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Internet over the ocean: A smart IoT-enabled digital ecosystem for empowering coastal fisher communities

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ABSTRACT

Coastal communities across the globe are prone to imminent disasters and emergencies due to their geographic placement, and their fishing occupations add to their exposure to ocean-related disasters more during their occupational voyage. The fishermen in the state of Kerala, India, lead a distinctive lifestyle compared to the mainstream community, primarily because of a significant digital divide. This divide hampers their access to livelihood support, such as live market information and impedes any potential improvement in their quality of life through digital services. The community's transformation is possible only through discrete and gradual steps of progression by bringing services to different areas such as education, connectivity, technology adoption, business, and livelihood. This study revealed prevalent gaps in the fishing community, including a lack of digital access and communication opportunities in the deep ocean, a deficiency in digital capacity preventing them from leveraging the benefits of Information and communications technology (ICT), leading to community isolation from digital inclusion and limiting economic opportunities. To address these issues, the study proposes an IoT-enabled digital ecosystem, transforming the community into a smart digital community. This ecosystem integrates a low-cost deep ocean communication solution, supportive software applications, a blockchain-based e-commerce platform, and a sustainable social change model for technology adoption. Proper adoption and utilisation of the digital ecosystem can strengthen the community's resilience to natural disasters, and climatic changes by providing relevant information and livelihood resilience by offering them an e-commerce platform to improve income and reduce their vulnerability. It will equip them to enhance their responsiveness to changing environmental and social factors and bounce back to build their innate resilience.

1. Introduction

With a coastline that stretches over 7500 km and the third-highest fish production in the world, India is home to more than 28 million fishermen, the majority of whom are small-scale fishermen [1,2]. According to the Indian Ministry of Fisheries [2] there are 3461 marine fishing villages with 1457 marine fish landing sites spanning nine maritime states and two union territories in India, the majority of which belong to the rural community [3]. Fishing is the key source of employment for millions of coastal people, approximately 4 million fishers, and 85 % of them have fishing as their primary source of income [4] thus contributing significantly to the country's food security and economy.

Generally, fishing is considered one of the world's most unreliable, unstable, and unsafe professions [5]. The dynamic variability of the ocean weather such as marine heat waves, and sea swell, impacts the spatiotemporal distribution of fish stocks [6]. It also increases the occurrence of emergencies such as the capsizing of fishing vessels, making this livelihood an unsafe occupation. The fishing community experiences a remarkably high loss of lives, with approximately 100,000 fishing-related deaths occurring globally each year [7], making it a particularly perilous occupation. Generally, for medium-sized fishing vessels (less than 100 feet in length), the fishermen can be away from the shore for 7–15 days and travel 120 km on average while at sea. During this time, they face unpredictable weather and extreme environmental conditions, without having a reliable communication facility. This lack

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of communication makes them unable to seek help during emergencies. Additionally, they are exposed to life-threatening dangers, including unpredictable collisions with other fishing vessels or ships (if their vessel is in the ship routes), engine failures, and unexpected situations such as pirate attacks and unintentional maritime border crossings, potentially leading to captivation by the neighbouring border force [8]. This unreliability, safety issues, and lack of reliable communication add up to their occupational vulnerability.

A livelihood is considered resilient if the community or individual practising it has proper access to human, physical, social, natural, and financial resources to build the capacity to recover from various shocks and disturbances, such as natural disasters, economic downturns, and conflicts with other stakeholders [9]. Additionally, according to the Sustainable Livelihoods Analytical Framework by the Department for International Development (DFID), the livelihood resilience of a household can be improved through income improvement, well-being improvement, reduced vulnerability, and resource optimisation [10]. In the context of the fishery as a livelihood, the current situation in the study community highlights their lack of access to digital services to build resilience capacity. These services could assist them in coping with unfavourable weather conditions at sea, such as accessing related weather forecasting information for the prevention of potential health hazards, addressing their over-dependence on middlemen who control the fish market, serving as the most influential stakeholders to reduce their vulnerability and increase their profit margin, and monitoring the marine resource depletion for optimised resource management policies [11].

One of the primary obstacles to enhancing fishermen's livelihood resilience, safety, and digital empowerment is the absence of digital services specifically designed for them. These services would aid them in various instances, such as accessing a wider range of customers without the interference of middlemen, providing live market information for informed decision-making, offering emergency information in the ocean, and providing Internet access deep in the ocean. Beyond 15 km from the shore, cellular coverage and Internet connectivity are unavailable. This makes them completely isolated from their community during the trip, lacking real-time business management from the ocean. The lack of real-time communication opportunities forces fishermen to rely on intermediaries at the fishing harbours, who provide periodic messages and advice based on their connectivity and market analysis. However, these services come at a cost, and often, intermediaries take a share of the fisherman's profit. This exploitation occurs due to the fishermen's limited access to real-time information during fishing trips.

