognizing the significance of SSF, there is an urgent need to address these challenges to enhance global FNS, foster economic development, and advance community well-being (Chuenpagdee, 2011; World Bank, 2012).

Designing appropriate Information Systems (IS) for SSF has emerged as a crucial strategy to tackle these challenges by helping these communities improve sustainability, efficiency, and resilience (e.g., FAO, 2020; Mock et al., 2013; Sujatha et al., 2006). Here, the term *Information System* refers to a single application designed to deliver real-time, customized information to users—specifically, small-scale fishers. Enhanced access to information is recognized as a critical consideration that leads to better decision-making, resulting in increased incomes and reduced vulnerability (FAO, 2020). However, many gaps remain, including infrastructure challenges, low digital literacy of users, economic constraints, and insufficient policy support (Dash et al., 2023). Many technological solutions, such as ICTs, are not designed based on the specific needs of SSF, which impedes their effectiveness (*ibid*). The scalability and sustainability of information technologies in SSF face significant challenges due to the inadequate consideration of vulnerable users' needs (Haambiya et al., 2021a). There remains a significant gap in the research regarding the development of customized applications that are tailored to the unique socio-economic and environmental conditions of SSF (Dash et al., 2023).

Participatory Design (PD) (Nygaard, 1987) has emerged as a useful methodology in SSF management, with various studies demonstrating its effectiveness in addressing complex challenges through the active involvement of local fishers (Dias & Seixas, 2019; Giuliani et al., 2022; Guanais et al., 2015; Jentoft & Chuenpagdee, 2009; Karr et al., 2017; Kraff, 2018; Nthane et al., 2020; R. Silvano et al., 2017). It has shown great potential in transforming SSF by directly involving fishers in the development of Information Technologies. For example, in South Africa, PD was employed to involve fishers in co-designing the Abalobi ICT platform, which was aimed at making the tool culturally relevant and empowering fishers to manage resources better and engage more equitably in the market (Nthane et al., 2020). PD approaches have been emphasized and utilized to ensure the relevance and usability of IS (Irestig et al., 2004). This emphasis is due to the fact that these approaches tend to produce practical solutions that users find easier to accept (*ibid*). In particular, PD fosters trust and ownership among fishers, which is crucial for successfully implementing new technologies (Ramírez & Quarry, 2004). While previous studies demonstrated the value of PD in developing new technologies for SSF, they lacked clarity regarding how the specific context and needs are assessed (e.g., Ramírez & Quarry, 2004; Irestig et al., 2004). This gap underscores the necessity for further research on how the PD should be implemented to effectively understand the diverse needs of SSF communities. Such research is crucial to ensure that the solutions are both practical and sustainable in addressing the unique challenges faced by these fisheries.

In this part of the thesis, we apply the Contextual Participatory Design (CPD) approach to understand the place-based challenges faced by small-scale fishers. While PD focuses on involving users in the design process, CPD emphasizes the importance of deeply understanding and incorporating the specific context of the users into the design process (Chamberlain et al., 2013; Puri et al., 2004; Simonsen & Robertson, 2013a). CPD ensures that the solutions are not only co-created with users but are also highly relevant and effective within their particular social, cultural, and environmental settings (*ibid*). CPD has emerged as a critical approach for addressing modern design challenges by emphasizing adaptability and responsiveness to the specific needs of users (Chamberlain et al., 2013). Its significance is particularly evident in rural and community-based projects, where traditional design methods often fail to account for the unique challenges of geographic isolation and cultural diversity (Puri et al., 2004).

Building upon the identified gaps, the primary objective of this paper is to propose how CPD can be effectively employed to develop IS tailored to the unique needs and conditions of SSF, specifically to enhance their FNS. By focusing on the distinct needs of these communities, the research seeks to offer new insights that have been overlooked in previous research. It identifies and incorporates user-related attributes that can enhance the effectiveness of IS using CPD approaches in vulnerable settings. The ultimate goal of this research is to ensure that the PD processes are relevant and beneficial for SSF by including their voices and needs within the IS. The paper is guided by the following research question: What are the key attributes of a contextual participatory design for an information system that can support decision-making in planning sustainable food systems aimed at the specific needs of vulnerable SSF communities in transitioning from vulnerability to viability? This paper focuses on vulnerable SSF in Kumirmari Island, Indian Sundarbans Delta. The analysis starts with exploring the SSF vulnerability and viability dynamics of SSF in Kumirmari using secondary data, with a particular emphasis on food and nutrition security. This is followed by a survey aimed at identifying user requirements and needs. By incorporating fishers' insights, the paper seeks to ensure that IS are both relevant and practical, addressing the unique challenges faced by SSF and amplifying their voices in the design process.

3.2. Designing Information Systems for Small-Scale Fisheries

Several studies have been conducted to identify how new technologies, such as IS and Information and Communication Technology (ICT), should be designed for SSF communities. The distinction between IS and ICT lies primarily in their scope and focus. IS is concerned with the integration of technology, people, and processes within organizational and social contexts to manage, process, and utilize information for decision-making, strategic planning, and operational support (Galliers et al., 2020; Laudon & Laudon, 2019). In contrast, ICT focuses specifically on the technological tools and infrastructure—such as hardware, software, telecommunications, and networks—used to store, transmit, and communicate information (Saba et al., 2023). Therefore, ICTs can be considered a subset of IS when they are used within a system to support processes, users, and organizational objectives. Previous studies on IS and ICT have primarily focused on identifying the socio-demographic factors that influence adoption, exploring the need for targeted interventions and the potential of ICT to improve socio-economic conditions, and examining the role of detection technologies in enhancing working conditions in fisheries:

A study by Raidah Mazuki (2016) focuses on identifying the socio-demographic factors that influence the adoption of modern fishing technology among coastal fishermen on the West Coast of Malaysia, assessing the relationship between technology acceptance constructs and the benefits of adoption. In 2019, Chuenpagdee et al. describe the development of the "Too Big To Ignore" information system, highlight its key features, and share findings derived from analyzing ISSF data, emphasizing the significance of this global database for SSF. Another study by Mazuki et al. (2020) emphasizes the need for targeted interventions, such as improved training programs, financial assistance, and better infrastructure, to enhance the socio-economic conditions of coastal fishermen through technology adoption. Dash et al. (2023) explore the potential of ICT to enhance profitability, minimize resource wastage, and improve socio-economic conditions. Marschke et al. (2020) explore the potential of detection technologies such as satellite surveillance and mobile apps for worker communication and reporting to improve working conditions in fisheries. The collective findings from these papers underscore the importance of IS and ICTs for SSF, and the critical role of users in technology adoption by ensuring that the design and implementation processes are informed by the fishermen themselves, thereby addressing specific needs such as digital literacy, financial barriers, tailored applications, and the necessary government and policy support (e.g., FAO, 2020; Chuenpagdee et al., 2019; Mazuki, 2016; Mazuki, 2020). These considerations are all essential for achieving relevant, accessible solutions and long-term sustainability. However, none of these studies incorporate PD approaches to utilize the insights and lived experiences of fishers in the design of IS. This gap reveals a significant opportunity for applying PD and CPD to ensure that the new technologies are not only user-friendly but also relevant, contextually appropriate and sustainable in the long term.

3.3. Study Area: Kumirmari Island Village, India

This paper explores the specific needs of the fishers in Kumirmari Island in the Sundarbans, India, concerning IS. Kumirmari is a village island located within the Gosaba Block of the South Twenty-Four Parganas district in West Bengal (Fig. 1). This unique locale is part of the Sundarbans, a region named after the *Sundari* tree species—a type of mangrove (Chanchani & Ranjan, 2019). The name "Sundarbans" aptly translates to the "Forest of the Sundari Trees," highlighting the rich natural heritage of this remarkable area (*ibid*). The Sundarbans, formed by the delta of rivers, is the world's largest mangrove ecosystem, stretching across Bangladesh and India, with approximately 9,630 of its 25,500 square kilometres situated in India (Bera & Sahay, 2010).

It is located 107 kilometres from Canning, the nearest town. Transportation commonly includes motorboats for travelling between islands and bicycles and rickshaws on the island. The village spans a total geographical area of 2,020.8 hectares (Chanchani & Ranjan, 2019). According to the Population Census of 2011, Kumirmari is home to a total of 4,344 households, encompassing a population of 17,451 individuals, with 8,885 males and 8,566 females (Population Census India, 2011). The literacy rate in Kumirmari village was recorded at a rate of 79% in 2011 (*ibid*). The village is subdivided into 13 local governing units known as *Gram Samsads* (Chanchani & Ranjan, 2019), and the governance of the village is overseen by the *Sarpanch*, an elected representative who administers local affairs (Population Census India, 2011).

Figure 14. Location of the study area: Kumirmari is a remote village located in the Sundarbans region of West Bengal, India, near the Bangladesh border.

Out of the total population, 7,530 individuals (43% of the population) are engaged in various work activities (Population Census India, 2011). Among these workers, 60% described their employment as 'main work,' indicating they were employed or earning for more than six months. The remaining 40% are involved in marginal activities, providing a livelihood for less than six months. Around 1,396 individuals are cultivators, either as owners or co-owners, while 2,372 are employed as agricultural labourers (Population Census India, 2011). Agriculture is the primary source of livelihood for the village. Those who do not rely on agriculture mainly depend on the forest for collecting non-timber forest products and fishing, or they work as daily wage labourers or migrate to cities and towns for employment (*ibid*). The fishers include both part-time and full-time participants, depending on access, season, and need, and they fish for both subsistence and market sale. The villagers of Kumirmari are also adjusting to climate change and the challenges of forest fishing by exploring and experimenting with inland fishing and aquaculture (Mukherjee et al., 2024, p. 186-187). Moreover, based on rough estimates, 22% of the villagers are landless, and 73% own 1,620 to 3,240 square meters of land

(Population Census India, 2011). This village also serves as an active Vulnerable-to-Viable (V2V) site.

Kumirmari village, characterized by economic vulnerability, food insecurity, and reliance on climate-sensitive livelihoods such as fishing and agriculture (Mukherjee et al., 2024), presents a valuable context for this study. The high percentage of marginal workers, landless households, and reliance on natural resources highlight the need for context-specific solutions for these communities. CPD ensures community involvement, addresses diverse needs, integrates local knowledge, and fosters trust, making it key to designing IS for vulnerable communities.

3.4. Methods

To explore how CPD can be effectively employed to develop IS tailored to the unique conditions of SSF, this paper used a multi-method approach designed to address the research objective. The methodology was structured in two main phases, each designed to address distinct aspects of the research objective: 1) understanding the contextual dynamics of vulnerability and viability concerning FNIS through a systems thinking approach, and 2) identifying user needs through gathering data from the fisher communities in Kumirmari Island, India. In this paper, the CPD approach is essential to ensuring that the IS developed are deeply rooted in the specific socio-economic, environmental, and cultural contexts of the SSF.

The first phase systematically explored the social, economic, political, environmental, technological, and health dimensions affecting the FNS of SSF in Kumirmari Island village. By adopting a systems thinking approach, we examined how these diverse dimensions interact and influence each other, recognizing that changes in one domain can have cascading effects across others. Systems thinking is an approach to understanding the world focusing on the connections and interactions between different components of a system rather than just examining the individual elements in isolation (Meadows, 2009, p. 11). Through a review of secondary data from various databases, including JSTOR, Google Scholar, and institutional repositories, vulnerability and viability factors pertaining to the FNIS of fishers in Kumirmari island were identified. This review provided an understanding of the context in which fishers live and the vulnerabilities or viabilities they experience.

Building on the insights from the first phase, the second phase involved direct engagement with the fishing communities to capture user-level insights. For this step, data collection was carried out through a structured survey administered to randomly selected fishing households in two communities on Kumirmari Island, Sundarbans, India. Responses were gathered at the household level, with one respondent per household in all cases. The sampling strategy involved a random selection of fishing households from two communities: vulnerable fishing households near the Raimangal and Korankhali rivers and viable fishing households near the Puijali River and the western bank of the Korankhali River. Random sampling in Excel was done by assigning each fishing household a unique number in the list and then using the random function to generate random values. Fishers near the Raimangal and Korankhali rivers face heightened vulnerability due to severe environmental risks such as land erosion and cyclones, along with limited market access and reliance on forest-based fishing. People near the Puijali River have more stable conditions with better roads, more job options, and stronger market connections. These two communities, encompassing approximately 410 households, were selected to represent the broader range of experiences within Kumirmari. The survey initially targeted 70 households but was extended to 80 to reach data saturation. *Saturation* refers to the point during data collection when no new themes or insights emerge, and subsequent data begin to repeat (Hennink & Kaiser, 2022). This indicates that further data collection would be redundant and that an adequate sample size has been reached (*ibid*). So, the data gathered are intended to capture the full range of perspectives or themes relevant to the research question. Only people aged 18 or older who take part in fishing were selected for this research. The survey was designed to gather their opinions using a mix of multiple-choice and open-ended questions to collect their personal insights. The survey questions were developed based on findings from the previous phase, with input from experts, including researchers specializing in vulnerability and small-scale fisheries, local area experts, and IS designers. An initial pilot was conducted with a small group of respondents to refine the questions and ensure their clarity. Qualtrics, an online survey platform, was utilized to administer this survey.

The survey focused on recognizing users' needs, perceptions, expectations, and decisions. Given the importance of these four factors, we introduce the User-Requirements Hierarchy (URH) as a key design framework guiding the contextual participatory design of IS for vulnerable communities (Fig. 3). The URH goes beyond basic functionality by structuring the IS design process to address the foundational needs of users, advance through their perceptions and expectations, and culminate in empowering them to make informed and contextually relevant decisions. It ensures that IS should not only meet the basic needs of the users but also empower them to make meaningful and contextually relevant decisions that enhance their livelihoods. For effective implementation of this framework, as with other PD approaches, designers should engage with users through iterative prototyping and testing, integrated training, and continuous feedback (Simonsen & Robertson, 2013a, pp. 5–21). This will help continuously improve the IS, making it more user-friendly and effective over time.

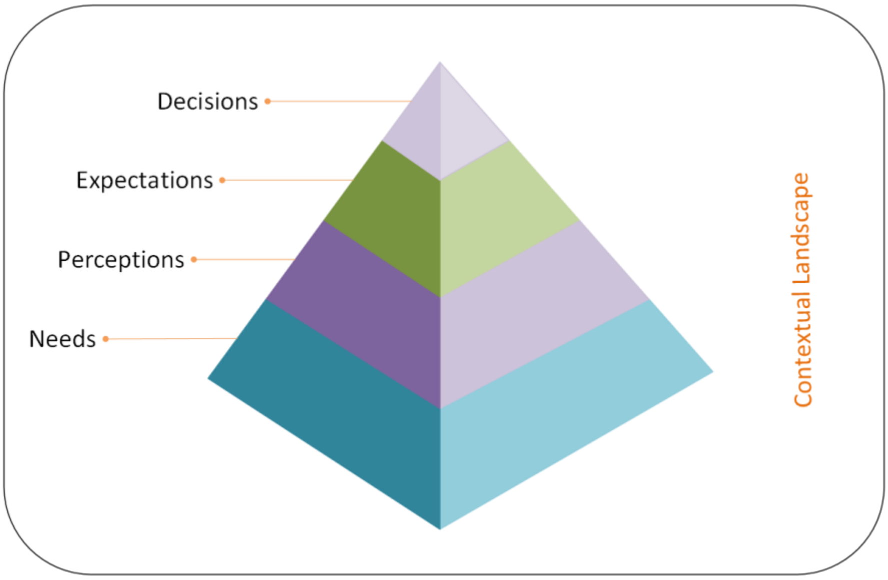

Figure 15. The User-Requirements Hierarchy (URH) for Information System Design

User needs represent the fundamental requirements; perceptions refer to users' understanding of the system's purpose and functionality; expectations encompass users' anticipations regarding the system's future performance; and decisions are the actions users take based on the information provided by the system.

Here, user's needs are the essential requirements that users have from the system, focusing on vulnerability and viability aspects. Users' perceptions refer to how users perceive or understand IS, including their interpretations of its purpose and functionality. User expectations are the anticipations or beliefs that users have about how an IS function and perform. And user decisions refer to the choices and actions users take based on the information and insights provided by the system. This includes not only immediate, short-term decisions but also medium-term and long-term strategic decisions. Despite the importance of these factors in IS design, they are often emphasized in a scattered manner rather than being evaluated systematically in PD studies. The survey was conducted to collect important user insights, highlighting their key role in the design process. Including user perspectives is crucial to making sure the system meets their needs, solves real challenges, and encourages participation (Ehn, 2008; Muller & Druin, 2012). Failure to consider user needs, as well as perceptions, and expectations can create a disconnect between the designed solutions and the actual needs of the community, leading to reduced adoption and scalability (Bodker et al., 2009; Davis, 1989). Ignoring these factors can reduce trust and acceptance, as people often resist new technologies when they are skeptical (Orlikowski & Gash, 1994; Venkatesh et al., 2003). Effective management of user expectations is critical to preventing resistance and ensuring the long-term relevance of the solutions (Bødker & Grønbæk, 1991; Kujala, 2003). Moreover, empowering users in the decision-making process fosters a sense of ownership and adaptability, which is crucial for integrating solutions into diverse local contexts and enhancing scalability (Sanders & Stappers, 2008; Schuler & Namioka, 1993). By fully considering these user-level factors, IS solutions can be better designed to meet the real needs of SSF, improving their viability and long-term sustainability.

Following data collection through the survey, the analysis was conducted mainly using thematic analysis. Data from secondary sources was analyzed to identify the vulnerabilities and viabilities of SSF in Kumirmari across social, economic, political, environmental, technological, and health dimensions. Then, the data was synthesized to map out the current vulnerabilities and viabilities of SSF. For the survey, a thematic analysis was conducted by coding open-ended responses to find common themes and patterns, offering deeper insight into fishers' experiences and perspectives.

Ethical considerations were addressed, and ethical approval was obtained from the University of Waterloo's Research Ethics Board prior to the commencement of the study. Verbal consent was obtained from all participants, ensuring that they were fully informed about the purpose of the study and their right to withdraw at any time. Confidentiality was strictly maintained, with all data anonymized to protect the identities of the participants.

3.5. Results

The results are presented in two parts: the overview of the factors that influence the vulnerability and viability of SSF in Kumirmari Island concerning their FNIS, and the results derived from the surveys regarding fishers' needs, perceptions, expectations, and decisions about the IS. The vulnerability and viability factors are grouped into six primary categories established in our previous research: food system, economic, social, political, technological, and health dimensions (Mohammadi et al., forthcoming).

3.5.1 Overview of the Vulnerability and Viability Factors

The analysis of secondary data revealed several critical factors influencing the vulnerabilities and viabilities of SSF, with a focus on the FNIS. The analysis highlighted that these fishers face significant vulnerabilities, underscoring the complexities of the local food system, where several interrelated factors such as environmental changes, socio-economic pressures, and reliance on natural resources all play a critical role.

Food System - In Kumirmari, the diet is heavily centred around rice, dal, and fish, which are staples for the local population (Banerjee & Vincent, 2021, p. 219-230). Fish plays a crucial role in the diet, providing a vital source of protein, which is often caught and consumed by the family, maintaining a diet deeply connected to the region's natural resources (*ibid*). This dependency underscores the vulnerability of the villagers to shocks, such as environmental hazards and socio-economic pressures which impact fish abundance. In addition, environmental factors such as intrusion of saline water and frequent cyclones reduce agricultural yields, forcing the community to rely more on external food sources, which may not be consistently available (Mitra & Saha, 2020, pp. 139–143).

Environmental - The degradation of mangrove forests and the decline in fish populations are clear indicators of environmental stress in Kumirmari (Hazra et al., 2002). Also, sea levels are increasing at a rate of 3.14 mm per year, leading to the loss of 86 square kilometres of land over three decades (Hazra et al., 2002). Moreover, the area faces rising temperatures and more intense cyclones, exacerbating coastal erosion and flooding. In 2020, Cyclone Amphan affected about 60 million people in the Sundarbans region [including Kumirmari] (Chatterjee & Roy, 2021). In the fishing sector, 58,000 hectares of ponds were affected by flooding and 8,060 boats were damaged (*ibid*). Cyclones and floods also cause saline water intrusion and waterlogging, affecting inland fish production (Mukherjee et al., 2024, p. 180). This is especially critical because the food system of SSF in Kumirmari relies heavily on the intricate network of water bodies that form the backbone of their livelihoods (Mukherjee et al., 2024, p. 180). Despite these challenges, villagers lack adequate training in adaptive fishing practices, particularly in managing fish diseases and dealing with prolonged salinization after cyclones (*ibid*).

Figure 16. House Impacted by High Tidal Waters in Kumirmari, Sundarbans.

The household involved in crab collection uses boats to harvest crabs from the tidal waters, reflecting the challenges of this coastal ecosystem.

Note. Photo taken by Amit Kumar Das, 2024.

Furthermore, the vulnerability of the fishers to FNIS is heightened by wildlife conflict, which poses risks to the lives of fishers, with some even losing their lives. Community members indicate that their work collecting fish, crabs, honey, and beeswax from creeks and mangrove forests exposes them to potential encounters with dangerous wildlife, including small sharks, crocodiles, and tigers (Mukherjee & Siddique, 2024, p. 53). Human-wildlife conflict, particularly with Bengal tigers, is a major concern, and people are killed by tiger attacks annually. Individuals in Kumirmari engage in fishing despite the life-threatening risks because it is their primary livelihood. For instance, a few months before our data gathering started, in February 2024, a man lost his life to a tiger attack while fishing in Gosaba, a mangrove forest (Telegraph India, 2024). Despite regulations prohibiting fishing in these areas, people violate these rules to sustain their livelihoods, sometimes paying the ultimate price with their lives (*ibid*). These wildlife conflicts can also pose risks to tigers' safety, as villagers have previously killed tigers in retaliation (Mallick, 2014). This cycle of fishers entering forests where tigers live, being attacked by tigers, or attacking tigers, can negatively affect the local food system. Tigers are vital for the Sundarbans ecosystem as predators that help maintain a balanced food web by regulating populations of prey species (Mallick, 2014). Also, their presence acts as an ecological indicator of the overall health of the mangrove forest habitat, ensuring the survival of many other species within this system (*ibid)*.

Economic - SSF face a highly fragile economic situation, with limited access to essential resources and unequal economic opportunities, making it difficult for them to sustain their FNS. The economic stability of Kumirmari's SSF is heavily dependent on the health of the local environment, particularly the mangroves and river systems, which are increasingly under threat from overexploitation and environmental degradation (Mitra & Saha, 2020, pp. 139–143). Declining fish stocks and water pollution have reduced the profitability of traditional fishing methods, forcing fishers to engage in less sustainable practices or supplementary activities, such as crab collection, which are also facing overexploitation (Sardar & Basu, 2022, pp. 635–647).

SSF face major economic challenges, with their livelihoods becoming more vulnerable over time (Biswas et al., 2024). Falling incomes and exploitation by middlemen make these communities vulnerable, as they often struggle to access fair markets, forcing them into exploitative financial arrangements (*ibid*). Offshore fishing is not an option for the marginalized fishers due to high costs, leading many to rely on risky small-scale estuarine fishing, where they face dangers from wildlife, including tiger attacks (Banerjee & Vincent, 2021, p. 72). The shift towards aquaculture and alternative livelihoods such as apiculture introduces new opportunities but also brings considerable challenges, as these modern practices often conflict with the region's traditional ways of life (*ibid*).

Figure 17. Inland Fishing in Brackish Water for Cultivating Gangetic Koi, in Kumirmari, Sundarbans.

The Gangetic Koi, known for its ability to thrive in low-oxygen environments and travel short distances on land, is cultivated in brackish water due to its adaptability to varying salinity levels.

Note. Photo taken by Amit Kumar Das, 2024.

Social - The fishers of Kumirmari are part of a marginalized community, facing significant social isolation due to their geographical location and lack of political representation (Mitra & Saha, 2020, pp. 139–143; Mukherjee et al., 2024). They also struggle with major social development challenges due to their remote locations, limited access to essential resources, and ongoing denial of their rights (Nandy, 2023). Many community members are descendants of refugees and part of socially excluded groups, making them even more vulnerable (Jalais, 2005). This exclusion makes it even harder for them to access essential resources and political representation, further increasing their vulnerability. Relying on traditional practices and limited education and job opportunities make it harder for them to improve their social status and adapt to modern economic challenges (DasGupta, 2024). Moreover, the training programs provided by the Department of Fisheries are rare and often hard to access, leaving fishers without the skills they need to adapt to changing conditions (Mukherjee et al., 2024, p. 180).

Political - These communities are often marginalized, with minimal representation in decision-making processes that directly impact their lives, such as participation in Joint Forest Management Committees (JFMCs) (Biswas et al., 2024; Nandy, 2023). Strict regulations governing access to forest resources and the lack of effective enforcement of conservation laws further exacerbate their vulnerabilities, as many are forced to operate illegally, as mentioned earlier, exposing them to harassment and fines by forest officials (Biswas et al., 2024; Mukherjee et al., 2024). Strict regulations around mangrove-based fishing further limit access to traditional fishing grounds, pushing fishers to depend more on inland and cooperative fishing. The community's lack of political representation also limits their ability to advocate for better policies and protections (Biswas et al., 2024). Gender discrimination exacerbates these challenges, as women fish workers are usually excluded from economic opportunities and decision-making, receiving little to no justice or recognition for their contributions (Nandy, 2023).

Weak governance makes these problems worse, as many policies for small-scale fishers are either poorly enforced or completely missing (*ibid*). Social security programs, such as pensions and accident insurance, are poorly managed, leaving fishers without vital safety nets. At the same time, exploitation by moneylenders and weak cooperative and trade union structures highlight the government's lack of support and inclusion for fishers (*ibid*). Moreover, the non-renewal of Boat License Certificates (BLCs), essential permits for fishing in buffer zones, has worsened the situation (Mukherjee & Siddique, 2024, p. 54). With only 924 active BLCs for thousands of fishers, many must rent permits at high costs or fish without them *(ibid)*. This leaves marginalized families vulnerable to harassment by officials, who confiscate their catches and impose fines. Additionally, those fishing without a license receive no compensation if attacked by tigers (*ibid*).

Technology and Infrastructure- SSF in West Bengal [including those in Kumirmari] have minimal to no access to essential services such as transportation, communication, education, energy, water, medical center and housing (Nandy, 2023; Chanchani & Ranjan, 2019). Residents mostly rely on solar power to run small devices such as lamps, fans, or TVs and to charge phones (Chanchani & Ranjan, 2019). The lack of essential infrastructure, such as cold storage and market access, further limits their ability to improve productivity and build resilience (Mukherjee et al., 2024b). Additionally, limited access to sustainable aquaculture practices makes adapting to environmental challenges harder (Giri et al., 2022). Also, there is a significant lack of technology and information access, depriving many people of essential knowledge (Mazuki et al., 2020). Mobile coverage is patchy, hindering communication during emergencies such as cyclones (Maa Laxmi Travels, 2023).

Health - Health risks in Kumirmari are primarily driven by environmental hazards and the lack of access to healthcare. The community is exposed to heavy metal pollution and saline water, which contribute to a range of health issues, including skin diseases, reproductive health problems, and chronic conditions (Chowdhury et al., 2017, 2023; Mukherjee et al., 2024). Poor healthcare infrastructure worsens these challenges, preventing residents of Kumirmari from getting the necessary medical care (DasGupta, 2024; Nandy, 2023). These challenges even compromise food safety and quality and weaken the community's ability to produce, access, and use food effectively, increasing the risk of FNIS.

Viabilities - Despite the vulnerabilities faced by small-scale fishers in Kumirmari, notable opportunities enhance their viability. The region's rich biodiversity and access to fish are vital in supporting food security, providing both a reliable food source and a means of income (Chowdhury et al., 2023). Environmentally, the community benefits from the mangroves, which can provide protection from natural disasters and serve as a source of livelihood through sustainable fishing (Mukherjee, 2023). Economically, the shift towards sustainable practices, such as sustainable aquaculture, alongside emerging tourism opportunities, offers new income streams and reduces reliance on the more hazardous, traditional mangrove-based activities (Chanchani & Ranjan, 2019; Mukherjee et al., 2024). Socially, the community's strong cultural traditions, such as the worship of Maa Bonbibi, help build psychological resilience and encourage collective action, which is essential for managing shared resources and adapting to change (DasGupta, 2024). Technologically, there are promising initiatives, including using mangrove flora for fish feed, which show potential for enhancing aquaculture sustainability and economic returns (Mitra & Saha, 2020). While these opportunities show the community's adaptability, more support in social protection and political advocacy is needed to help them reach their full potential (Mukherjee, 2023; Nandy, 2023).

Together, these dimensions offer a multidimensional understanding of the challenges and opportunities facing SSF in Kumirmari, helping to identify where targeted IS interventions can enhance FNS and long-term sustainability.

3.5.2. A Deep Dive into Survey Results

The survey respondents were predominantly from experienced fishing households, with 96% having more than five years of experience. Most respondents were middle-aged, with 35% falling within the 35-44 age range, followed by 25% aged 45-54. Educational accomplishment among respondents was generally low, with over half (51%) having completed only elementary or middle school, and 15% not having completed elementary school. Respondents showed significant involvement in aquaculture as an alternative livelihood, with 54% identifying as aquaculturists. Technologically, all respondents reported using smartphones (100%), with regular or consistent internet access reported by the majority (99%) (Fig. 2). However, the smartphones were typically not their own, as they were intended for their children, who often assisted them in using the device for accessing information. This access suggests that while the community faces educational and economic challenges, they are relatively well-connected digitally, which could facilitate the adoption of IS. The findings showed serious food security concerns among fishers. Only 27% consistently had enough food, while 41% experienced occasional shortages, and 31% faced regular or ongoing food insecurity.

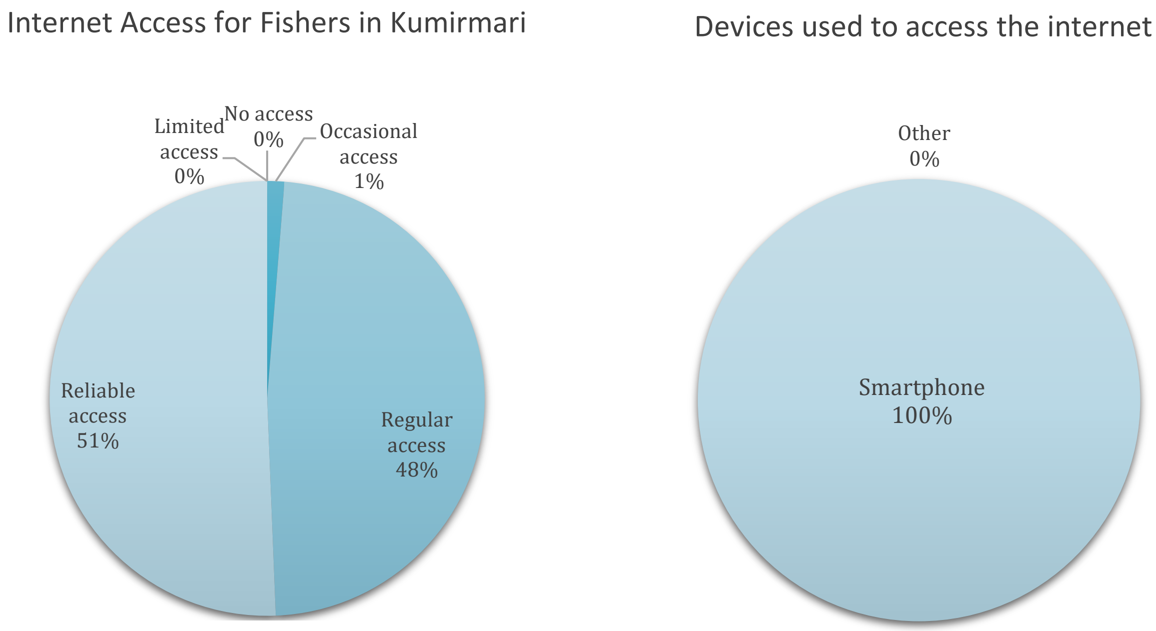

Figure 18. Stability of internet access in Kumirmari and the devices used by fishers.

The survey results below display the distinct needs, perceptions, expectations, and decisions of SSF, offering essential guidance for designing an IS (See Table 1). These results provide important insights into what these fishers specifically need, how they perceive the IS, what they expect from it, and the types of decisions they make that involve it.

Table 2. Summary of the survey findings: insights into fisher needs, perceptions of information systems, expectations, and decisions.

User-Centered Factors			% of Total	Count
Needs	Vulnerabilities	Data on laws and regulations	23.12%	43
		Data on wildlife hazards	6.99%	13
		Data on economic shocks	41.40%	77
		Data on social shocks	0.54%	1
		Data on natural disasters	27.42%	51
		Other	0.54%	1
Needs	Viabilities	Weather updates	16.17%	43
		Information about where groups of fish gather	25.94%	69

		Training materials	2.26%	6
		Data on the alternative livelihood options	3.01%	8
		Data on available technologies and infrastructure	21.43%	57
		Data on finance and credit facilities	27.44%	73
		Data on social support networks	1.88%	5
		Information on local and traditional knowledge	1.13%	3
		Other (Data on fishing season and fish seed)	0.75%	2
Perceptions	Design Consideration	Simplified user interface	30.30%	80
		Audio and visual aids	30.30%	80
		Multilingual support	29.92%	79
		Interactive learning tools	2.65%	7
		Offline functionality	0.76%	2
		Local support centers	0.76%	2
		SMS-based system	4.55%	12
		Printed materials	0.38%	1
		Other	0.38%	1
Perceptions	Capabilities	Mapping and navigation tools	3.99%	11
		Training and education tool	20.29%	56
		Communication platform	22.10%	61
		Emergency Response Support	26.09%	72
		Regulatory Compliance Assistance	27.17%	75
		Other	0.36%	1
Perceptions	Functionalities	Data gathering	1.12%	1
		Data storage	2.25%	2
		Data processing and analysis	6.74%	6
		Producing output such as incident reporting, alert system	80.90%	72
		Other	8.99%	8
Expectations	Improvements	Access to timely and accurate information	21.13%	71
		Access to information about Sustainable Fishing Practices	21.43%	72
		Access to information about the market	21.73%	73
		Access to information about microfinance institutions and insurance schemes	19.94%	67
		Access to information about educational resources	8.63%	29
		Opportunities to provide feedback	7.14%	24
Expectations	Involvement in design	Not at all involved	8.75%	7
		Somewhat involved	27.50%	22
		Moderately involved	21.25%	17

		Involved	30.00%	24
		Highly involved	12.50%	10
Decisions	Decisions for the next year	Crab Collection	14%	15
		Shrimp Cultivation	30%	32
		Saline Water Fishing	6%	7
		Fresh Water Fishing	11%	12
		Not Planned yet	21%	23
		Profitability Improvement	1%	1
		Inland Fishing	6%	6
		Continue/Improve Current Practices	9%	10
		Sustainable practices	2%	2
	Decisions for the next 5 years	Crab Collection	7%	6
		Shrimp Cultivation	23%	21
		Saline Water Fishing	7%	6
		Fresh Water Fishing	1%	1
		Mix Water cultivation	1%	1
		Not Planned yet	36%	33
		Profitability Improvement	1%	1
		Inland Fishing	3%	3
		Pond Conversion Plans	5%	5
		Continue/Improve Current Practices	6%	6
		Sustainable practices	5%	5
		Other	4%	4

Needs - The user needs are categorized into vulnerabilities and viabilities which IS should address to ensure that it effectively supports the users. Regarding vulnerabilities, the highest priorities among respondents are real-time updates on economic shocks (41%), natural disasters (27%), and changes in regulations and laws (23%). In contrast, social shocks (0.54%) are of minimal concern, reflecting a more focused concern on immediate, tangible threats. For enhancing viability, fishers prioritize access to data on finance and credit facilities (27 %), information on fish-gathering locations (26 %), and data on available technologies and infrastructure (21%). However, social support networks (1.8%) and local traditional knowledge (1.1%) are perceived less important, suggesting that community-based resources may be undervalued by fishers.

Perceptions - The survey results highlight user perspectives on the key design considerations, features, and functions that IS should provide for SSF. The design considerations for IS reflect an apparent demand for simplicity and accessibility. The top three design priorities mentioned by fishers are a simplified user interface (30%), audio-visual aids (30%), and multilingual support (29.9%). These findings indicate that technological interventions should be easy to use and accommodate the community's diverse languages. On the other hand, features such as offline functionality (0.7%) are among the least prioritized.

Respondents ranked incident reporting and alert systems as the most important IS functionality, with 81% prioritizing this feature. In contrast, data processing and analysis (7%) and data storage (2%) were seen as less important. When considering the capabilities of IS, the highest priorities identified by respondents include regulatory compliance assistance (27%), emergency response support (26%), and communication platforms (22%). On the other hand, mapping and navigation tools (3.99%) were among the least prioritized.

Expectations - Fishers in Kumirmari emphasized the necessity for better access to information about market linkages (22%), sustainable fishing practices (21%), while providing timely and accurate information (21%). The least prioritized improvements include access to educational resources and training programs (9%) and opportunities for fishers to express concerns within the system (7%). When considering involvement in the design of IS, there is a strong preference for participatory approaches, with 30% of respondents favouring being "involved" and 12.50% favouring "highly involved" in the design process. Only 9% believe fishers should not be involved at all.

Decisions - The survey data reveals a clear tendency towards prioritizing shrimp. The survey data shows a strong preference for shrimp cultivation, with 30% of respondents prioritizing it in the next year and 21% planning for it over the next five years. This indicates a strategic focus on shrimp as a key area for growth and profitability. Additionally, the conversion of paddy fields into shrimp ponds and the rise in saline water fishing indicate a broader shift toward inland and aquaculture practices, which are seen as safer and more economically viable. A substantial portion of respondents (33%) have not yet planned their decisions for the next five years. The low priority given to sustainable practices (2% for the next year and 5% for the next five years) suggests a need for greater education and support to promote long-term environmental and economic sustainability. Overall, the survey data strongly suggests that fishers' main decisions are centred around improving their livelihoods. It underscores the critical role of well-designed IS in supporting SSF by providing the necessary data and resources to adapt to changing conditions and improve livelihoods effectively.

3.6. Discussion

This paper examined the vulnerability and viability factors affecting Kumirmari fishers and explored their information system needs to address these challenges. The findings highlight the importance of designing IS that aligns with fishers' real-life experiences, helping to reduce vulnerabilities and strengthen viabilities through targeted technological solutions. This aligns with ethical imperatives, ensuring that technology serves the interests of the community rather than the interests of designers or powerful entities, avoiding potential unintended consequences that might arise from user exclusion or technology deployment (Costanza-Chock, 2020). We argue that CPD requires considering contextual system dynamics as well as user dynamics in the design of an IS. This consideration reflects the principles of systems thinking, which emphasize the importance of understanding how individual elements within a system interact with the broader context to influence outcomes (Meadows, 2008, pp. 2–5). By combining contextual and individual perspectives, CPD ensures that the IS addresses both larger systemic complexities and specific user needs. This approach enhances the system's relevance, usability, and long-term sustainability.

From a contextual perspective, the vulnerabilities identified through secondary data can be better understood using the PAR model. FNIS is a manifestation of these vulnerabilities, and the PAR framework (Wisner et al., 2004) helps explain how vulnerabilities are created and exacerbated over time. While it is traditionally used for hazards, its structure allows for a systemic understanding of vulnerabilities including root causes, dynamic processes, unsafe conditions, and hazards (*ibid*). Based on the secondary data and given the PAR framework, at the core of the vulnerability are the root causes such as restricted access to resources, lack of equitable economic opportunities, marginalization, and political underrepresentation, which create systemic inequities that constrain the livelihoods of fishers. These root causes can drive dynamic pressures, including environmental degradation, declining fish populations, and poor social schemes. These dynamic pressures translate into unsafe conditions, where fishers are forced to depend on fragile natural resources, adopt risky small-scale or illegal fishing practices, and are forced to cope with poor access to essential services such as healthcare and transportation. These vulnerabilities leave the fisheries community in Kumirmari highly vulnerable to hazards such as intense cyclones, flooding, and wildlife conflicts, which disrupt food systems and livelihoods.

Table 3. Categorizing Vulnerabilities Using PAR: Root Causes, Dynamic Pressures, Unsafe Conditions, and Hazards

In this model, root causes are the structural inequalities in political, economic, and social systems that create unequal access to resources and opportunities. Dynamic pressures translate these root causes into immediate vulnerabilities through processes such as environmental degradation, rapid urbanization, and weak governance. Unsafe conditions are the tangible circumstances, such as poor housing or fragile livelihoods, that directly expose individuals to hazards, ultimately leading to disaster when hazards occur.