Enhancements in weather forecasting systems and ocean information services have been devised to provide early warnings of potential disasters and emergencies in the ocean. However, currently, during emergencies such as high tides, collisions between two fishing vessels, ship-to-boat collisions, bad weather, or cyclone formation, timely information cannot be effectively disseminated to the stakeholders at the shore due to the unavailability of the Internet over the ocean beyond 15 km from the shore. Similarly, stakeholders onshore, such as administrators from the Department of Fisheries, fishing vessel owners, and family members of the crewmen, currently lack a solution that could initiate real-time tracking and monitoring for fishing vessels. However, there are some existing services such as mKRISHI Fisheries App [12], Nautide [13], Sagara, Search and Rescue Aid Tool (SARAT) [14], INCOIS feedback app, Tuna (PFZ) services, "Sagar Vani" - an integrated information dissemination system [15], Windy.app [16], Fisher Friend Mobile Application (FFMA) [17], etc., that can be used where the cellular network coverage is available. Even so, the fishermen are hesitant or unable to use them due to the lack of digital access, knowledge, and skills to use digital technologies and services.

Lack of digital literacy makes the fishermen rely solely on conventional methods for their livelihood and business, impacting their resilience, sustainability, and overall quality of life. The conventional methods, which rely on the expertise of fishermen to anticipate sea state and weather conditions, determine the spatial location of fish, and gather information from auction dealers, are commonly used for establishing dynamic pricing when selling the daily catch and deciding when to return to the shore. However, these conventional methods cannot provide real-time information on changes in weather, sea state, market dynamics, etc., thereby affecting the resilience of the fishermen's livelihood system. The limitations of these conventional methods make fishermen susceptible to exploitation by intermediaries and restrict their access to a broader consumer base, unlike business owners using e-commerce platforms.

Digital literacy empowers fishermen to diversify their livelihood opportunities, leading to increased profit margins. For instance, the increased use of digital payments in rural areas has led to the growth of the digital economy, creating new opportunities for businesses and entrepreneurs and improving livelihoods [18]. A study by Ye and Yang (2020) [19] presents a revelatory case whereby a mobile platform empowers rural people through structural, psychological and resource empowerment. Several smartphone applications are designed to empower the rural population in various fields such as delivering timely information, providing market information and healthcare services [20]. This, in turn, improves their overall quality of life by allowing them to achieve greater profits with the same effort or maintain the same profit with less effort. These observations also highlight the digital divide within the community, stemming from the lack of digital access at sea and insufficient digital skills to utilise available technologies for enhanced safety and resilience. In the literature, the digital divide is defined as the inequalities that exist in access to and use of the Internet [21] and other ICT opportunities. The current digital divide exacerbates the communities' ability to be inclusive of the mainstream community. Specifically, it hampers the ability of fishermen communities to integrate with urban and suburban communities that have 24x7 digital access. This significantly impacts the digital outcomes of the community. Here, digital outcomes refer to using ICT to access information online to enhance their livelihood and safety. These challenges can be addressed through the development of a digital ecosystem tailored for the fisher community.

This research focuses on addressing the aforementioned challenges, including the lack of connectivity at sea (i.e., Digital Access), limited skills to use digital services (i.e., Digital Capacity, which is the ability to use and perceive the possibilities of the technology) and lack of real-time market information for dynamic decision making by introducing the "OceanNet Digital Ecosystem (ODE)." The ODE comprises multiple solutions designed to meet the specific needs of fishermen, ultimately providing a pathway to have a communication medium at sea for enhancing their safety, and livelihood resilience through digital advancements. A digital ecosystem is a modular, digitally connected, loose network of interacting organizations or a collection of platforms, software, and applications specific to it [22,23]; therefore, the proposed solution is called a digital ecosystem.