Root Causes	*Dynamic Pressures*	*Unsafe Conditions*	*Hazards*
- Restricted access to vital resources	- Environmental degradation (e.g., mangrove deforestation, coastal erosion)	- High dependency on natural resources (e.g., fish as a staple food)	- Intense cyclones
- Lack of equitable economic opportunities	- Climate change impacts (e.g., rising sea levels, salinization, temperatures, and fish population decline)	- Limited livelihood options (e.g., forced illegal fishing)	- Flooding and Tidal Surges
- Marginalization of communities (e.g., Kumirmari fishers)	- Socio-economic pressures (e.g., fines for illegal fishing, declining incomes, lack of market access)	- Forced reliance on risky small-scale or traditional fishing practices	- Wildlife conflict (e.g., tiger attacks)
- Lack of political representation	- Governance failures (e.g., non-renewal of BLCs, inadequate enforcement of laws, poor social schemes)	- Lack of access to essential services (e.g., healthcare, transportation)	
- Gender discrimination	- Limited access to training and skills for sustainable practices		

From an individual perspective, integrating the four user-centric factors—needs, perceptions, expectations, and decisions—into IS design can significantly enhance users' ability to make informed choices. The survey results indicate that fishers in Kumirmari have a strong need for real-time updates on economic shocks, followed by data on natural disasters, as well as data on laws and regulations. An information system could support fishers by providing up-to-date data on laws and regulations, and by raising awareness about fishing bans, gear restrictions, and sustainability efforts. This is crucial, as inconsistent enforcement of fishing prohibitions across regions can lead to various issues. In areas with weak enforcement, fishers may turn to illegal practices, contributing to overfishing and resource degradation (Islam et al., 2017). Such disparities can undermine the sustainability of marine and coastal ecosystems. By enhancing access to regulatory information and promoting consistent awareness, an information system can help level the playing field and support more sustainable fishing practices across communities.

Fishers' primary expectation from an IS is improved market information access, while they perceive incident reporting systems as the most critical IS feature. Also, their key decision-making priority is to expand shrimp cultivation as a response to economic pressures. These findings suggest that the communities are highly aware of their immediate vulnerabilities. The strong focus on real-time, actionable data reflects an adaptive mindset, emphasizing the urgency of having timely information to protect their livelihoods. However, while fishers prioritize immediate benefits, there is less emphasis on long-term educational resources and training programs. This prioritization is driven by pressing economic and environmental challenges, where immediate survival needs outweigh long-term investments in sustainability. This behaviour aligns with Maslow's hierarchy of needs (Maslow, 1943), where individuals first seek to secure basic necessities before focusing on higher-order aspirations such as education and long-term planning. While addressing users' current needs is essential, this finding underscores the importance of not overlooking long-term decisions and sustainability. Future IS design should balance immediate support with forward-looking strategies, ensuring that fishers have the tools not only to navigate short-term crises but also to build long-term resilience.

Crab collection and shrimp cultivation are two of the most desired livelihoods that fishers consider for their future decision-making, with the hopes of leveraging IS to enhance these practices. Shrimp cultivation, while economically promising, can pose significant sustainability challenges, including soil salinization, mangrove destruction, and biodiversity loss, which threaten long-term ecological balance (Chowdhury et al., 2017; Dasgupta et al., 2022). IS can be crucial in equipping fishers with accurate and timely data on their livelihood options, enabling them to make informed and sustainable decisions. IS can assist fishers in identifying sustainable long-term livelihood options by offering insights into market trends, environmental conditions, and economic opportunities. For example, sustainable aquaculture practices, such as mangrove-friendly aquaculture, offer potential but require proper planning, training, and support to succeed (Saha & Mitra, 2020). IS can facilitate this transition by providing real-time data on environmental factors such as water quality and salinity, enabling fishers to adopt eco-friendly practices that minimize environmental impact while improving productivity.

A comparison of the literature review and survey findings reveals both strong alignments and key gaps. The survey's emphasis on real-time economic data aligns with the literature, which identifies economic instability as a major challenge for SSF (Biswas et al., 2024; Mitra & Saha, 2020, pp. 139–143). Both sources emphasize how economic factors directly impact the daily survival of these communities. Similarly, the survey's focus on real-time environmental data reinforces the literature's recognition of environmental challenges as significant threats to SSF (FAO, 2017). This highlights the urgent need to integrate environmental data into IS to strengthen climate resilience for fishers. The overlapping emphasis on economic and environmental dimensions underscores a critical requirement: future IS for fishers must be designed to simultaneously address both financial stability and environmental sustainability to ensure long-term effectiveness.

While the literature highlights social isolation and political marginalization as critical challenges for small-scale fishers (SSF), the survey reveals a notable divergence—these aspects received minimal attention from respondents. This suggests that fishers may not perceive social issues as urgent or within their control, instead prioritizing immediate, tangible concerns such as economic stability and environmental risks. This low prioritization of social vulnerabilities could be linked to survival bias (Hulme, 2010), where individuals focus on pressing daily struggles rather than broader, less immediate challenges. To address this, IS designers can subtly integrate the system's social and health support features. By embedding these elements without overwhelming users, fishers can gradually recognize and address these vulnerabilities while focusing on their most pressing priorities.

From a systemic perspective, the mental models among SSF in Kumirmari reflect the pressures of short-term survival strategies, such as overexploiting natural resources and regulatory violations, as responses to systemic inequities and vulnerabilities. Mental models, as cognitive frameworks, significantly shape how individuals [including future IS users] perceive the world, process information, and make decisions (Senge, 1990). Conservation efforts, such as the establishment of the Sundarbans Tiger Reserve with strict buffer and core zone regulations, have historically restricted villagers' access to resources crucial for their livelihoods, emphasizing a top-down approach rather than inclusive governance (Mukherjee et al., 2024). Villagers fear forest officials more than tigers, reflecting the systemic exploitation they face. Excessive fines and restrictions on fishing activities worsen their economic hardship and deprivation. The manipulation of licensing systems further deepens this inequality, as wealthy intermediaries and agriculturalists reap the benefits, while poor fishing communities remain marginalized and struggle to access their traditional livelihoods. The lived realities of communities in the Indian Sundarbans are often overshadowed by conservation discourses that prioritize biodiversity over human needs, effectively silencing local voices (*ibid*).

While most respondents in Kumirmari have regular access to the internet and use smartphones, the primary warning system remains traditional loudspeakers, which have proven effective. While they remain effective, the widespread use of smartphones presents an opportunity to modernize the disaster warning system. A hybrid system combining loudspeakers, mobile alerts, and communication Apps would enable faster, more reliable, and wider-reaching communication. Mobile phones offer an effective means of disseminating information and warnings in SSF communities, as well as enhancing communication and coordination before, during and after disasters (FAO, 2024; Jentoft & Eide, 2011). By improving network coverage, enhancing digital literacy, and ensuring affordability, mobile phones can serve as effective tools for disaster preparedness, mitigation, and response for SSF (*ibid*).

To encourage sustainable decision-making, IS must not only meet the users' immediate needs but also gradually transform their mental models toward long-term sustainable practices. Targeting leverage points within the system [such as shifting underlying paradigms to prioritize long-term sustainability over immediate survival] is essential for improving resilience and sustainability (Meadows, 2009). By addressing these areas, IS can drive systemic change, promoting more sustainable and equitable outcomes (Meadows, 2009; Senge, 1990). By integrating principles from complex adaptive systems and participatory system dynamics, IS can become a powerful tool for fostering community resilience. These systems enable iterative learning, allowing communities to adapt to shifting conditions while promoting systemic awareness. Importantly, they can help identify leverage points, critical junctures where small interventions can lead to significant, lasting changes, thus empowering local stakeholders to influence broader socio-ecological systems toward more sustainable and equitable futures.

The research highlighted that when designing IS, it is crucial to consider users' needs, perceptions, expectations, and future decisions to create fair and sustainable technology. Engaging users as active collaborators in the design and development of IS ensures that technology is co-created with, by, and for communities, preventing data colonialism by ensuring that value is not only extracted from but also shared with and returned to these communities. It also challenges solutionism, which assumes that technology alone can fix complex social issues (Costanza-Chock, 2020) by prioritizing community-led approaches. Giving users a voice in design enhances their agency, ensuring they have control over the technology that impacts their lives. This approach fosters community ownership and empowerment, where people are active participants rather than passive recipients of technology, leading to more just, inclusive, and effective systems.

PD approaches may unintentionally reproduce colonial patterns by oversimplifying community dynamics if they reduce communities to passive recipients rather than active collaborators. Emphasizing IS development for fishers without critical reflection risks assuming that technological interventions are inherently beneficial, is a viewpoint rooted in the colonial-modernist belief in technology as universally advantageous (as explained by Couldry & Mejias, 2019). Recognizing and critically examining these assumptions is essential to ensure IS truly serves the community's well-being, avoids reproducing colonial hierarchies, and aligns genuinely with local needs and values.

This research evaluated the requirements of the fishers in Kumirmari Island and emphasized the importance of integrating their contextual and user-centric dynamics in IS design. It is important to note that participatory strategies should include centering community voices, addressing power dynamics, reframing problems to challenge dominant narratives, ensuring accountability, and focusing on sustainability (Costanza-Chock, 2020). PD should not impose solutions, but it should support community-led processes and address systemic issues. It should ensure that design serves those most affected by the problem while enabling sustainable changes (*ibid*). By recognizing the interconnectedness of user-centred dimensions, stakeholders should address not only immediate needs but also structural vulnerabilities while boosting current viabilities. Through this lens, IS becomes a tool not for day-to-day operations but for long-term resilience, empowering SSF to navigate uncertainties, such as environmental, economic, and social challenges, while enhancing their current viability. Moving forward, further research should explore how these insights can be applied and incorporated into other vulnerable communities and how iterative, community-driven design processes can be scaled to a broader scale. This approach could serve as a model for empowering vulnerable communities worldwide, helping them transition from vulnerability to viability in an increasingly complex and interconnected world.

In this study, we did not explore the day-to-day operational needs of fishers—for instance, whether they fish using boats or nets. These details could be significant, as the experiences and perspectives of a boat owner may differ from those of others. If future research aims to inform the design of an information system tailored to fishers' needs, it will be essential for researchers to conduct fieldwork to observe firsthand the technologies in use and gain a deeper understanding of the fishers' practical requirements.

The findings of this paper will be directly applied within the IS which will be designed by the Vulnerability to Viability (V2V) Global Partnership, a transdisciplinary network that brings together experts and stakeholders from Africa, Asia, Canada, and other regions worldwide. The V2V initiative seeks to identify the varied factors influencing the vulnerability of SSF and to collaborate with fishing communities, NGOs, government bodies, and universities to strengthen SSF sustainability. This paper is the first step in identifying the most urgent needs of the target SSF community that the IS should prioritize. Subsequent research phases will expand to address concerns in this community and other target communities, ensuring that the IS remains responsive and adaptable to the diverse challenges faced by small-scale fishers globally.

3.7. Conclusion

This study highlights that effective IS design for SSF requires a user-centred design approach that is both multi-level and context sensitive. This approach integrates macro- and meso-level vulnerabilities and viabilities with user-level needs, expectations, perceptions, and decisions. Doing so ensures that IS solutions are not only technically robust but also deeply aligned with the realities of SSF communities. Such alignment is critical in enabling SSF to navigate challenges such as environmental threats, economic shocks, and regulatory changes. Our study shows that users tend to focus on their immediate, tangible needs rather than long-term ones. This is particularly relevant in communities where daily challenges are more pressing. Through iterative engagements, users may begin to articulate broader aspirations or systemic demands. Beyond immediate problem-solving, a well-designed IS facilitates the transition from vulnerability to viability, equipping SSF with the tools and knowledge necessary to sustain and improve their livelihoods and long-term resilience. This paper highlights the importance of human-centered, participatory approaches in IS design, ensuring that technological solutions empower rather than impose, fostering a sustainable and adaptive future for SSF.

This study contributes to the evolving discourse on inclusive I design by demonstrating the value of grounding technological interventions in the lived realities of small-scale fishers, achieved through a comprehensive understanding of their needs at various levels. Participatory design, when implemented with attention to data sovereignty, decoloniality, and user agency, goes beyond functional adequacy, it becomes a tool for empowerment, equity, and resilience. Aligning with prior research (Costanza-Chock, 2020; Senge, 1990), our findings reaffirm that centering users' voices, particularly those historically marginalized, is essential not only to avoid extractive data practices but also to counteract technological solutionism. IS design must be situated within broader sociopolitical contexts, addressing structural inequities and power asymmetries that shape both user needs and institutional responses. By prioritizing local systems and decision-making processes, such systems can facilitate collective agency, promote epistemic justice, and contribute to long-term sustainability by addressing the multifaceted nature of user needs. Importantly, this work revalidates that participatory and iterative IS development is not merely a technical exercise, but a transformative act of solidarity that reconceptualizes technology as a shared, community-driven practice, guiding communities toward sustainable futures.

While this study focuses on Kumirmari, its insights are valuable for other vulnerable communities, including those in Chilika Lake, Odisha, and beyond. Similar PD approaches have proven effective in addressing the common challenges SSF face—from environmental threats to economic instability and policy gaps—across diverse contexts, contributing to resilience and sustainability efforts (Béné et al., 2010; Johnson et al., 2018). By supporting the Sustainable Development Goals (SDGs)—particularly SDG 2 (Zero Hunger)—this PD approach offers a scalable and adaptable model that can be tailored to different contexts. It reinforces the importance of inclusive, context-sensitive, and user-cantered design. Beyond its academic contributions to PD and IS design, this study provides practical insights that can inform initiatives, policies, and practices, helping shape more equitable and effective food systems for SSF communities worldwide.

Chapter 4

Towards Sustainable and Polycentric Information Systems for Small-Scale Fishers: Lessons from Kumirmari Island, India

Small-scale fisheries face unique challenges in accessing and utilizing information systems due to socio-economic constraints and limited technological infrastructure. These barriers hinder their ability to use digital tools for decision-making, resource management, and market access. Despite its importance, a scalable and standardized approach to information system design for vulnerable communities remains notably absent. This paper introduces the PUCT dimensions (Polycentricity, User-Centricity, Contextuality, Technicality) as an integrated approach for designing these systems for vulnerable fishing communities. Grounded in the theory of participation and the polycentric approach and by proposing the PUCT dimensions, this research aims to facilitate the generation of transformative knowledge by addressing the distinctive requirements and contextual nuances of fisheries. The study explores the current experiences of fishers with available IS through surveys. Following this, interviews are conducted with the Fisher Friend Mobile App designers, one of the information systems mentioned by fishers as being used by them, to gain insights into how this system is designed. The findings provide valuable insights into how information systems can be optimized for greater impact in fishing communities. The research informs current, and future IS, offering insights for creating more contextually relevant, accessible, inclusive and sustainable systems tailored to the evolving needs and environments of users.

Keywords: Participatory Design, Polycentric Governance, Transformative Knowledge, Information System, Small-Scale Fisheries

4.1. Introduction

Small-scale fisheries (SSF) play a critical role in global food and nutrition security (FNS), livelihoods, and cultural heritage, yet they often operate in environments marked by socio-economic constraints, limited technological infrastructure, and regulatory challenges (Béné & Friend, 2011; Berkes, 2001). Despite their importance, these communities frequently face barriers in accessing and utilizing information systems (IS) designed to support their activities. Here, the term *Information System* refers to a single application designed to deliver real-time, customized information to users. Existing IS frameworks often fall short by emphasizing technical efficiency and scalability over the needs of SSF, resulting in systems that are neither user-friendly nor contextually relevant (Heeks, 2017). Addressing this disconnect requires an approach that focuses on tailored, accessible, and adaptable IS solutions designed with the realities of SSF in mind.

IS in vulnerable communities face a multitude of challenges and limitations. High failure rates are common in IS projects in developing countries [such as those involving SSF] due to design-actuality gaps, where system designs don't align with the local context (Heeks, 2002). These gaps are worsened by "hard-soft" discrepancies, where the rational IS design clashes with the political and behavioural realities of communities. At the same time, inadequate infrastructure, limited resources, and a lack of technical and human capacity further impede the success of these initiatives *(ibid)*. SSF face lots of challenges and limitations when it comes to designing and utilizing IS for effective fisheries management. Financial constraints are a significant barrier, as the high cost of mobile phones and GPS devices makes them inaccessible for many fishers, necessitating financial support to ensure access to these tools (Brown et al., 2001; Guguloth et al., 2018). Language barriers further complicate the use of these systems, especially when software and instructions are unavailable in local languages (Guguloth et al., 2018). Compounding these issues is the general lack of technical knowledge and inadequate access to training programs, which limits fishers' ability to operate these tools for critical tasks (Guguloth et al., 2018; Hamm, 1993). Moreover, infrastructure deficiencies, including poor mobile network coverage and lack of repair services, hinder real-time monitoring and communication, particularly in remote areas (Riolo, 2006). Even when technologies are available, some fishers are reluctant to adopt these solutions due to skepticism or a preference for traditional methods, which impedes the integration of IS into fisheries management (Haambiya et al., 2021b; Quagrainie et al., 2016). These gaps reveal the need for IS to bridge technological divides and the socio-cultural and institutional barriers that impede their adoption.

SSF communities possess a range of strengths, capacities, and resilience that make them valuable partners in the design and implementation of IS. These communities often have deep, generational knowledge of marine ecosystems, which is critical for understanding and managing fisheries sustainably (Johannes, 1998). Their strong social networks and cooperative traditions enable collective action, resource-sharing, and mutual support (Berkes, 2004). It can help share resources for acquiring technology and spreading knowledge efficiently. Many SSF communities have demonstrated remarkable adaptability in the face of changing environmental and economic conditions, blending traditional practices with emerging technologies to sustain their livelihoods (Folke, 2006). Furthermore, their cultural identity and attachment to proven practices can serve as a foundation for integrating traditional ecological knowledge into transformative solutions [such as IS] (Butler et al., 2012; Espinoza-Tenorio et al., 2013), creating hybrid systems that are both innovative and culturally aligned.

The complexity and variability of SSF make data collection and management difficult (Lane & Stephenson, 1999; Tilley A., 2020). The lack of data integration and standardization in fisheries statistics leads to inconsistencies and data fragmentation, limiting the effectiveness of IS (FAO, 2024; Hamm, 1993; Papaconstantinou et al., 1998). Environmental and anthropogenic stresses such as overfishing and habitat modification further complicate the creation of IS capable of addressing the SSF' challenges effectively (Chaudhuri, 2004; Truong et al., 2005). High implementation costs, dependency on external support, and insufficient capacity building further hinder the development and maintenance of IS (Brown et al., 2001; Hamm, 1993). These complexities highlight the need for IS that integrate diverse knowledge systems and promote interoperability, ensuring their applicability across varied contexts. Moreover, despite their resilience, SSF communities are increasingly facing challenges, such as climate change and overfishing, that may exceed the capacity of traditional practices alone, making technological interventions necessary not to replace but to enhance traditional methods and help address more complex and modern challenges for long-term sustainability.

Existing design and utilization approaches for IS have mainly evolved to improve data collection, monitoring, and decision-making. Early frameworks, such as Arnason's (1990) Minimum Information Management and Papaconstantinou et al.'s (1998) "Mastertable" approach, laid the foundation for promoting cost-effective management strategies and integrating national statistics. More advanced systems, such as the Advanced Fisheries Management Information System (AFMIS), incorporate real-time data to support adaptive management, while recent initiatives such as the PeskAAS project (Tilley A., 2020) and Fish Market Information Systems (FMIS) (Quagrainie et al., 2016) enhance decision-making and transparency. Despite advancements, previous methods remain fragmented and fail to address the complexities of these communities with a unified approach. Therefore, a scalable and standardized approach to integrating diverse knowledge systems and ensuring IS platform interoperability is lacking. Future methodologies should aim to create more interconnected and responsive systems that promote sustainability and community-led management while overcoming technical and infrastructural limitations (Haambiya et al., 2021b; Tilley A., 2020).

This research aims to address the gap in studies on IS for vulnerable communities. The objective of this research is to identify and develop key dimensions essential for designing polycentric IS tailored to vulnerable communities, with a specific focus on small-scale fisheries in Kumirmari Island, Sundarbans, India. The ultimate goal is to empower these communities by facilitating knowledge access and fostering their transition toward greater viability and resilience. This paper suggests the key dimensions and then evaluates the existing IS used by SSF in Kumirmari analyzing users' experiences by focusing on how these systems meet the key dimensions and the users' needs. Finally, it conducts interviews with the Fisher Friend Mobile App (FFMA) designers, an information system mentioned by fishers as being used by them, to evaluate their design strategies. The findings bridge the gap between theoretical principles and practical application, offering a clear pathway for translating fragmented ideas into practical, impactful solutions that are both contextually relevant and implementable.

The results of this study will be implemented in the IS developed by the Vulnerability to Viability (V2V) global partnership, a transdisciplinary network that connects experts and stakeholders from various countries worldwide. This research builds upon our previous findings regarding the vulnerability and viability factors affecting SSF (Mohammadi et al., forthcoming-a) and the user-centred attributes that the IS should address (Mohammadi et al., forthcoming-b). Future research phases will broaden this inquiry, ensuring that the IS prototype remains responsive and adaptable to the diverse challenges encountered by small-scale fishers around the globe.

4.2. Information System for SSF

The design of IS for SSF has evolved through key phases, driven by technological and methodological advancements. One of the earliest contributions to this field was the Minimum Information Management (MIM) framework by Arnason's (1990), which promoted a minimalist approach to fisheries management by focusing on collecting essential data. The MIM framework, based on economic theory, was designed to promote cost-effective management of IS, focusing on simplicity when data collection tools were limited. A few years later, the Integrated Fisheries Information Systems (IFIS) in the Mediterranean (Papaconstantinou et al., 1998) marked a significant advancement. IFIS promoted data standardization and harmonization across multiple regions and countries using a data integration framework. This framework provided a "Mastertable" that unified national data on fleet characteristics, fishing efforts, and socioeconomics. It provided a consistent and comprehensive approach to regional fisheries management *(ibid)*. These early efforts were mainly focused on addressing data collection and standardization, laying the groundwork for more complex methodologies.

Later on, advancements in technology and research methodologies shifted the focus towards more integrative and data-driven approaches. During the 2000s, the introduction of Geographic Information Systems (GIS) and Decision Support Systems (DSS) drove significant changes in fisheries management systems. Geospatial analysis and spatial data modelling became central to fisheries management, as exemplified by GIS's application in American Samoa for spatial analysis of longline fisheries, contributing to ecosystem-based management (Riolo, 2006). Concurrently, DSSs integrated simulation modelling, genetic algorithms, and operations research techniques to optimize fleet management, profitability, and resource sustainability. For example, the DSS in the Northeastern U.S. fishery employed Monte Carlo simulations to evaluate fishing schedules and optimize activities, balancing conservation and profitability (Truong et al., 2005). Management systems such as the Advanced Fisheries Management Information System (AFMIS) utilized a coupled model framework that integrated real-time oceanographic data with fish stock assessments to support adaptive management strategies (Brown et al., 2001). The field continued to evolve into the 2010s and beyond, incorporating machine learning and open-source tools such as R Shiny for real-time data integration and predictive analytics, as seen in the PeskAAS project (Tilley A., 2020). Around the same time, Fish Market Information Systems (FMIS) began using information theory to reduce market information asymmetry through automated analysis and real-time communication channels, such as the multi-language FMIS implemented in Ghana (Quagrainie et al., 2016).

Recent research efforts focus on stakeholder engagement and capacity building through participatory frameworks. The use of participatory action research (PAR) and co-management approaches emphasizes the importance of merging traditional knowledge with modern tools. For instance, participatory GIS (PGIS) methodologies involve stakeholders in mapping fishing activities to ensure spatial data accurately represents local realities (Tilley A., 2020). In Malawi, community-based management employed ICT tools to involve local fishers in monitoring their compliance with regulations, facilitating an inclusive approach to fisheries management (Haambiya et al., 2021b). These evolutions signify a shift from data-centric, top-down management to more holistic, adaptive, and inclusive approaches. Recent methodologies focus on sustainability by engaging stakeholders in the design, implementation, and decision-making processes. Despite the recognized vulnerabilities of

SSF, there is a significant gap in research on designing IS that can empower these communities and support them in building resilience.

4.3. Methods

This methodology is developed in response to the absence of existing unified approaches that effectively address the socio-economic, cultural, and environmental complexities of vulnerable communities, including SSF. Given this gap, the approach uses participatory design (PD) and polycentric governance (PG) as core principles. These elements are incorporated to support inclusivity, adaptability, and the generation of transformative knowledge in future IS. PD has been suggested as a means to involve end-users in the design process, ensuring that systems are more aligned with their needs and contexts (Simonsen & Robertson, 2013b). However, PD alone may not fully capture the complexities, power dynamics, and long-term challenges faced by SSF. Therefore, polycentric approach (Ostrom, 2010) offers a complementary method by advocating for multiple centers of decision-making. By integrating PD and polycentric governance, our proposed framework aims to provide a more holistic solution that fosters equitable access, sustainable management, and community empowerment in SSF.

The methodology is structured into three main phases, each designed to address a specific aspect of the research objective. The first phase involved identifying the key domains of a framework for an IS that can help vulnerable communities transition from vulnerability to viability. By transitioning from vulnerability to viability, we mean transitioning from a state of high exposure to risks and challenges with limited capacity to respond effectively, to a state of secured survival, with foundational systems in place to ensure long-term functionality and stability. In this step and drawing insights from studies on fisheries management, IS, Information and Communication Technology for Development, and stakeholder engagement practices, the key components of the proposed approach for IS design are identified. Building on the findings from the initial phase and our previous studies (Mohammadi et al., forthcoming-a; Mohammadi et al., forthcoming-b), the second phase focused on assessing how these domains are currently addressed by the IS used by fishers in Kumirmari Island, India. Lastly, the third phase involved conducting interviews with designers of one of the leading IS—FFMA—in the region to gain insights into how the framework's domains are being implemented and identify areas for further improvement.

This study focuses on the fishers on Kumirmari Island, a remote village in the Sundarbans region of West Bengal, India. Kumirmari, part of the world's largest mangrove ecosystem, has a population of 17,451 across 4,344 households (Population Census India, 2011). In 2011, 43% of the population was engaged in various work activities, with most working in agriculture or forest-related jobs (*ibid*). The fisher communities' resilience and well-being in the area are significantly impacted by wildlife conflicts, environmental and socio-economic challenges, health risks, and limited access to technology and resources (Mitra & Saha, 2020; Mukherjee, 2023; Mukherjee et al., 2024a). Despite the vulnerabilities, practices such as sustainable honey collection, eco-tourism, and rainwater harvesting showcase the communities' commitment to balancing livelihoods with ecological preservation (Biswas et al., 2024; Chanchani & Ranjan, 2019; Mukherjee & Siddique, 2019). Regarding access to digital resources, the majority of fishing households in Kumirmari have access to both smartphones and the Internet. (Mohammadi et al., forthcoming-b). Given its unique combination of vulnerabilities, viabilities, and technological potential, Kumirmari Island presents an ideal context for conducting research on IS design for vulnerable communities. Moreover, this island serves as one of the main study sites for the V2V Global Partnership.

Figure 19. Ponds along the river embankment, Kumirmari, India

The pond is used for black Prawn, Tiger Prawn cultivation, and Asian Seabass (Barramundi).
Note. Photo taken by Amit Kumar Das, 2024.

Data collection involved a structured survey administered to randomly selected fishing households from two communities on Kumirmari Island, Sundarbans, India: vulnerable fishers near the Raimangal and Korankhali rivers and viable fishers near the Puijali River and the western bank of the Korankhali River. The survey was completed by one representative from each household. Fishers near the Raimangal and Korankhali rivers face high risks due to severe environmental threats such as land erosion and cyclones. Their challenges are worsened by limited market access and reliance on forest-based fishing. In contrast, fishers near the Puijali River have better circumstances, including good infrastructure, diverse livelihood opportunities, and easier market access, which help strengthen their economic stability. These two communities include about 410 households. The original target of 70 household surveys was increased to 81 to ensure data saturation. The survey consisted of closed and open-ended questions and the survey questions were formulated in collaboration with experts in the field to ensure their relevance and accuracy. These experts included six researchers and IS designers, including two who contributed local insights from the area. A pilot test was conducted to refine the questions for clarity; then, the survey was completed utilizing Qualtrics as the online survey platform. The survey was administered by a research assistant who had extensive knowledge about the area and proficiency in data collection within fishing communities.

Figure 20. Coastal canal fishing, Kumirmari village

Note. Photo taken by Amit Kumar Das, 2024.

The survey questions addressed vulnerabilities and viabilities encountered by SSF as identified by our previous study, covering environmental, social, economic, political, technological, and health aspects (Mohammadi et al., forthcoming-a). In addition, the survey explored user-level needs, perceptions, expectations, and decisions, as suggested in our previous work in this community (Mohammadi et al., forthcoming-b), aiming to deepen our understanding of how these factors are integrated into existing IS.

Following the surveys, three interviews were conducted to explore one of the main IS utilized by fishers in Kumirmari, the Fisher Friend Mobile Application (FFMA), as identified through the survey results. The interviewees, experts who are current or previous collaborators of the M.S. Swaminathan Research Foundation (MSSRF), were engaged in the technical or social design aspects of the IS. The social design aspect included gathering feedback from the communities on the design.

The FFMA is an innovative digital tool designed to support the livelihoods of small-scale fishers in India by providing real-time, actionable information. Developed by the M.S. Swaminathan Research Foundation (MSSRF) in collaboration with Qualcomm, the app was first launched in 2007 as a Binary Runtime Environment for Wireless (BREW)-based solution. It later evolved into an Android-based platform in 2013, supported by Qualcomm's Wireless Reach Program. FFMA initially served fishing communities in Tamil Nadu and Puducherry, but its success has since expanded to cover India's entire coastline. The app is currently used by more than 80,000 fishers across 592 villages in India (MSSRF, 2021). It supports multiple languages, including Tamil, Telugu, Malayalam, and Kannada, ensuring accessibility for diverse linguistic groups. FFMA has been recognized for its contribution to disaster management and community empowerment, winning the Tech for Good Award in 2021, for its innovative use of ICT in socially impactful projects (MSSRF, 2022).

The interviews explored how different parts of the proposed approach were used to design and implement the IS. This step aimed to understand the practical dimensions that enable the implementation of IS. It also tested the framework to offer insights into its relevance and effectiveness in meeting the designers' need. The analysis focused on understanding how the current IS aligned with the framework's components and where gaps or areas for improvement existed.

The data analysis combined statistical techniques with thematic analysis. Quantitative survey data were analyzed using descriptive statistics, with results presented as percentages to highlight user-level factors. Qualitative data from open-ended survey questions and interviews were analyzed thematically by coding responses to identify common themes and patterns. This approach provided a deeper understanding of participants' experiences and perspectives.

4.4. PUCT Dimensions for Information System Design

This study suggests the application of the integrated PUCT Dimensions (Fig. 1) for IS development for vulnerable communities. The proposed approach is grounded in the Theory of Participation (Reed et al., 2018) and Polycentric Governance (Ostrom, 2010) and findings from our previous studies. In our first manuscripts, we highlighted the importance of considering context and scale in addressing vulnerability for developing effective and sustainable interventions. Our second manuscript emphasized prioritizing user needs through user-driven and context-driven design, demonstrating the value of fishers' engagement in creating impactful systems.

Incorporating the survey findings from Kumirmari Island that elucidate user-centred needs, perceptions, expectations, and decisions (Mohammadi et al., forthcoming-b) underscores the significance of polycentricity, contextuality, user-centricity, as well as technicality dimensions in information system development and utilization. The findings highlight how these dimensions interact to shape effective solutions for the challenges faced by fishers in Kumrimari. The emphasis placed by fishers on needs, such as the demand for real-time data on economic and environmental risks, highlights the importance of context. Furthermore, fishers' perceptions of system functionalities highlight the importance of polycentric, multi-level governance and enhanced stakeholder engagement. Their expectations regarding greater user involvement in IS design reinforce the importance of polycentricity. The study also emphasizes the significance of mechanisms facilitating collaboration and knowledge sharing among users—social aspects that can enhance collective learning. Overall, the findings highlight the importance of supporting fishers in acquiring actionable knowledge through IS (*ibid*).

Building upon these insights, the development framework evolved from Participatory Design (PD) principles, integrating its foundational elements—context, design, scalar fit, and power dynamics—into four dimensions: (1) Polycentricity, (2) Contextuality, (3) User-Centricity, and (4) Technicality.

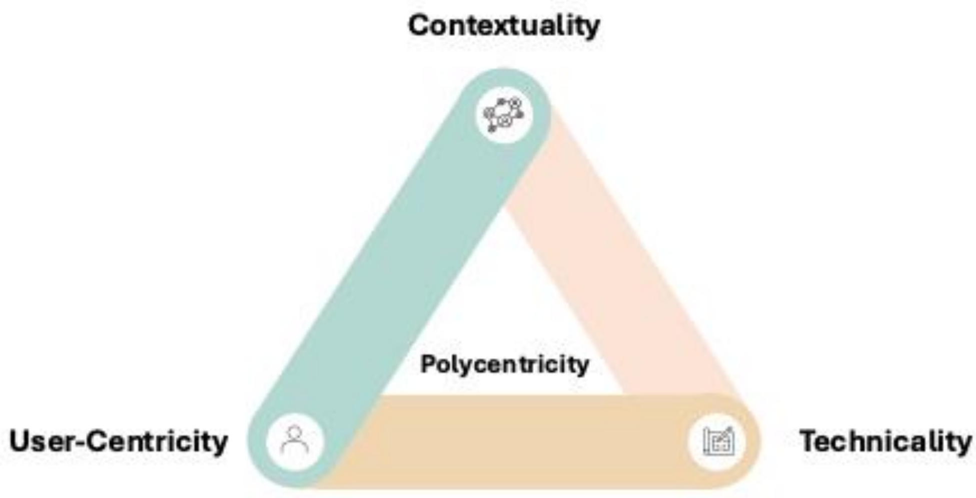

Figure 21. PUCT Dimensions (Polycentricity, User-Centricity, Contextuality, Technicality) for Information System Design.

Information systems for vulnerable communities can be understood as complex adaptive systems (CAS), composed of numerous interacting agents, each exhibiting unique behaviors that evolve and adapt in response to the changing environment over time (Holland, 1992). This framework underscores the dynamic, interconnected, and evolving nature of IS. Such systems demonstrate self-organizing behaviors, adapting through diverse stakeholder interactions and generating emergent outcomes shaped by both internal processes and external feedback loops. In the context of IS, this adaptability enables systems to continuously evolve and align with the shifting needs and priorities of vulnerable communities, ensuring more effective and sustainable solutions over time.

Polycentric Governance is well-suited for managing CAS, particularly in contexts like resource management, sustainability, and community-driven decision-making (Bristow & Healy, 2014). Polycentric governance is a system where multiple, overlapping autonomous decision-making authorities operate at different scales (Galaz et al., 2012; Ostrom, 2010). These centers are autonomous but interact to address collective issues, promoting self-governance and adaptability (*ibid*). Incorporating polycentricity into IS development is crucial because it allows for decentralized decision-making, enabling multiple centers of authority to collaborate and respond flexibly to the complex, evolving needs of the system and its users. The co-creation and collaborative processes involving diverse stakeholders, has emerged as a promising approach to achieving sustainable development. Therefore, at its core, the proposed approach incorporates polycentric principles, which guide toward decentralized authority across multiple levels—local, regional, and national—to ensure decisions are made in closer alignment with the community's specific needs (Carlisle & Gruby, 2019; Ostrom, 2010). Overlapping jurisdictions in this approach allows different authorities to address the same issue, providing flexibility and preventing gaps (Ostrom, 2010). Additionally, independence and interdependence among different bodies promote coordination without concentrating power, fostering accountability and transparency (*ibid*). Therefore, polycentricity is crucial for information system design as it fosters adaptability, inclusivity, and resilience by integrating diverse decision-making centers, ensuring institutional fit, mitigating risks, and promoting collaborative innovation in complex, multi-stakeholder environments (Carlisle & Gruby, 2019; Ostrom, 2010; Reed et al., 2018).

The findings from the first and second manuscripts highlight the importance of polycentricity in IS design by demonstrating the complexity and diversity of community contexts. The first manuscript reveals significant variation within a single region, such as the Caribbean, where different islands face distinct vulnerability factors. Similarly, the second manuscript shows significant differences in responses within a single village, where users have diverse skills, expectations, and needs, requiring tailored IS solutions. For example, some users expressed plans to expand aquaculture, probably a decision driven by their local motivations. These examples illustrate the limitations of a centralized or uniform approach and emphasize the need for a polycentric model. Involving researchers and diverse stakeholders in the design process ensures that IS systems remain adaptive, context-sensitive, and aligned with sustainability goals.

Operationalizing polycentricity in IS design can involve utilizing modular and scalable technologies that enable localized customization, as demonstrated by the "ImproveMyCity" application (Tsampoulatidis et al., 2021, p. 186), while embracing iterative development to refine designs through continuous user feedback, as seen in the "Global Forest Watch" project (Skarlatidou & Haklay, 2021a, p. 149). Operationalizing polycentricity in IS design can also involve collaborative workshops for community-driven requirement definition, establishing a central platform for shared services with localized customization, or creating advisory committees or councils to co-develop strategies with diverse communities.

The contextuality dimension in the framework ensures that systems are tailored to the specific social, economic, political, geographic, and environmental conditions of the community. By considering the contextual factors, IS designers can create systems that are relevant and effective in meeting the community's needs. For example, tailoring systems to fit rural settings, where access to resources and infrastructure may be limited, ensures that the system is appropriate for the local context (Puri et al., 2004). Scalar fit, which considers the timing and location needs of the community (Reed et al., 2018), is also critical for ensuring that systems are scalable and can be adapted to different settings. Systems should provide current and relevant data to users to inform timely decision-making. Moreover, systems that reflect local conditions are more likely to be adopted and sustained over time, as they align with the users' experiences and challenges (Falconi & Palmer, 2017). In addition, addressing long-term livelihood goals is essential for helping vulnerable communities because it enhances their resilience, adaptive capacity, and ability to achieve sustainable livelihoods, ensuring they can better cope with future uncertainties and reduce dependency on immediate relief (Adger, 2006; Chambers & Conway, 1992; Folke et al., 2005). Incorporating the contextual dimension is crucial for creating IS that are effective, sustainable, and culturally relevant.

The user-centricity dimension ensures that systems are accessible, usable, and relevant to the specific needs of users, here the fishers. Accessibility is pivotal, particularly in vulnerable communities where language, internet access, and technical skills can limit user engagement (e.g., Chamberlain et al., 2013). Usability makes the system easy to use, even for non-technical users. A user-centred design helps include user feedback during development (Teixeira et al., 2011). Allowing users to customize analytical and visualization tools also helps meet their needs. Affordability is key, especially in low-resource settings. Open-source or low-cost solutions can provide better options (Mindel et al., 2018). By focusing on usability, customization, and affordability, the IS can better serve the community and encourage wider use.

To ensure agency, an IS must focus on accessibility and usability, offering intuitive and inclusive interfaces for diverse users (Norman, 2013). It should give users control over their data with clear options to input, manage, and share information (Friedman & Hendry, 2019). Customizability and adaptability are essential, allowing the system to fit users' needs (Schneiderman, 2020), and Transparency in processes and privacy policies builds trust (Nissenbaum, 2010). The system can evolve based on user input by using participatory design and feedback mechanisms, ensuring ongoing relevance and empowerment (Bødker, 2015). A user-centred design approach allows users to give feedback and influence the development and governance of the IS.

The technicality dimension ensures that systems are robust, scalable, adaptable, and sustainable. A successful IS requires robust infrastructure comprising reliable hardware and software, accurate and actionable data for informed decision-making, user-centric privacy and security measures to protect sensitive information, and sustainability-focused design and operations (sharma et al., 2022; Skarlatidou & Haklay, 2021a). The technical dimension of the PUCT dimensions is crucial for ensuring the system's effectiveness, sustainability, and adaptability, particularly for vulnerable communities. Here, sustainability-focused design and operation refer to creating efficient, responsible, and resilient systems, ensuring they meet current needs while preserving the ability of future generations to fulfill their own requirements.

Proper selection of software and hardware is fundamental as it directly impacts the system's performance and user interaction. For instance, ensuring operational efficiency depends on the system's ability to handle different data formats and seamlessly integrate with other services (Lukasik, 2000). Furthermore, transforming data into actionable knowledge supports decision-making (Ackoff, 1989; Grieves, 2024), which is highly important in vulnerable settings, and systems must be designed to support this process. Interoperability is essential for seamless collaboration and data integration across diverse systems and stakeholders (Lukasik, 2000; Skarlatidou & Haklay, 2021a, p. 44). It facilitates data exchange and integration into broader systems (Skarlatidou & Haklay, 2021, pp. 44–45). Adaptability is another key aspect, as systems must evolve with changing user needs and technologies to remain relevant over time (Grieves, 2024). Privacy and security are vital considerations in protecting sensitive user data, particularly in decentralized systems used by marginalized groups (Lukasik, 2000; van Rest et al., 2014). Additionally, continuous integration of updates and user feedback is significant to keep systems functional and responsive to user demands for long-term usability (Mindel et al., 2018).

Access to IS for vulnerable communities, including SSF, is a complex issue requiring the involvement of multiple stakeholders. Governments play an important role in establishing the infrastructure and policies for equitable access, while technology developers and NGOs collaborate to design IS solutions tailored to the specific needs of these communities. The PUCT dimensions proposed here, with polycentricity at their core, are essential for ensuring that the design and implementation of IS are inclusive, reflecting the community's context, culture, and local knowledge.

4.5. Results

4.5.1. Analysis of the Survey Results

Based on the survey findings, four primary IS platforms are utilized by fishers in Kumirmari and all respondents used at least one information system: (1) the West Bengal Fisheries Department Website, (2) the Fisher Friend Mobile App, (3) the mKRISHI Fisheries App, and (4) the Kolkata Fish Market App. Among these, the West Bengal Fisheries Department Website, a government-operated system, is the most prominent IS in use, followed by the Fisher Friend Mobile App. The West Bengal Fisheries Department Website provides fishers with access to various e-services such as vessel registration, identity cards, and other support programs. The Fisher Friend Mobile App provides fishers with services such as fishing zone info, weather and ocean forecasts, GPS navigation, emergency contacts, disaster alerts, news, and market prices (FFMA, n.d.). The mKRISHI Fisheries is a specialized platform that provides fishers with different information, including real-time weather updates, market prices, and expert advice to enhance sustainable fishing practices to improve their livelihoods (Tata Consultancy Services, n.d.). And the Kolkata Fish Market App mainly connects fish vendors and buyers (kolkatafish, n.d.).

Guided by the PUCT dimensions, survey questions related to the polycentric dimension asked users whether the IS incorporates them in its design and allows them to provide feedback and input for ongoing system improvements. The user-centricity dimension examined how easily users interact with the system, emphasizing accessibility, usability, and the system's ability to support effective use. The questions about the contextuality dimension explored the IS's ability to capture the real-world realities faced by fishers, including their social, economic, political, and environmental contexts. Finally, the questions focusing on the technical dimension provided insight into the operational efficiency of the IS, including software functionality, hardware reliability, data empowerment, privacy, security, and long-term sustainability. Mapping the survey data onto these dimensions reveals an improved grasp of how the available IS perform:

Polycentricity Dimension - The survey results show that existing systems have significant weaknesses when applying a polycentric approach. The lack of inclusivity in the design process is clear, as 99% of respondents reported having no opportunity to provide input during system development. This lack of user participation suggests that most IS used by fishers follow a top-down governance model, limiting their ability to adapt based on user needs and feedback. This issue is further highlighted by the failure to incorporate user feedback for improvements, with 100% of respondents stating that their input had no impact on the system's long-term functionality.
Overall, 48% of users consider the current information system management only moderately effective.

Table 4. Summary of survey findings evaluating fishers' experiences with the existing information system in Kumirmari village, with a focus on the polycentricity dimension

Question	Response	Variance
Have you found organized opportunities to provide input during the design phase of the information system?	1.23% Yes 98.77% No	NA
Do you feel the information system effectively incorporate user feedback for improvements in the long term?	0% Yes 100% No	NA
To what extent do you consider the management of the existing information system to be effective?	1.22% Not effective at all 20.73% Slightly effective 48.78% Moderately effective 19.51% Very effective 9.76% Extremely effective	0.65

User-Centricity Dimension - The results show mixed findings on accessibility, usability, and utilization of the current IS. While 54% of respondents rated the systems as "very accessible," challenges remain in usability and utilization. Only 6% felt confident using the system, and 67% found it only "slightly user-friendly," indicating a lack of intuitive design. The absence of voice commands, reported by 89% of users, creates difficulties for those with low literacy or older adults, as they must rely on reading to interact with the system. Voice activation could improve access for those who prefer oral communication. Language support is another concern. Only 15% of respondents said the IS supports multiple languages "very well." In multilingual SSF communities, limited language options negativel impacts inclusivity. It makes the system less accessible for users who are not fluent in its default language. The lack of educational resources further limits IS utilization. Nearly 50% of users reported having no training materials on key system functions. Overall, while the system is accessible, it struggles with usability, inclusivity, and support, reducing its effectiveness for fishers.

Table 5. Summary of survey findings evaluating fishers' experiences with the existing information system in Kumirmari village, with a focus on the user-centricity dimension.

Question	Response	Variance
How well does the information system accommodate different languages, particularly those spoken by fishers in your area?	51.85% Very well 28.40% Well 14.81% Moderate 3.70% Poor 1.23% Very poor	0.33
How transparent and user-friendly is the information system's design and representation for you?	0% Very user-friendly 16.05% Moderately user-friendly 66.67% Slightly user-friendly 17.28% Not user-friendly	0.1
Does the information system incorporate voice-activated commands or audio features to accommodate users with limited literacy or those who prefer oral communication?	11.11% Yes 88.89% No	0.4
How much does the information system helps you access educational resources and information so you can use the system effectively?	7.41% A lot 50.62% Moderate 40.74% Little	0.46
How confident are you in your ability to effectively use the information system?	6.17% Confident 32.10% Moderately confident 56.79% Slightly confident 4.94% Not confident	0.42
How accessible is the information system for you to use? Consider factors such as internet	54.32% Very accessible	0.76

connectivity, and availability of devices such as smartphones or computers.	8.64% Moderately accessible 37.04% Accessible

Contextuality Dimension – Fishers' responses highlight both the strengths and weaknesses of the current IS. The system mainly provides economic information (58%), followed by regulation-related data (22%), environmental insights (10%), social factors (7%), and technological updates (3%).

The systems perform relatively well in addressing environmental challenges, with 52% of respondents rating its understanding as "very well" and 33% as "extremely well." However, the system falls significantly short in addressing social vulnerabilities, such as inequalities, and conflicts, with 80% of respondents rating it as "not well." In terms of fostering community cooperation and support, the system demonstrates moderate effectiveness, with 55% of respondents rating it "moderately well" and 26% as "extremely well."

When it comes to governance, the system performs strongly in providing information about rules and regulations, such as fishing licenses and safety measures, with 52% of respondents rating it as "very effective" and 32% as "moderately effective." Economically, the system excels in providing real-time pricing data for fish and seafood, with 64% rating this as "very well" and 6% as "extremely well." It also effectively provides details about consumer preferences, with 42% rating it as "very effective." However, the system shows moderate performance in helping fishers identify the best places to sell their catch, with 50.62% rating it "very effective." Financial knowledge support is notably limited, with 56% of respondents rating its assistance in budgeting and saving as "slightly effective." Similarly, the system provides limited insights into available technologies and methods for improving fishing practices and marketing competitiveness, with 57% rating it as "slightly well." Health-related information is another area where the system performs poorly, as 74% of respondents indicate it does not address health risks at all.

Table 6. Summary of survey findings evaluating fishers' experiences with the existing information system in Kumirmari village, with a focus on the contextuality dimension.

Question	Response	Variance
What type of information does this information system primarily provide?	58.09% Economic (e.g., market data) 22.06% Governance/Regulations/ Management information (e.g., information about rules/policies, or marine protected areas) 9.56% Environmental information (e.g., climatic information) 7.35% Social (information on resources for conflict resolution, or access to fair opportunities) 2.94% Technological (e.g., information about advancements in fishing methods, or available infrastructure)	NA
How well do you think the current information system reflects a good understanding of the environmental challenges faced by fishers? These environmental challenges may include: 1- changing weather patterns and ocean conditions which may cause disruptions in fishing activities, 2- pollution affecting fishing operations, 3- extreme weather events, affecting fishing operations, etc.	32.93% Extremely well 52.44% Very well 13.41% Moderately well 1.22% Slightly well 0% Not well	0.48
How well do you think the current information system provides a good understanding of social factors impacting the vulnerabilities of fishers? These social factors can be related to culture, inequalities, conflicts, tensions, etc.	3.66% Extremely well 7.32% Very well 7.32% Moderately well 1.22% Slightly well 80.49% Not well	1.27
How effectively do you think the current information system helps fishers come	25.61% Extremely well	0.59

together, cooperate, and support each other within the community? IS can do these by providing platforms for communication and knowledge-sharing.	54.88% Moderately well 14.63% Slightly well	
How effective do you think the current information system is at giving fishers information about rules and regulations that affect them? These rules and regulations may be related to fishing licenses, catch limits, conservation measures, safety regulations, and any other rules that impact their operations.	51.85% Very effective 32.10% Moderately effective 9.88% Slightly effective	0.57
How well do you think the current information system reflects a good understanding of real-time pricing data for different fish and seafood products to help small-scale fishers in adjusting their catch to market prices?	6.17% Extremely well 64.20% Very well 24.69% Moderately well	0.43
How effectively do you believe the current information system gives details about the types of fish or seafood that people are buying? This information can help small-scale fishers align their catch with evolving consumer preferences.	8.64% Extremely effective 41.98% Very Effective 43.21% Moderately effective 6.17% Slightly effective	0.55
How effectively does the information system help fishers find the best places to sell their catch?	6.17% Extremely effective 50.62% Very effective 38.27% Moderately effective 4.94% Slightly effective	0.47
How do you rate the current information system in helping you understand financial concepts, like budgeting, saving, investing, and managing debt, so you can make better financial decisions for your operations?	1.23% Extremely effective 7.41% Very effective 30.86% Moderately effective 55.56% Slightly effective	0.57

	4.94% Not effective	
How well do you think the current information system provides a good understanding of available technologies, tools and methods for fishing practices and marketing to improve their competitiveness?	13.58% Very well 27.16% Moderately well 56.79% Slightly well	0.57
How well do you think the current information system provides information about health risks, like diseases or epidemics, that might affect the health and work of small-scale fishers?	8.64% Well 11.11% Average 3.70% Not well 74.07% Not at all	1.27

Technicality Dimension - Technical questions assess system reliability, data handling, security, and sustainability. However, key limitations arise, particularly in data presentation, which creates barriers for users with limited technical skills. 72% of respondents reported that complex data, such as weather forecasts or market prices, is not presented in an easily understandable format. This issue shows that the system lacks important accessibility features to meet different user needs. Hardware problems are also a challenge, with 91% of respondents reporting delays in real-time interactions, likely due to weak network infrastructure or limited server capacity. These delays reduce the system's usefulness, especially when timely data is needed, such as for monitoring environmental changes. Security is another concern, as only 56% of respondents rated the system's privacy protection as moderate, while 25% rated it as slight. This raises concerns about security protocols, which may discourage users from fully using the system, especially when sharing sensitive information such as location data.

While some users rated the systems as "fairly effective" for long-term use, 5% of users indicated that it does not provide sufficient alerts for significant events. This points to a broader issue of operational resilience, especially in the face of rapidly shifting environmental and market conditions that are typical in the fishing industry. These technical limitations—ranging from delays in real-time data provision to insufficient security and long-term planning—present substantial barriers to the system's overall sustainability.

Table 7. Summary of survey findings evaluating fishers' experiences with the existing information system in Kumirmari village, with a focus on the technicality dimension.

Question	Response	Variance
Does the information system take your location into account when providing data? For example, does the information system recognize whether you are in Kolkata or Kumirmari, and does it tailor the information it provides based on your location?	Yes 3% No 96%	NA
How well does the information system give timely information and alerts about possible dangers or risks to prevent vulnerabilities?	4.94% Extremely well 33.33% Very well 43.21% Moderately well 18.52% Slightly well	0.66
Does the information system present complex data (such as weather forecasts or market prices) in a format that is easily understood, using icons, colors, etc.?	28.40% Yes 71.60% No	0.2
Have you experienced any delays in real-time interactions with the information system?	91.36% Yes 8.64% No	0.08
How well do you think the information system protects your privacy? The system should keep your data safe from unauthorized access and store it securely.	3.70% Extremely well 16.05% Very well 55.56% Moderately well 24.69% Slightly well	0.56
What types of raw data have you stored in the information system in the past year?	54.81% Market prices	NA

	24.44% Fishing licenses 9.63% Catch data 5.19% Fishing locations	
How well do you think the information system protects your privacy? The system should keep your data safe from unauthorized access and store it securely.	84.38% Summaries 6.25% Graphs/Charts 6.25% Spatial maps	NA
How does the information system facilitate the creation and sharing of knowledge?	77.66% Providing reports 19.15% Collaboration tools	NA
Have you made any specific decision in the past year that you used the information system for?	40.74% Yes 37.04% Maybe 22.22% No	0.6
Can the system predict future trends? These could include changes in fish populations, market demand, environmental conditions, or other relevant factors.	58.02% Yes 41.98% No	0.24
Are there features for setting up alerts or notifications to inform users of significant changes or events that require attention?	45.68% Yes 51.85% No 2.47% Not applicable	0.29
To what extent do you think the information system has features for long-term use and effectiveness?	14.81% Very well 41.98% Well 43.21% Fairly well 0% Not at all	0.5

The existing IS for fishers in Kumirmari village exhibit critical deficiencies in user-centred design, technical functionality, and contextual relevance. Key shortcomings include the lack of mechanisms to integrate user feedback into system design and long-term improvements, insufficient location-specific data, and delays in real-time interactions. Privacy and security concerns, along with the lack of user control over data, weaken trust to the systems. Limited educational resources and training further reduce user confidence. The systems also fail to adequately address environmental challenges, financial literacy, and social cohesion. These gaps underscore the urgent need for a holistic, inclusive, and adaptive approach to designing IS that effectively support small-scale fishers.

4.5.2. Interview Results

According to Information System design experts, the Fisher Friend Mobile Application (FFMA) was developed as a comprehensive support tool for SSF in India. It provides real-time information to improve both safety and productivity. Since its pilot launch in 2013, the app has evolved into a DSS with key features such as disaster alerts, market prices, and international boundary warnings. FFMA offers dynamic data, including weather forecasts, ocean conditions, and fishing zone coordinates, helping fishers decide when and where to fish, which reduces risks from unpredictable marine environments and minimizes the time and resources needed to locate fish.

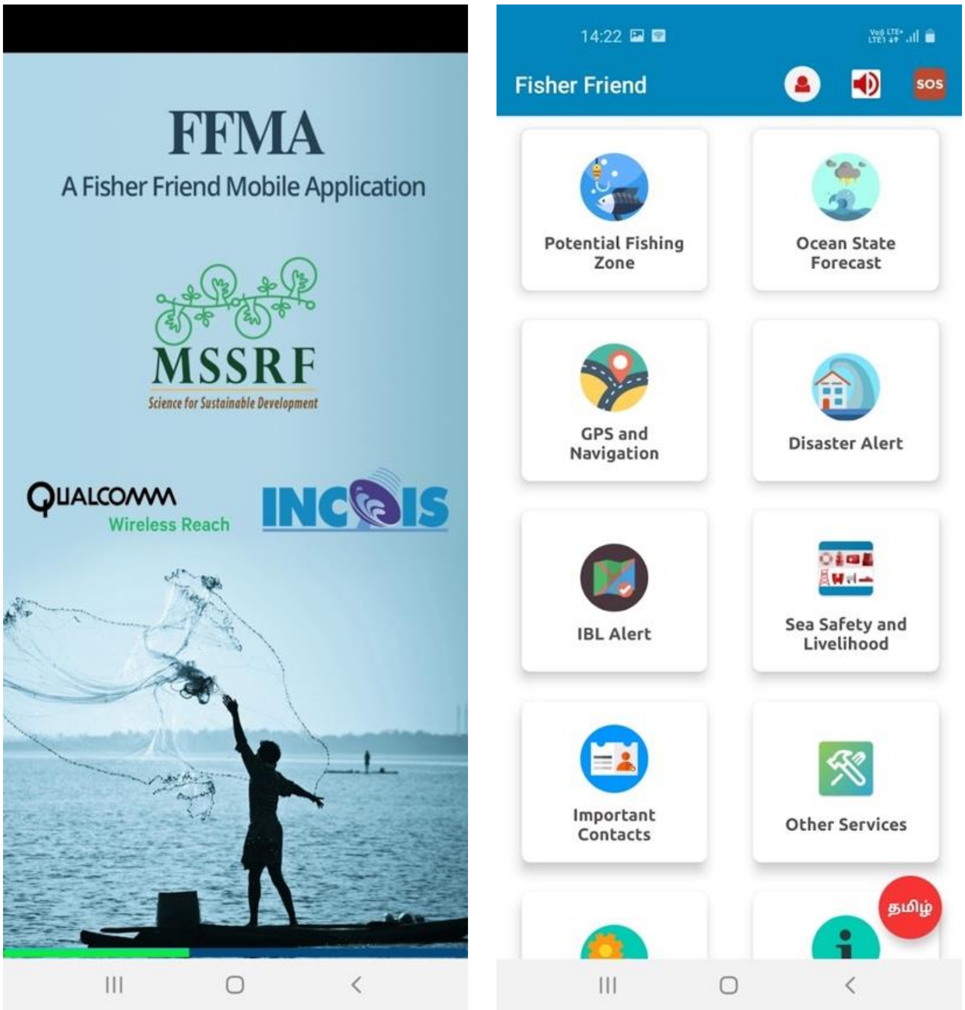

Figure 22. The Fisher Friend Mobile Application (FFMA) app interface

Polycentricity Dimension- Multiple stakeholders collaborated in the decision-making process, contributing to the success of the Fisher Friend Mobile Application (FFMA). These included fishers, government agencies, and scientific institutions such as the M.S. Swaminathan Research Foundation (MSSRF), Qualcomm, and the Indian National Centre for Ocean Information Services (INCOIS). While fishers provided valuable input and feedback, they did not have independent decision-making authority. Instead, their contributions were incorporated into the broader framework led by the primary development and management teams. Interviewees emphasized that user feedback, particularly from fishers, was essential in shaping the app's features. This feedback was collected through field visits and pilot testing in Tamil Nadu, Andhra Pradesh, and Kerala, where fishers highlighted the need for specific functionalities.

A key lesson from this process was the importance of continuous user engagement to keep the app responsive to fishers' needs. However, coordinating across stakeholders presented significant challenges. Interviewees reported difficulties maintaining regular communication with fishers in remote areas, requiring substantial logistical efforts and resources. Managing stakeholder relationships also required careful coordination to ensure the app provided timely and accurate data. One interviewee suggested that future FFMA governance improvements could come from greater involvement of fishers, local fishing cooperatives, and market associations in decision-making. This inclusion, he noted, would help access more detailed, region-specific data and provide better regulatory insights.

Contextuality Dimension - Interviewees recognize FFMA as a vital tool for fishers in coastal areas, especially after the 2004 tsunami in the Indian Ocean, which severely disrupted the fishing industry. The disaster made fish shoals more unpredictable, making it difficult for fishers to sustain their livelihoods. This event increased the demand for real-time and accurate data on hazards and fishing zones. The app was developed to address some of these challenges by providing updated information on ocean conditions, helping fishers make informed decisions, and adapting to changing marine environments.

Interviewees emphasized FFMA's critical role in providing real-time weather updates, including cyclone alerts, high winds, and tidal conditions. The app uses satellite imagery from INCOIS to monitor fishing zones and weather patterns, helping fishers avoid dangerous conditions at sea. Participants highlighted that this information is essential for safer trip planning, protecting both lives and assets. By reducing risks linked to unpredictable weather, FFMA is a valuable safety tool. Additionally, the app provides key data on sea surface temperatures and currents, assisting in identifying fishing zones. Interviewees noted that climate change has altered fish migration patterns, making it harder for fishers to rely on traditional knowledge alone. Despite these advantages, interviewees acknowledged that further development and refinement are needed to enhance the app's effectiveness.

Another aspect highlighted by the interviewees was FFMA's role in promoting sustainable fishing practices. The app provides information on seasonal fishing bans and restricted zones, ensuring that fishers comply with regulations to protect marine biodiversity. Following these guidelines, fishers prevent overfishing and preserve fish stocks, which is critical for maintaining their livelihoods in the long term. In addition, FFMA addresses certain economic challenges by providing market price information for fishers, though issues such as poor market access and dependence on middlemen persist. Moreover, FFMA reduces conflicts by integrating international boundary warnings, preventing fishers from inadvertently crossing into restricted waters.

They highlighted that FFMA not only provides fishers with critical information but also includes interactive features that allow fishers to report dangers and share alerts within their community. This feature is particularly valuable for enhancing collective safety and responsiveness to immediate threats. Fishers can use the app to report hazards such as cyclones, rough sea conditions, navigation obstacles, or accidents they encounter while at sea.

FFMA effectively addresses technological vulnerabilities by providing real-time and accessible information. Interviewees highlighted that its simple design and offline capabilities allow fishers with limited digital skills or weak connectivity to benefit from its features. The app uses wireless networks to let fishers download critical information when a signal is available. This data remains accessible offline, ensuring they have the latest updates even in remote areas. However, downloading large data files has been challenging for those with low-end phones or limited storage. FFMA also automatically synchronizes when a wireless connection is restored. This ensures that fishers receive updated information when they return to coastal areas with better network coverage.

User-centricity Dimension – Interviews revealed that accessibility and usability were key concerns in FFMA's development. Due to varying digital literacy levels among fishers, the design team prioritized a simple and user-friendly interface. Important features such as voice-activated commands, colour-coded information, and offline functionality were identified as essential for improving accessibility. The team continues to enhance these features to better serve users across different regions. The app is available in nine languages, including Tamil, Telugu, Malayalam, and Kannada, making it more accessible across India's coastal areas. However, challenges remain in expanding its user base. Older fishers hesitated to adopt the technology, highlighting the need for additional training and support. Another challenge is that many fishers use only basic features, limiting their engagement with the app. This suggests the need for continuous feedback mechanisms to understand users' evolving needs. Interviewees recommended that future updates include personalized training tools and targeted educational content to help fishers fully utilize the app's advanced features.

Technicality Dimension – Interviewees noted that in the early stages of the project, Qualcomm played a key role in both developing the technology and providing fishers with GPS devices. Distributing these devices ensured that fishers could benefit from the tool. The devices enabled fishers to use features such as GPS navigation, even in areas with limited digital infrastructure.

According to the FFMA experts, connectivity was a significant challenge, especially in remote areas with unreliable or unavailable internet access. To address this, different stakeholders, including local governments, telecommunications providers, and development partners worked together to expand internet coverage in these regions. These efforts ensured fishers could use the app's real-time features when a signal was available. Additionally, the app's offline functionality allowed fishers to access pre-downloaded information at sea or in areas without connectivity. By making such improvements, fishers remained connected to vital information, even in difficult conditions. As smartphone adoption increased among fishers, the project transitioned to a more scalable model; an Android version of FFMA was launched. This version enabled users to download and use the app and made the app more accessible to wider communities. The interviewees noted that this transition was a significant milestone, empowering fishers to integrate the app into their daily lives more seamlessly.

Despite these advancements, the development of FFMA has faced several challenges across hardware, software, data management, connectivity, privacy, and sustainability. Privacy and security were identified as key concerns. The stored data by fishers has raised questions about data ownership and long-term security. Addressing this issue transparently and providing users with greater control over their data was highlighted as a priority for future updates. Moreover, ensuring the long-term sustainability of FFMA remains a significant challenge. While initial funding facilitated its development and deployment, maintaining and regularly updating the app will require continuous financial and technical support. An interviewee emphasized that adapting the app to evolving hardware and addressing emerging needs are crucial for ensuring its continued relevance and impact. The respondents noted that efficient collaboration among stakeholders—including users, government bodies, non-profits, and private sector partners—will be critical to sustaining the app's positive contributions to India's fishing communities.

Given the interview results, the FFM, as a DSS provides real-time information on borders, fishing zones, and weather, aims to support fishers' safety, sustainability, and empowerment. Its design, with offline access and multilingual support, makes it accessible to diverse fishing communities. Collaboration with government bodies and scientific institutions has helped shape the app to meet fishers' needs. However, some challenges remain. Fishers have limited decision-making authority, and low-end devices yield some problems. Privacy and security concerns are still unresolved. Connectivity problems in remote areas and hesitance among older users also slow adoption. To fully realize the app's potential, continuous funding and solutions for logistical challenges are necessary for long-term sustainability.

4.6. Discussion

The findings from surveys evaluating user experiences with existing IS for fishers in Kumirmari and insights from interviews with FFMA experts reveal a mixed performance across the dimensions of polycentricity, user-centricity, contextuality, and technicality.

While FFMA leverages collaborative inputs from multiple stakeholders, it mirrors broader IS challenges in excluding users from key decision-making processes. From a decolonization perspective, this exclusion can be seen as a continuation of top-down approaches that fail to recognize and incorporate indigenous knowledge, local practices, and the lived experiences of the very communities these systems are designed to serve. In this context, the absence of meaningful user agency in the design and implementation of systems like FFMA can perpetuate inequities, sidelining the expertise and cultural relevance that local communities bring to the table.

Similarly, while FFMA demonstrates notable strengths as a decision-support tool—providing real-time data, multilingual support, and offline functionality—surveys indicate that such features are not accessible for them or fully optimized, limiting their usability. For example, the languages provided by FFMA are generated using Google Translate, which can sometimes result in translations that are difficult to understand, making it challenging for users to effectively navigate and use the system. Moreover, although FFMA showcases notable strengths, such as real-time data, multilingual support, and offline functionality, these features, while beneficial in theory, are not universally accessible or fully optimized for the communities they aim to assist. This gap highlights an equity concern: without adequate infrastructure, digital literacy, or local adaptation, such features fail to reach their full potential. Therefore, in the long run, the technology may inadvertently widen the digital divide, as those with the least access to resources are also the least able to benefit from the system's capabilities.

Contextually, FFMA's ability to address some of the environmental challenges sets it apart, but the survey underscores a wider lack of data on climate, financial literacy, and social and health-related vulnerabilities across IS. This is while prior systems often have focused on providing environmental and economic information (FAO & WorldFish, 2020). The lack of attention to financial literacy, social, or health vulnerabilities in FFMA and other IS may stem from differing stakeholder priorities or an insufficiently holistic view of the challenges SSF communities face. Thus, the emphasis on certain dimensions of vulnerability over others may reflect both a focus on broader environmental concerns and a failure to adequately capture the diverse, multifaceted nature of SSF communities' needs. This highlights the importance of adopting a more integrative approach to data collection and system design—one that recognizes the interdependence of environmental, economic, social, and health vulnerabilities to better serve the holistic needs of these communities.

On a technical level, FFMA's offline features and adaptability to low-connectivity environments represent meaningful advancements in addressing the digital divide often encountered by SSF communities. However, these strengths are tempered by recurring issues shared by the users about currently available IS. For instance, 96% of fishers reported that the available IS fail to consider their specific location when providing data, limiting the relevance and usefulness of the information provided. Additionally, 91% of users experienced delays in real-time interactions with the system, highlighting significant concerns regarding system responsiveness and efficiency. These findings reveal opportunities for technical enhancements, particularly in improving the system's ability to deliver more context-specific, timely, and reliable information. Such improvements are essential for ensuring that IS are not only technically effective but also equitable and inclusive, meeting the diverse needs of SSF communities across various geographic and socio-economic conditions.

The findings suggest that the full capabilities of the FFMA are not accessible or usable by fishers in Kumirmari, primarily due to issues such as the irrelevance of the information provided or unusable translations. These barriers limit the ability of fishers to fully engage with the system and, by extension, to take active ownership over their agency. From an equity and decolonisation perspective, this indicates that the system's design does not adequately reflect the diverse, lived experiences of these communities, nor does it empower them to fully utilize the tools available. While FFMA addresses some critical gaps in existing IS, particularly in terms of real-time data and environmental monitoring, significant opportunities remain to improve the inclusivity, usability, and long-term sustainability of such systems. Differences in local fishing contexts, access to technology, and emerging challenges can further exacerbate the limitations of FFMA. These disparities highlight the need for polycentric, localized, context-specific solutions that are designed by SSF communities.

To overcome existing challenges and limitations, valuable lessons can be drawn from other parts of the world. Scalable offline capabilities, such as predictive data updates, can address intermittent connectivity issues, while server-side optimizations and edge computing can reduce delays and improve responsiveness (Antoniou & Potsiou, 2021; Haklay, 2021). Given the financial constraints faced by fishers and the challenges posed by unreliable electricity, optimizing IS for low-cost devices with lightweight, energy-efficient software is essential. Corbett and Derrickson (2021) similarly emphasized this approach for First Nations communities in Canada. Easy-to-use designs, such as maps and simple step-by-step guides, can also help users of varying skill levels navigate the system. Platforms such as Sapelli designed for on-literate and illiterate users in Central Africa demonstrate that simple tools—such as pictures, audio prompts, and easy physical interactions—can significantly help users, even with no technical skills, navigate systems effectively (Vitos, 2021). Robust data privacy frameworks, with transparent storage, user consent, and data deletion options, are essential for building trust and ethical compliance (Skarlatidou & Haklay, 2021b). Moreover, the sustainability of the system can be supported through partnerships with NGOs, cooperatives, and academic institutions, leveraging open-source platforms and shared-maintenance frameworks for adaptability and cost-effectiveness (Theilade et al., 2021).

As IS increasingly handle sensitive user data, recent developments in privacy and security research highlight the necessity of robust data governance frameworks (Acquisti et al., 2016). The current apps' lack of encryption protocols and the absence of user control over data deletion raise critical privacy concerns. As privacy regulations such as the General Data Protection Regulation (*GDPR*, n.d.) and India's proposed Data Protection Bill (*Ministry of Electronics and Information Technology, Government of India*, n.d.) gain traction, available IS including FFMA must evolve to comply with emerging standards, ensuring that users retain control over their data and that their information is safeguarded against breaches. IS systems should incorporate privacy-by-design principles, robust data encryption, clear consent protocols, and user-friendly interfaces that allow individuals to understand and control their data (Ramachandra et al., 2022; van Rest et al., 2014). This will empower users and communities with greater control over their data and how it is used (Costanza-Chock, 2020), creating opportunities for technological sovereignty and data agency (Kennedy et al., 2015).

The IS available in vulnerable communities, such as FFMA, face long-term sustainability challenges due to several factors, including financial constraints. Several systems are functioning globally that effectively serve both general and marginalized populations, exemplifying sustainability in action (Skarlatidou & Haklay, 2021). Projects such as OpenStreetMap leverage community-driven contributions to reduce costs while attracting corporate sponsorships. Sapelli and Prey Lang Forest Monitoring demonstrate the power of co-design with local communities, ensuring cultural relevance while relying on cost-effective technologies and NGO funding (*ibid*). Hush City and ImproveMyCity highlight user-centred designs that deliver clear societal benefits, supported by research grants and municipal partnerships (*ibid*). Global Forest Watch combines advanced analytics with a freemium model, balancing broad accessibility with monetized premium services (*ibid*). These systems achieve sustainability and overcome financial barriers through the integration of adaptable technologies, active community involvement, and diverse funding sources.

The PUCT dimensions suggested in this study, if applied appropriately, can actively resists and reconfigures colonial legacies ingrained in digital systems and development paradigms (as outlined by Machado de Oliveira, 2021). By emphasizing polycentricity, the framework challenges the centralized, hierarchical structures characteristic of colonial and modernist systems (Machado de Oliveira, 2021, p. 43), promoting decentralized governance that promotes multiple centers of knowledge and power. User-centricity aligns with the concept of "radical tenderness," (Machado de Oliveira, 2021, p. 115) fostering compassionate engagement with users' lived experiences and resisting paternalistic, top-down solutions. Contextuality reconfigures colonial dynamics by rejecting universal design principles, embracing instead a "depth education" perspective that values complexity, uncertainty, and culturally specific knowledge systems (Machado de Oliveira, 2021, p. 88). However, the component of technicality must be critically and reflexively employed to avoid inadvertently reproducing colonial legacies, as uncritical application of technology can perpetuate dependency or digital colonialism (Couldry & Mejias, 2019; Machado de Oliveira, 2021).

The results of this research highlight that despite the efforts to integrate user-centricity into the existing IS, significant gaps remain. These gaps may raise several concerns, such as centring the existing IS on "unmarked" users. As explained by Costanza-Chock (2020) these unmarked users are typically assumed to be members of the dominant communities, neglecting the marginalized users. In the context of available IS in Kumirmari, this means that the needs and experiences of vulnerable fishers are overlooked or ignored. Currently implemented participatory and user-centred approaches can unintentionally reproduce exclusion, ignoring the diversity of users (Costanza-Chock, 2020). This is mainly because design processes are centred on a limited range of users, and they end up prioritizing the needs of some users over others. Based on interviews, FFMA's focus on gathering feedback from fishers in Tamil Nadu, Andhra Pradesh, and Kerala may have unintentionally prioritized the needs of these communities over others, neglecting the experiences of those outside these areas. Even when users' input is well-captured, it might be limited to specific design stages [such as a pilot stage], ultimately leaving the power with the design or management team (*ibid*). The next concern that arises is the unequal distribution of affordances. In FFMA, using auto-translation tools for different languages raises this concern. These tools do not always produce clear translations, and information might be hard for the fishers to understand.

Given the concerns, information systems, while valuable, can cause or reproduce inequalities. This is deeply intertwined with the concept of data colonialism, in which IS are designed without properly capturing the realities of marginalized and vulnerable communities (Couldry & Mejias, 2023).[1] Moreover, the findings align with and expand upon the existing body of literature, which raises concerns on community accountability[2] (Costanza-Chock, 2020) and user agency in decision-making (e.g., Bødker, 2015; Friedman & Hendry, 2019; Sachs, 2010). As Sachs (2010) highlighted, such systems risk reinforcing top-down governance, neglecting user specificities and inputs. The results reveal a persistent reliance on top-down governance in IS design, which undermines agency by excluding users from critical decision-making processes. Moreover, implementing polycentricity without ongoing reflexivity might privilege certain voices aligning with global discourses or funding requirements, inadvertently marginalizing less audible or culturally distinct perspectives. Therefore, continuous critical reflection, inclusive participation, and commitment to "depth education," (Machado de Oliveira, 2021, p. 88) which embraces complexity and uncertainty, are essential to ensure that the PUCT does not replicate the subtle yet pervasive dynamics of coloniality it seeks to transform.

Based on the findings, the design processes of available IS in Kumirmari may have included the limited group of users only in limited phases, which could significantly restrict the users' influence over system functionalities. Such approaches contrast with frameworks such as design justice (Costanza-Chock, 2020), which puts the most vulnerable communities at the centre of the design process, and Assets-Based Community Development (Byrne & Sahay, 2007), which emphasizes leveraging local agency and community capital to co-create meaningful solutions. Existing systems also contrast with polycentric approach principles (Ostrom, 2010; Andersson & Ostrom, 2008), which emphasize the importance of multi-level, decentralized systems that enable collaboration among diverse stakeholders for decision-making. This misalignment perpetuates challenges identified in prior critiques, such as data deprivation (Naudé & Vinuesa, 2021) and data discrimination (Chun, 2021). Data deprivation and discrimination represent critical challenges in data governance for vulnerable communities, where they either lack access to the necessary data for informed decision-making or face

1. Data colonialism argues that the ongoing exploitation of vulnerable groups for economic gain is occurring through data extraction (Couldry & Mejias, 2023).

2. Community accountability is about the full inclusion of, accountability to, and control by people with direct lived experience of the conditions designers are trying to change (Costanza-Chock, 2020).

systemic biases in data collection or utilization (Naudé & Vinuesa, 2021; Chun, 2021). These challenges further marginalize and misrepresent them. This study particularly highlights these issues among older users and individuals with low digital literacy. Given the findings, an evolution from centralized, control-oriented systems to polycentric designs is imperative for empowering SSF communities.

To transition from vulnerability to viability, systems should be designed as tools for empowerment rather than just efficiency enhancers. The concept of "resources" as critiqued by Shiva (2010) underscores the need to redefine technology as a means to foster ecological harmony and human dignity, rather than tools of exploitation. Fishers need systems that can turn data into actionable information suited to their local environment and requirements. These systems can ensure that viability is not just about immediate survival but also about sustainability. Building on the PUCT dimensions, effective IS design can facilitate the transition from data to knowledge, to practice, and ultimately to community empowerment, creating a transformative pathway toward sustainability and resilience. Data serves as the foundational element, providing factual inputs that, when structured and contextualized, are transformed into knowledge to guide understanding and decision-making (Ackoff, 1989). However, knowledge gains its true value when applied in practice, understood here as the shared historical and social resources, frameworks, and perspectives that sustain mutual engagement in action (Wenger, 1998). Practice is not merely the application of knowledge but also the collective processes that enable communities to respond effectively to challenges *(ibid)*. Knowledge becomes transformative when it promotes agency and collective action, allowing vulnerable fishers to take ownership of their livelihoods and governance systems. Transformative knowledge drives sustainable action through collaboration among fishers and between fishers and other stakeholders, enabling effective responses to challenges. This transformative ecosystem creates a dynamic and interconnected web of practices, relationships, technologies, and structures that can work to dismantle oppressive systems and foster a more just and equitable design process. This system goes beyond simply "fixing" problems and instead focuses on fundamentally changing the way things are designed, made, and experienced, with a deep commitment to centering the voices and needs of marginalized communities (Costanza-Chock, 2020). It challenges the status quo, promoting justice, and empowering communities, rather than simply reproducing existing power structures.

This research goes beyond the idea of "inclusion" and advocates for a redistribution of power and resources to ensure that vulnerable users of IS have decision-making power and ownership over the processes. Developing systems with PUCT in mind facilitates the co-management of practices, empowering users to not only take action but also to drive systemic change, address inequities, and contribute to building resilience (Ostrom, 2010; Wenger, 1998). Empowerment goes beyond providing access to resources—it provides the ability to navigate socio-ecological complexities, participate in decision-making, and make transformative change. The system's ability to equip users with transformative knowledge and enable them to engage in sustainable practices is crucial for strengthening communities and empowering them. The proposed approach bridges theory and practice in IS design, emphasizing the importance of having inclusivity, adaptability, and sustainability in mind when designing these systems. This research contributes to the larger conversation on leveraging technology to empower marginalized communities.

4.7. Conclusion

The PUCT framework suggested in this study addresses the complex interplay between diverse decision-making needs and the dynamic values of communities. The findings highlight the necessity of bridging the divide between the design and development of technological solutions and the lived realities of end-users in vulnerable communities, such as SSF living in Kumirmari village, India. By integrating findings from surveys that reveal significant gaps such as accessibility, user engagement, and training, alongside expert insights from FFMA demonstrating user-centred approaches and multi-stakeholder collaboration, the research underscores the potential for innovative, polycentric solutions to drive meaningful change.

The study emphasizes that evolving from user-centred to polycentric design is crucial for fostering resilient and inclusive systems. Polycentric design broadens collaboration beyond individual stakeholders by integrating interconnected systems, decentralized decision centers, and governance structures to address complex challenges effectively. This approach ensures that technology development remains adaptable, user-centred, and context-sensitive while leveraging the strengths of diverse, decentralized decision-making. Polycentricity supports iterative developments, aligning such systems with "dynamic values" that evolve with societal and technological shifts (Smit & Pitt, 2024).

The study advocates for a paradigm shift from addressing vulnerability to realizing viability by embedding adaptive, scalable solutions that not only mitigate immediate challenges but also build pathways for long-term sustainability. These solutions must adapt to diverse sociocultural and technological contexts, helping marginalized communities move from dependence to resilience and self-reliance. At the heart of this approach is transformative knowledge, which can guide decision-making and meaningful interventions. Systems designed with PUCT in mind can overcome systemic inequalities, strengthen community capacity, and build trust, empowering fishers to take control of their futures.

Future research should further explore the reciprocation between participatory and polycentric approaches, examining how these principles can harmonize across complex ecosystems. By doing so, the field can move toward designing systems that are not only technologically advanced but also deeply rooted in the needs, values, and aspirations of the communities they serve. By prioritizing these principles, IS can empower the most marginalized, fostering a more equitable and resilient world.

Chapter 5

Conclusions

Existing information systems for SSF often fail to meet their needs due to challenges in data collection and the inability to address their unique characteristics and requirements (FAO, 2024). To address this gap, this thesis aimed to identify the key principles for designing IS tailored to vulnerable small-scale fishing communities, ensuring equity, empowerment, and transformation to guide them toward food and nutrition security, thereby supporting their transition to viability. This thesis proceeded to address the critical challenge of designing inclusive and transformative IS for vulnerable communities, including marginalized SSF, who face unique socio-economic vulnerabilities and environmental challenges. By integrating systematic literature review, machine learning analysis, participatory design, and polycentric dimensions, this research proposed an approach to developing IS that addresses the unique needs of SSF communities. The findings demonstrate that for an information system to be effective, it must be user-centered, context-specific, technically sound, and polycentric. In doing so, this research contributes to the broader discourse on digital transformation in fisheries, offering a pathway toward more sustainable and resilient SSF systems.

5.1. Summary of Key Findings

This study explored the essential design principles for IS aimed at helping fishers transition from vulnerability to viability. The first phase focused on capturing system or contextual knowledge relevant to fishers. The second phase delved into understanding the needs and expectations of fishers, referred to as target knowledge. Finally, the third phase focused on identifying the key dimensions essential for the IS design process. This final stage ensured that the system not only supports transformative knowledge but also encourages sustainable action over time.

The first manuscript investigated the dynamics of island fishers' food systems by adopting an approach that integrates vulnerability and viability analysis, utilizing a systematic literature review, exploratory data analysis, and the Random Forest algorithm with lagged, rolling, and expanding features to capture time dependencies. The literature review was conducted across all islands globally, while the subsequent quantitative analyses specifically focused on SIDS. Using a systematic literature review and following the PRISMA 2009 guidelines (Liberati et al., 2009), the key factors influencing food and nutrition security among fishers on islands were identified and categorized into seven domains: food systems, environment, economy, social aspects, governance and institutions, health, and technology and tools. Exploratory data analysis uncovered patterns and trends within the data related to the vulnerability and viability factors identified in the literature. The results of the exploratory analyses highlighted a substantial surge in the exportation of marine food from the islands, as well as significant increases in access to the internet, Gross National Income (GNI), and aquaculture production. The RF analysis demonstrated the significance of various factors, including the food trade balance, access to education, agriculture's value added to GDP, and inclusive policies, among others, in determining the vulnerability or viability of island fishers. The exploratory and RF analyses were conducted at global, regional, and national scales, highlighting the significant differences that can be captured, and providing critical insights into the importance of scale in such investigations.

Figure 23. Vulnerability and viability tree; factors identified in the literature influencing food and nutrition security of small-scale fisheries in island regions.

The second manuscript employs a user-centric approach to align the IS with the specific requirements of SSF. Grounded in Participatory Design principles (Nygaard, 1987), this phase collects and analyzes data from secondary sources and surveys with fishers in Kumirmari Island, Sundarbans, India. The study highlights the importance of a multi-level, context-sensitive PD approach in developing IS for SSF, facilitating their transition from vulnerability to viability. Here, the User-Requirements Hierarchy or URH was introduced to guide toward a user-centered contextual participatory design of IS. The URH guides the design process, addressing foundational needs, advancing through perceptions and expectations, and empowering informed decision-making.

Based on the reviewed secondary data, the core vulnerabilities of fishers in Kumirmari include restricted access to resources, lack of equitable economic opportunities, marginalization, and political underrepresentation, which create systemic inequities that constrain their livelihoods. In addition to these vulnerabilities, there are also viabilities such as biodiversity, access to fish and mangroves, strong cultural practices, and the emergence of livelihood options such as tourism. The identified vulnerability and viability factors align with the seven dimensions outlined in the first paper. However, the survey reveals that social and health dimensions have received less attention from fishers as requirements for inclusion in IS.

The survey results indicate that the most critical need for fishers in Kumirmari is real-time updates on economic shocks; their primary expectation is improved access to market information; the most significant perception concerns the importance of incident reporting systems within the IS; and their key decision-making priority is increasing shrimp cultivation in response to economic pressures. While meeting users' needs is important, this research emphasizes that long-term sustainability must not be overlooked. To achieve this, a multi-stakeholder approach is essential, bringing in environmental experts and other specialists during both the design phase and ongoing revisions. Their expertise helps ensure that IS solutions remain effective, adaptable, and aligned with both user needs and broader sustainability goals. Such inclusive approaches ensure that IS remain robust, contextually relevant, and adaptable to evolving user needs as well as environmental and technological conditions.

The third manuscript, building on the findings from previous steps, integrated polycentric dimensions (Ostrom, 2010), informed by the Theory of Participation (Reed et al., 2018), which emphasizes context, design, power, and scalar fit. Drawing insights from the previous manuscripts and studies on fisheries management, IS, and information and communication technologies, as well as stakeholder engagement practices, the PUCT dimensions (Polycentricity, User-Centricity, Contextuality, Technicality) were identified. Utilizing PUCT dimensions, this phase of the thesis involved conducting surveys with SSF in Kumirmari to gather insights into their experiences and challenges with existing IS. Then, interviews with experts involved in designing the Fisher Friend Mobile Application or FFMA—a decision support system for SSF in India—offered valuable insights into current practices.

Findings show that available IS in Kumirmari face critical limitations, such as technical shortcomings, including delays in real-time data processing, poor visualization, weak privacy protections, and a lack of long-term sustainability. User experiences with existing IS and interview insights show mixed results across PUCT dimensions. While FFMA aims to collaborate with stakeholders, it often mirrors broader system challenges by excluding users from key decisions. This study highlights recurring issues in IS design while also pointing to potential solutions.

The study reveals a reliance on top-down governance in IS design, which marginalizes end-users and excludes them from critical decision-making processes. The study advocates for a shift toward a polycentric approach, which expands collaboration beyond single stakeholders and embraces interconnected systems and structures to address multifaceted challenges. Survey findings highlight the deficiency in providing data related to climate conditions, financial literacy, and social and health vulnerabilities across IS platforms. This study extends the discourse by incorporating broader contextual dimensions and underscores the importance of integrating adaptable technologies, community-led processes, multi-stakeholder collaborations, and diverse funding sources to overcome financial barriers and ensure sustainability. It calls for an adaptive, user-centred, and context-aware approach to IS development, using decentralized and polycentric decision-making to create more effective and inclusive systems.

Studies on technology development for vulnerable communities often fail to consider long-term impacts, overemphasize technology as a quick solution, neglecting the complexity of information; often reflecting a solutionist and universalist approach (Costanza-Chock, 2020), assuming one-size-fits-all solutions without accounting for context, power, and cultural factors. Here we would like to emphasize a pluralistic approach highlighting a crucial need for context-specific solutions (Costanza-Chock, 2020), embracing the diversity of knowledge systems, and the involvement of varied stakeholders in the design process.

The manuscripts collectively show that transformative IS require a deep understanding of system dynamics and local contexts, active engagement with users and communities, and polycentric governance mechanisms to ensure adaptability and inclusivity. This research supports community-led processes, redistributing power, and addressing systemic issues to ensure that IS serve those most affected by the vulnerabilities while fostering sustainability.

5.2. Contributions to Knowledge

Overall, this thesis addresses the existing gap in the literature regarding IS for fishers, providing a better understanding of the potential to support their needs. This study makes several important contributions to the literature and practice:

First, it contributes to the design of IS that accounts for the diverse and complex characteristics of small-scale fishing communities, which have often been overlooked in mainstream fisheries technologies (as explained by studies such as Chuenpagdee et al., 2019). This study highlights the factors that IS can help address and lays the foundation for more context-sensitive IS interventions. By integrating both vulnerability and viability analyses, this study extends beyond a sole focus on vulnerability, offering a more comprehensive understanding of the dynamics at play. This dual approach of combining qualitative insights with computational analysis not only reveals the intricate dynamics within these systems but also brings attention to the interdependencies and power structures that often remain obscured in traditional analysis. Also, through machine learning, the study captures the complexity of these interactions and how they shape systemic outcomes. The study utilizes RF with rolling, featuring, and expanding features to capture the temporal dynamics of the system. This approach enhances the model's ability to reflect real-world changes and provide insights that are sensitive to both short-term fluctuations and long-term trends in the data.

Second, this part of the study clarifies how IS should be designed to meet the specific needs of small-scale fishers. SSF are often underrepresented in existing IS and technological interventions, which are usually not designed based on their specific needs (Chuenpagdee et al., 2019; Machado et al., 2021; Haambiya et al., 2021a). This part breaks users' requirements down into multiple levels—needs, expectations, perceptions, and decisions —and offers guidance for future IS development and interventions to target these levels effectively. This study argues that future developments in IS design and PD should extend beyond addressing users' immediate, day-to-day needs and instead aspire to support and inspire long-term, sustainable decision-making. Most prior studies have overlooked encouraging long-term decision-making; rather than designing systems that provide users with the data and information needed to support sustained, future-oriented decisions, they have focused primarily on involving users in the participatory design process itself (as discussed by Bratteteig & Wagner, 2016).

While the study confirms the importance of user-centric and context-sensitive designs in improving inclusivity and accessibility, it discusses that the user-centric and PD approaches can still be extractive, especially if the communities are used to generate profits (Costanza-Chock, 2020). PD processes can sometimes become tokenistic, where community members are involved to legitimize a design project (*ibid*). They can also move toward solutionism [the idea that all problems can be solved with technology], ignoring other types of development (*ibid*). Pluriverse challenges have also been raised as current systems are mainly focusing on providing one universal way for technology design (*ibid*). To overcome this, the suggested polycentric approach argues that community members should not just be involved but should have control over the design process.

Third, the fourth chapter outlines the broad aspects that IS should consider during design, including polycentricity and contextuality. These considerations ensure that IS tools are not only functional but also meaningful and sustainable within their intended contexts. The application of the PUCT framework in this study introduces a critical approach that not only includes marginalized voices but ensures technical robustness, and contextual relevance. This approach counters the traditional top-down, one-size-fits-all models that often fail to consider the diversity of social, cultural, and economic contexts in which systems operate. By centering community agency and contextual integrity, the research advances IS development towards more inclusive and equitable practices. Ultimately, the study proposes a replicable framework for developing sustainable, just, and empowering IS, aligning with ongoing calls for transformative technology that amplifies the voices of the most vulnerable (Escobar, 2021; Stirling, 2020).

This thesis advances the field of inclusive IS design by offering a theoretical and practical foundation for creating transformative digital ecosystems. By addressing a critical gap in the literature, it suggests moving from a participatory toward a polycentric design of IS to not only mitigate vulnerabilities but also enhance community viability. It contributes novel insights into designing IS for socio-environmental resilience, emphasizing that adaptive technologies can enable equitable and sustainable changes. It advances the theoretical framework of polycentric governance by demonstrating its applicability within digital ecosystems, emphasizing how decentralized, multi-stakeholder decision-making can enhance inclusivity and adaptability.

5.3. Practical Implications and Recommendations

This thesis highlights the need for polycentric IS that integrate localized knowledge to better serve vulnerable communities. Many existing IS frameworks are top-down and fail to align with the real-world needs of users, limiting their effectiveness and adoption. By embracing community-driven insights and multi-level governance, IS can become more adaptive, inclusive, and responsive to local challenges. To achieve this, design practices must prioritize collaborative development, ensuring that systems are co-created with the communities and stakeholders they serve. Capacity-building initiatives, such as financing, training programs, and knowledge-sharing platforms, should be integrated to improve digital literacy and participation among vulnerable communities. Additionally, investment in connectivity infrastructure, such as affordable internet and Wi-Fi networks is crucial to ensure accessibility. Developing stronger collaborations between IS designers, researchers, and policymakers is also essential for bridging gaps in institutional support and governance, making IS solutions more inclusive, effective, and sustainable. Methodologically, both qualitative and quantitative approaches, including ethnographic and co-design methods, are necessary to understand stakeholder needs. By incorporating the practical considerations mentioned in this study, designers can develop information systems that empower vulnerable populations, fostering inclusivity, equity, and long-term sustainability.

5.4. Limitations of the Study

This study faced several limitations, particularly in designing IS for vulnerable communities, where communication barriers, institutional cooperation, and logistical constraints posed challenges. One major challenge was finding a common language, as community members were unfamiliar with the term IS and, therefore, associated terms. To address this, a round of pilot data gathering was conducted to establish a common language that resonated with participants, ensuring clarity and meaningful engagement with respondents.

The initial goal of the study was to conduct interviews with government officials to gain insights into the role of government policies and strategies in shaping the design and implementation of IS for SSF. However, there were significant limitations in accessing government officials, which hindered the ability to gather institutional perspectives. In Kumirmari, three interviews were arranged through government bodies, but in each case, the data collected was ultimately not usable. For example, the interviewees left the discussions prematurely, which meant that the interviews did not yield the expected depth of information. This lack of cooperation from government bodies restricted the study's access to crucial institutional insights, which could have informed a more comprehensive understanding of the governmental approach to IS in SSF contexts. In response to these challenges, the study adapted its methodology by shifting the focus to IS designers, incorporating interviews with them to gain a more practical and operational understanding of how information systems are developed and implemented in these settings. This pivot allowed for the exploration of technical and design aspects of IS, providing valuable insights into the systems' capabilities, limitations, and the specific needs they are intended to address in SSF communities.

5.5. Future Research Directions

Future research must bridge key methodological gaps to ensure IS development is both technically robust and socially responsive. One critical area requiring attention is the role of communication in IS design—specifically, how interactions between fishers, developers, and policymakers influence system usability and long-term adoption. Understanding these dynamics will help create more inclusive and effective IS that align with the needs of fishing communities. Studies should explore methodologies that facilitate polycentric dialogue, enabling various stakeholders to contribute meaningfully to system. Research should also examine the role of tacit knowledge—the unspoken, experience-based insights that fishers and designers bring to IS development—ensuring that implicit assumptions do not unintentionally exclude local expertise. Furthermore, addressing the lack of longitudinal studies is essential, as current analyses fail to capture how fishing communities' needs, environmental conditions, and technological landscapes have evolved over time. Another critical gap is traceability, where inconsistent data standards and weak regulatory compliance hinder the effective use of digital tools for sustainability. Filling these gaps with holistic and adaptive approaches will ensure that IS not only enhance operational efficiency but also empower fishers with greater agency, resilience, and long-term sustainability.

5.6. Final Remarks

This thesis serves as a guide for designing IS that empower vulnerable communities by ensuring these systems are developed with and for their users. By adopting polycentric approaches, IS can become dynamic platforms that enable informed decision-making and support the transition from vulnerability to viability. The findings highlight the importance of user context, agency, and decentralized governance in ensuring community empowerment, equitable resource access and inclusive decision-making. The proposed approaches provide a blueprint for researchers, developers, NGOs, and policymakers to design IS that not only address the immediate challenges of communities but also enable their transition towards viability and long-term empowerment. By refining existing IS design methods, this thesis lays the groundwork for creating a transformative ecosystem for future innovations that integrate technology with community aspirations, driving sustainable and inclusive development.

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Appendices

Appendix A. List of Small Island Developing States (SIDS)

1. Antigua and Barbuda	14. Guyana	27. Singapore
2. Bahamas	15. Haiti*	28. St. Kitts and Nevis
3. Bahrain	16. Jamaica	29. St. Lucia
4. Barbados	17. Kiribati*	30. St. Vincent and the Grenadines
5. Belize	18. Maldives	31. Seychelles
6. Cabo Verde	19. Marshall Islands	32. Solomon Islands*
7. Comoros*	20. Federated States of Micronesia	33. Suriname
8. Cuba	21. Mauritius	34. Timor-Leste*
9. Dominica	22. Nauru	35. Tonga
10. Dominican Republic	23. Palau	36. Trinidad and Tobago
11. Fiji	24. Papua New Guinea	37. Tuvalu*
12. Grenada	25. Samoa	38 Vanuatu
13. Guinea-Bissau*	26. São Tomé and Príncipe*	

* *Also, Least Developed Country*

Source: (UN, n.d.)

Appendix B. List of SIDS Excluded from the Analysis Due to the Data Unavailability

Antigua and Barbuda, Bahrain, Belize, Dominica, Federated States of Micronesia, Grenada, Kiribati, Marshall Islands, Nauru, Palau, Samoa, Singapore, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Tonga, Tuvalu, Vanuatu.

Appendix C. Indices

Appendix C-1: Indicators, Measurement Units, and data Sources

	Indicators	Units	Sources
1	Overexploited Stocks	Percent (%)	Sea Around Us
2	Marine Trophic Index (MTI)	Index	Sea Around Us
3	Overall Ocean Health Index Score	Index	Ocean Health Index
4	Total Damages	Adjusted ('000 US$) per capita	The international disasters database (EM-DAT)
5	Total Greenhouse Gas Emissions	t of CO2 equivalent per capita	World Bank
6	Population Living in Areas Where Elevation Is Below 5 Meters	% of total population	The World Bank
7	UHC Service Coverage Sub-Index on Infectious Diseases	Percent (%)	World Health Organization
8	GDP	Per Capita - Current US$	The World Bank
9	Domestic Credit to Private Sector	% of GDP	IMF
10	Inflation, GDP Deflator	Annual %	The World Bank
11	GNI	Per Capita Current LCU	The World Bank
12	Aquaculture Production	KG per capita	The World Bank
13	Agriculture, Forestry, And Fishing, Value Added	% of GDP	The World Bank
14	Food Trade Balance	Tonnes per capita (live weight)	FishStatJ
15	Access To Advanced Education	Score ranges from 0 to 120	Social Progress Imperative
16	Individuals Using the Internet	% of population	The World Bank
17	Personal Rights	Score ranges from 0 to 120	Social Progress Imperative

18	Personal Freedom & Choice	Score ranges from 0 to 120	Social Progress Imperative
19	Literacy Rate, Adult Female	% of females ages 15 & above	The World Bank
20	Women Business and The Law Index Score	scale 1 to 100	The World Bank
21	Inclusiveness	Score ranges from 0 to 120	Social Progress Imperative
22	Fragile States Index (FSI)	Score ranges from 0 to 120	The Fund for Peace (FFP)
23	Government Effectiveness	Percentile Rank, Lower Bound of 90% Confidence Interval	The World Intellectual Property Organization (WIPO)
24	Political Stability and Absence of Violence/Terrorism	Percentile Rank, Lower Bound of 90% Confidence Interval	The World Bank
25	Regulatory Quality	Percentile Rank, Lower Bound of 90% Confidence Interval	The World Bank
26	Voice And Accountability	Percentile Rank, Lower Bound of 90% Confidence Interval	The World Intellectual Property Organization (WIPO)
27	Existence Of Fisheries Regulations and Organizations	3=High 0=Low	Sea Around Us
28	Global Innovation Index	Score	The World Intellectual Property Organization (WIPO)
29	Renewable Energy Consumption	% of total final energy consumption	The World Bank

30	Total Marine Food Production (Capture/Aquaculture)	Per Capita Tonnes - live weight	FishStatJ
31	Catches By Artisanal + Subsistence Fishing Sectors	Tonnes	Sea Around Us
32	Prevalence Of Nutritional Deficiencies	Percent (%)	The Institute for Health Metrics and Evaluation (IHME)
33	Marine Food Supply Per Capita	Per Capita Tonnes - live weight	FishStatJ
34	Total Food Supply	kcal/capita/day	UNdata

Appendix C-2: Definitions of the Indices

- Access to Advanced Education: Refers to the availability and opportunity for individuals to pursue advanced education or higher levels of learning, such as post-secondary education, vocational training, or professional development programs. It reflects the degree of educational attainment and opportunities for lifelong learning within a country or region. (Source: Social Progress Imperative)
- Agriculture, forestry, and fishing, value added: Represents the additional value generated by the agriculture, forestry, and fishing sectors after deducting the cost of inputs. It measures the contribution of these sectors to the overall economy, reflecting their economic importance and productivity. (Source: The World Bank)
- Aquaculture production: Refers to the cultivation or farming of aquatic organisms, such as fish, shellfish, and plants, under controlled conditions. It includes the production of seafood through methods such as fish farming and aquaponics. (Source: The World Bank)
- Catches by Artisanal + Subsistence Fishing Sectors: Refers to the quantity of fish and seafood caught by artisanal and subsistence fishing sectors. It includes small-scale, traditional, and non-commercial fishing activities that are typically carried out by local communities for sustenance or local trade. (Source: Sea Around Us)
- Domestic credit to private sector: Refers to the amount of credit or loans provided by domestic financial institutions, such as banks, to the private sector, including individuals and businesses. It reflects the availability of credit, and the level of financial support provided to the private sector within a country. (Source: IMF)
- Existence of Fisheries regulations and organizations: Indicates the presence or existence of regulations and organizations dedicated to managing and regulating fisheries. It reflects the commitment and capacity of a country or region to implement sustainable fishing practices and protect marine resources. (Source: Sea Around Us)
- Food Trade Balance: Indicates the balance between a country's food exports and imports. It reflects the net quantity of food products a country exports or imports and provides insights into its self-sufficiency in meeting domestic food demand. (Source: FishStatJ)

- Fragile States Index (FSI): Represents an index that assesses the level of fragility and instability of states or countries. It considers factors such as social conflict, political instability, economic vulnerability, and human rights abuses. A higher index score indicates higher levels of fragility. (Source: The Fund for Peace - FFP)
- GDP: Gross Domestic Product, which represents the total value of goods and services produced within a country's borders in a specific time period. It serves as an indicator of the economic output and overall economic activity of a country. (Source: The World Bank)
- Global Innovation Index: Represents an index that measures and ranks countries' innovation capabilities and outcomes. It assesses factors such as research and development investments, intellectual property protection, and technological advancements, providing insights into a country's innovation potential and performance. (Source: The World Intellectual Property Organization - WIPO)
- GNI: Gross National Income, which represents the total income generated by a country's residents, including income from abroad (such as remittances and investments). It reflects the overall economic output and income earned by the citizens or nationals of a country. (Source: The World Bank)
- Government Effectiveness: Indicates the effectiveness and efficiency of a government in delivering public services, implementing policies, and governing a country. It reflects the capacity of the government to manage resources, provide essential services, and address societal needs. (Source: The World Intellectual Property Organization - WIPO)
- Inclusiveness: Reflects the degree of inclusiveness or inclusivity within a society, considering factors such as social, economic, and political participation. It assesses the level of equal opportunities, social cohesion, and the extent to which diverse groups are included and empowered. (Source: Social Progress Imperative)
- Individuals using the Internet: Indicates the number or percentage of individuals within a population who have access to and actively use the internet. It reflects the level of digital connectivity and access to information and communication technologies. (Source: The World Bank)

- Inflation, GDP deflator: Represents the rate of inflation based on the GDP deflator, which measures the overall price level of goods and services produced within an economy. It indicates the percentage change in prices over time and provides insights into the purchasing power and stability of a country's currency. (Source: The World Bank)
- Literacy rate, adult female: Represents the percentage of adult females within a population who are literate or have basic reading and writing skills. It serves as an indicator of educational attainment and empowerment of women. (Source: The World Bank)
- Marine Food Supply per capita: Indicates the availability of marine food resources (fish and seafood) per person within a population. It reflects the quantity of seafood that is potentially accessible for consumption and can provide insights into the adequacy of marine food supply for meeting nutritional needs. (Source: FishStatJ)
- Marine Trophic Index (MTI): A measure that quantifies the average trophic level of marine ecosystems, indicating the position of a particular fish or marine species within the food web. It provides insights into the overall health and stability of marine ecosystems. (Source: Sea Around Us)
- Overall Ocean Health Index score: A composite score that assesses the overall health and sustainability of ocean ecosystems based on various indicators, including biodiversity, habitat quality, ecosystem services, and human use and impact. It provides a comprehensive evaluation of the state of the ocean's health. (Source: Ocean Health Index)
- Overexploited stocks: Refers to stocks of fish or marine species that are being harvested at unsustainable levels, exceeding their reproductive capacity and leading to a decline in their population size. (Source: Sea Around Us)
- Personal Freedom & Choice: Encompasses the individual's ability to exercise personal freedoms, make choices, and lead a self-determined life. It includes aspects such as freedom of movement, freedom of religion, and the ability to participate in social, cultural, and economic activities. (Source: Social Progress Imperative)
- Personal Rights: Refers to the fundamental rights and freedoms that individuals possess, including civil liberties, political rights, and legal protections. It encompasses

rights such as freedom of speech, freedom of assembly, and the right to a fair trial. (Source: Social Progress Imperative)

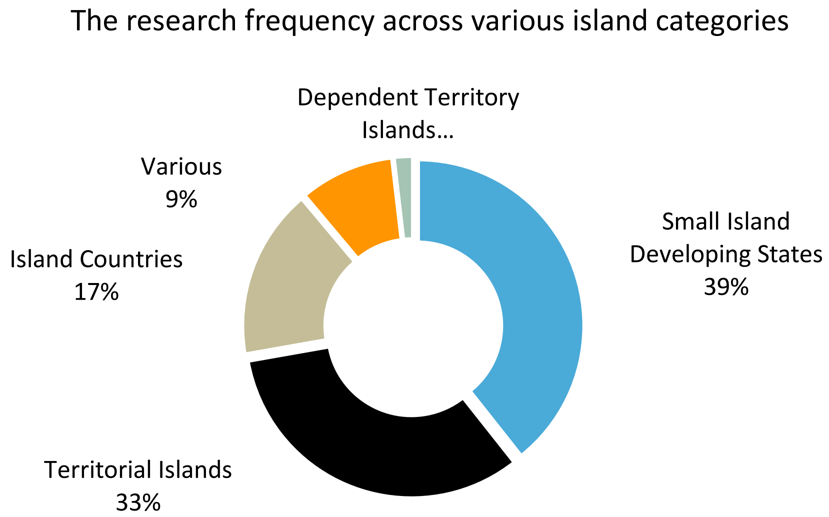
- Political Stability and Absence of Violence/Terrorism: Reflects the level of political stability and absence of violence or terrorism within a country. It assesses factors such as political unrest, armed conflict, and terrorist activities, providing insights into the overall security and stability of a nation. (Source: The World Bank)
- Population living in areas where elevation is below 5 meters: Indicates the number of people residing in regions with an elevation lower than 5 meters above sea level. This variable is relevant for assessing vulnerability to sea-level rise and associated risks such as flooding and coastal erosion. (Source: The World Bank)
- Prevalence of Nutritional deficiencies: Represents the extent or proportion of the population affected by various forms of nutritional deficiencies, such as deficiencies in essential nutrients such as vitamins, minerals, or macronutrients. It provides insights into the nutritional status and health challenges faced by a population. (Source: The Institute for Health Metrics and Evaluation - IHME)
- Regulatory Quality: Represents the quality and effectiveness of regulatory frameworks and institutions in ensuring compliance, enforcing laws, and promoting fair and transparent business practices. It measures the extent to which regulations are conducive to economic development and provide a stable and predictable environment for businesses. (Source: The World Bank)
- Renewable energy consumption: Refers to the utilization or consumption of energy derived from renewable sources such as solar, wind, hydropower, and biomass. It indicates the share of energy consumption that comes from sustainable and environmentally friendly sources. (Source: The World Bank)
- Total Damages: Represents the cumulative economic, social, and environmental losses caused by natural and man-made disasters. It includes the costs associated with infrastructure damage, loss of life, displacement, and other impacts resulting from disasters. (Source: The international disasters database - EM-DAT)
- Total Food supply: Refers to the overall quantity of food available within a country or region, encompassing both domestic production and imports. It provides a measure of

the total food resources available to meet the nutritional needs of the population. (Source: UNdata)

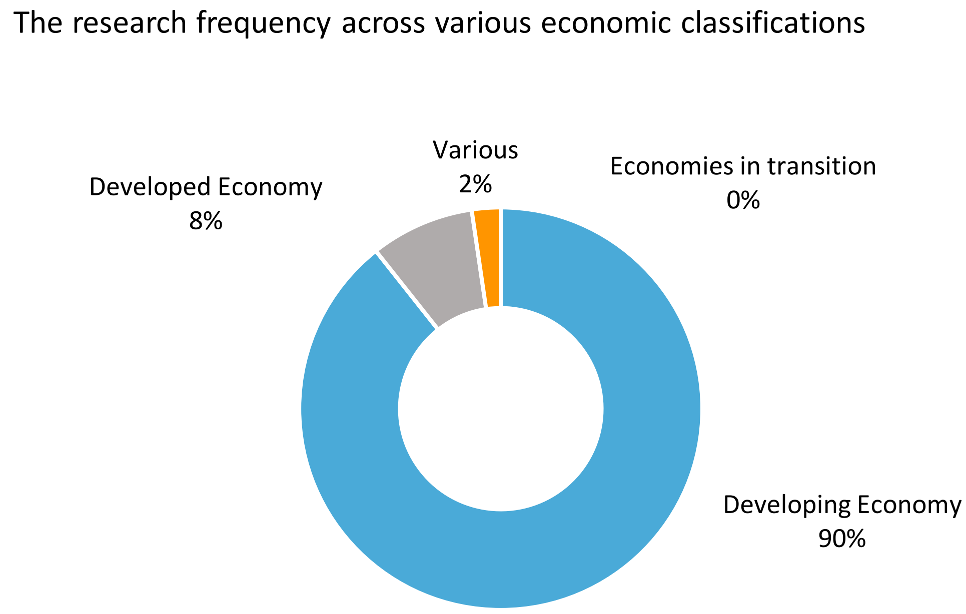
- Total greenhouse gas emissions: Refers to the sum of all emissions of greenhouse gases, including carbon dioxide, methane, nitrous oxide, and fluorinated gases. It measures the total contribution of human activities to climate change and global warming. (Source: World Bank)
- Total marine food production (capture/aquaculture): Represents the total production of food from marine sources, including both capture fisheries (wild-caught fish) and aquaculture (fish farming). It reflects the overall quantity of seafood produced from marine resources. (Source: FishStatJ)
- UHC Service Coverage sub-index on infectious diseases: A sub-index that measures the extent of Universal Health Coverage (UHC) in terms of service coverage for infectious diseases. It reflects the availability, accessibility, and quality of healthcare services related to infectious diseases within a country or region. (Source: World Health Organization)
- Voice and Accountability: Reflects the extent to which citizens have the ability to participate in decision-making processes, hold governments accountable, and exercise their civil and political rights. It assesses factors such as freedom of expression, access to information, and the presence of democratic institutions. (Source: The World Intellectual Property Organization - WIPO)
- Women Business and the Law Index Score: Refers to the score obtained from the Women Business and the Law Index, which measures the legal rights and protections available to women in the business sector. It evaluates gender-based legal disparities and discrimination in areas such as property rights, access to credit, and employment regulations. (Source: The World Bank)

Appendix D: The Result of the Systematic Literature Review

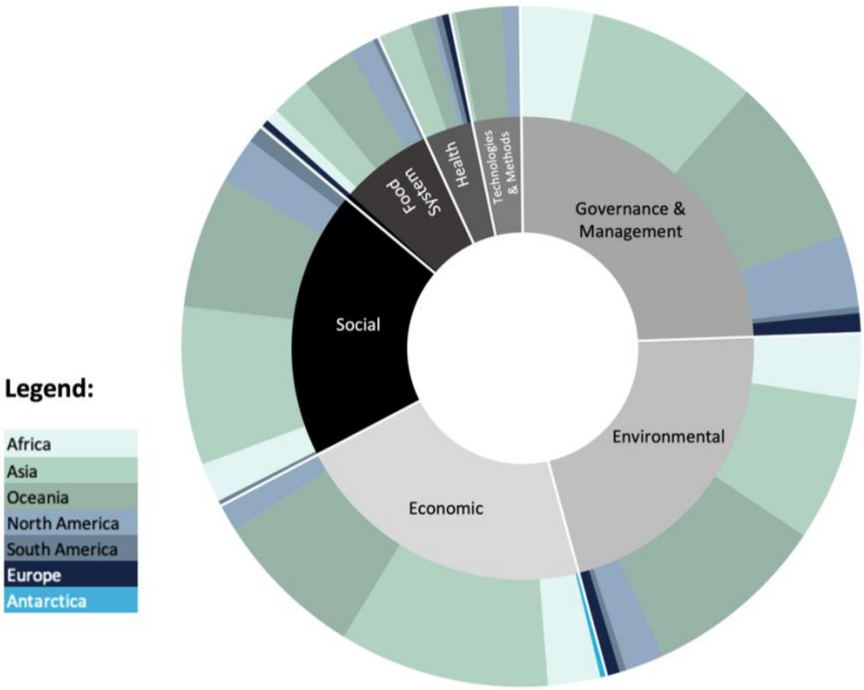
Appendix D-1: Frequency of Research on Food and Nutrition Security among Small-Scale Fisheries Based on Different Island Types



Appendix D-2: Frequency of Research on Food and Nutrition Security among Small-Scale Fisheries based on Different Island Types



Appendix D-3: Vulnerability and Viability Dimensions Covered In the Literature in Different Regions



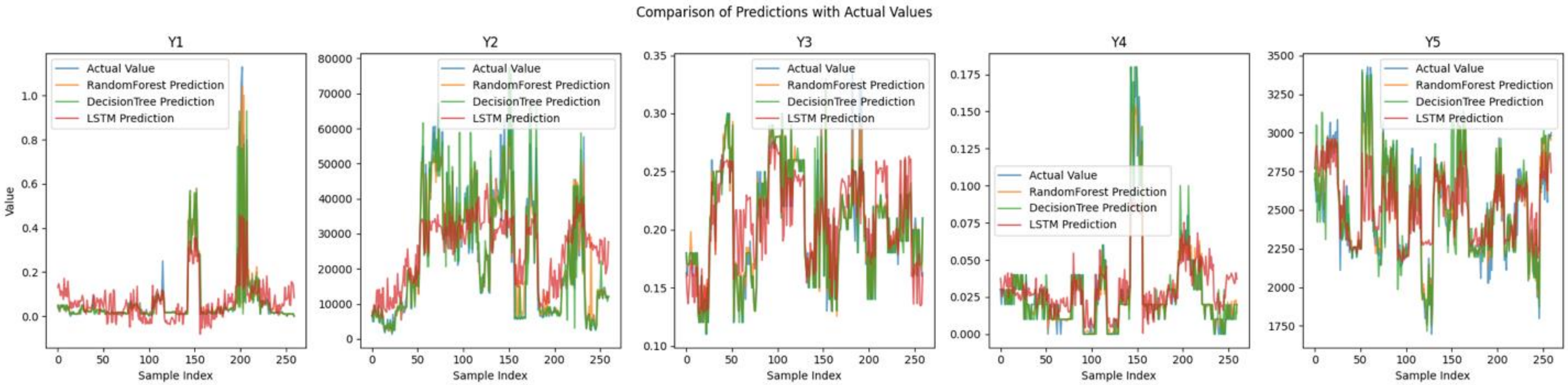
Appendix E. Random Forest Results

Appendix E-1. The Average Impact of Vulnerability and Viability Factors on Food and Nutrition Security in Small Island Developing States

Predictor Variable	Total Production per capita (capture/aquaculture)	Catches by Artisanal + Subsistence Fishing sectors	Prevalence of Nutritional deficiencies	Marine Food Supply per capita	Food supply
Food Trade Balance	5.72	0.24	0.23	10.00	0.26
Access to Advanced Education	0.23	0.10	0.44	0.22	6.98
Agriculture, forestry, and fishing, value added	0.14	0.45	6.44	0.35	0.27
Inclusiveness	0.06	5.92	0.23	0.15	0.18
Overall Ocean Health Index score	0.34	1.22	0.32	2.90	0.14
Marine Trophic Index (MTI)	0.05	0.17	1.89	0.46	0.70
Population living in areas where elevation is below 5 meters	0.93	0.24	0.35	1.03	0.13
Total greenhouse gas emissions	0.08	0.59	0.91	0.39	0.67
Literacy rate, adult female	0.05	0.08	0.24	1.81	0.29
Women Business and the Law Index Score	0.09	0.14	1.39	0.41	0.23
Regulatory Quality: Percentile Rank, Lower Bound of 90% Confidence Interval	0.08	0.79	0.07	0.29	0.80
Renewable energy consumption	0.04	0.12	0.12	1.27	0.30
Overexploited stocks	0.10	0.21	0.71	0.43	0.40
Personal Freedom & Choice	0.05	0.37	0.12	0.21	0.85
Total Damages	0.07	0.15	0.07	0.78	0.28
Existence of Fisheries regulations and organizations	0.06	0.61	0.08	0.44	0.09
Political Stability and Absence of Violence/Terrorism: Percentile Rank, Upper Bound of 90% Confidence Interval	0.04	0.69	0.10	0.33	0.11
Personal Rights	0.04	0.07	0.14	0.78	0.21
Domestic credit to private sector	0.04	0.18	0.08	0.47	0.47
GNI	0.12	0.09	0.39	0.25	0.26
Government Effectiveness	0.03	0.18	0.07	0.25	0.57
Aquaculture production	0.06	0.28	0.10	0.28	0.35
Voice and Accountability	0.06	0.11	0.18	0.63	0.08
Fragile States Index (FSI)	0.03	0.08	0.10	0.48	0.26

Global Innovation Index	0.04	0.20	0.14	0.35	0.20
GDP per capita	0.04	0.07	0.22	0.14	0.43
Inflation, GDP deflator	0.06	0.10	0.09	0.39	0.17
Individuals using the Internet	0.08	0.08	0.13	0.15	0.17
UHC Service Coverage sub-index on infectious diseases	0.10	0.14	0.07	0.11	0.11

Appendix E-2. Comparison of Predictions with Actual Values



Glossary

- **Capacity:** "The combination of all the strengths, attributes and resources available within an organization, community or society to manage and reduce disaster risks and strengthen resilience" (UNISDR, 2017).

- **Data colonialism** provides a framework for understanding how data practices can perpetuate historical patterns of exploitation and control, particularly affecting marginalized populations in the Global South. (Couldry & Mejias, 2023)

- **Exposure:** "The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas" (UNISDR, 2017).

- **Food system resilience** is defined as the capacity over time of a food system and its units at multiple levels, to provide sufficient, appropriate and accessible food to all in the face of various and even unforeseen disturbances (Tendall et al., 2015).

- **Natural Hazard**: "any natural process or phenomenon that may cause loss of life, injury or health impacts, property damage, loss of livelihoods and services, social and economic disruption or environmental damage" (UN/ISDR, 2009)

- **Resilience** refers to the magnitude of disturbance that can be absorbed before a system changes to a radically different state, as well as the capacity to self-organize and the capacity for adaptation to emerging circumstances (Adger, 2006).

- **Robustness** is the ability to withstand a disruption (or a series of disruptions) to maintain the planned performance (Nair and Vidal, 2011; Simchi-Levi et al., 2018)

- **Stability** is the ability to return to a pre-disturbance state and ensure a continuity (Ivanov and Sokolov, 2013; Demirel et al., 2019)

- **Sustainable development** is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs (The Brundtland definition) (WCED, 1987).

- **System resilience** is the system's ability to tolerate and/or adapt to disruptions over time (Hoddinott, 2014) in order to continue performing its responsibilities and delivering the desired results (Walker et al., 2006).

- **User-centered design** refers to a design process that is "based upon an explicit understanding of users, tasks, and environments; is driven and refined by user-centered evaluation; and addresses the whole user experience. The process involves users throughout the design and development process and it is iterative." (Costanza-Chock, 2020, p. 77)

- **Viability** is the ability of a community to address risks and to adapt to the changing environment, with or without external help (Berkes & Nayak, 2018; Nayak & Berkes, 2019). Also, viability is defined as the ability of a system to maintain itself and survive in a changing environment over a long period of time through a redesign of the structures and replanning of economic performance with long-term impacts (Ivanov 2018b, p. 59; Ivanov and Dolgui 2020b).

- **Vulnerability**: "The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards" (UNISDR, 2017).

A Lyrical Ending

Coromandel Fishers by Sarojini Naidu (1879–1949)

I would like to close this thesis with a poem by Sarojini Naidu, an Indian political activist and poet, celebrating the fishermen's strong connection to the sea and their resilience in the face of challenges. The poem reflects positive possibilities and resilience, and I hope this thesis serves to inspire and uplift in the same spirit.

Rise, brothers, rise; the wakening skies pray to the morning light,
The wind lies asleep in the arms of the dawn like a child that has cried all night.
Come, let us gather our nets from the shore and set our catamarans free,
To capture the leaping wealth of the tide, for we are the kings of the sea!

No longer delay, let us hasten away in the track of the sea gull's call,
The sea is our mother, the cloud is our brother, the waves are our comrades all.
What though we toss at the fall of the sun where the hand of the sea-god drives?
He who holds the storm by the hair, will hide in his breast our lives.

Sweet is the shade of the cocoanut glade, and the scent of the mango grove,
And sweet are the sands at the full o' the moon with the sound of the voices we love;
But sweeter, O brothers, the kiss of the spray and the dance of the wild foam's glee;
Row, brothers, row to the edge of the verge, where the low sky mates with the sea.