The research team has developed a real-time communication system for fishermen that provides digital connectivity and helps them receive emergency warning services. The first part of the solution is an IoT-based architecture to provide Internet access over the ocean. It has been designed and developed to enhance digital access. Initially, the system was tested by researchers through deployment on three fishing vessels, conducting sea trials to verify its envisioned long-range connectivity. Subsequently, the system was further deployed on eleven additional fishing vessels, with a total of fourteen vessels utilising it during their regular fishing trips. The research has also produced a real-time tracking mobile application aimed at enhancing safety at sea. The IoT system, facilitating real-time communication, is integrated with web and mobile platforms, effectively improving digital access opportunities. Engaging with multiple stakeholders has boosted their motivation to use the system, and regular use has honed their skills in leveraging it for communication, safety, and overall resilience.

The digital outcomes of the OceanNet Digital Ecosystem (ODE), specifically increased safety at sea and enhanced livelihood resilience, are further fortified through the integration of blockchain technology into its design. Blockchain technology serves as the backbone for establishing a middleman-free online e-commerce framework, ultimately enhancing fishermen's livelihood opportunities. This, in turn, contributes to bolstering their overall resilience against coastal risks and reducing dependence on intermediaries, thereby impacting their economic stability positively. Utilising a Blockchain-based e-commerce platform for fish sales can significantly enhance the resilience of fishermen's livelihoods by addressing several key factors. Firstly, removing intermediaries eliminates exploitation and allows them to capture a larger share of the profits, increasing their financial capital and reducing vulnerability to income shocks [24]. Secondly, reaching a wider customer base through the platform expands their market access and reduces dependence on local fluctuations, improving their ability to adapt to changing market conditions [11,25]. Thirdly, clear price determination based on market demand and automated auctions empowers fishermen with greater control over pricing (resistance), fostering a more equitable system [9]. This can also potentially increase income, reduce their vulnerability, and improve their capacity to absorb shocks [26]. Overall, the platform offers a diversification strategy [27] by providing a new income stream, strengthening their overall livelihood resilience.

This comprehensive digital ecosystem architecture integrates opportunities to enhance digital access, digital capacity, and digital outcomes. The proposed ecosystem empowers fishermen and other stakeholders to access digital services and analyse spatiotemporal patterns of the fishing vessels, which can later be utilised to plan future fishing trips. It also enables them to understand the interrelationships between different factors, such as fish availability, type of fish, and market demands, which can be considered to plan future activities, ultimately enhancing the livelihood of the fisherman community. Livelihood involves specific capabilities, activities, and assets that are required to earn for living [28]. The proposed ODE focuses on both safety and livelihood. However, the success of the proposed ecosystem is dependent on the technology adoption by the fishing community. This has been considered from the initiation of the research work. The realisation of the envisaged digital outcome hinges upon the active utilisation of the digital ecosystem by fishermen, their families, vessel owners, and other stakeholders. This usage is vital for communication, livelihood, safety, and overall improvement of resilience and quality of life within the community. The adoption of new technology necessitates a model that incorporates social elements, including local actors, the environment, culture, traditional behaviours, and motivational factors [29].

The above-considered points have specifically been integrated into this initiative, and this paper explains the approaches used in detail. To achieve this, an optimal technological platform was constructed based on community-centred methods for an assured alignment with their real-life challenges. A sustainable social change model, inspired by the Technology Adoption Model (TAM) [30] and based on community characteristics, abilities, and motivation to adopt new technology, has been proposed. The sustainable social change model envisions developing a set of associated methodologies and a roadmap to achieve the envisioned digital empowerment through community participation and engagement with the technological services through the access provided by the network. The researchers assume that the desired digital outcome will be achieved through the successful prolonged usage of the technology and social pressure to use it. This study details the efforts to develop a smart fishing community, equipping them to use digital resources and services during their occupational voyage to receive timely emergency warning messages and maintain communication with the shore. Furthermore, this paper presents the lessons learned from the problems identified, the steps taken to improve the solution, the technology diffusion process, and the sustainable social change model developed. These elements collectively equip the community towards becoming a sustainable smart coastal fishing community.

Based on the existing challenges discussed above and the research gaps identified and presented in section 3, the key research questions considered for reducing the digital divide and empowering the fisher community are as follows.

1. How can a digital ecosystem be developed to achieve real-time disaster risk reduction and enhance resilience to ocean emergencies?
2. How can the fishing community be empowered to utilise the developed technologies for enhanced safety and livelihood?

The rest of the paper is organised as follows: Section 2 details the methods used during the different phases of this research. Section 3 reviews the current related literature and presents the identified gaps. Section 4 presents the research results and provides a detailed description of the architecture and components of the digital ecosystem and its implementation details. Section 5 provides a discussion on how the research questions have been answered in the study. Section 6 presents the limitations of the study and Section 7 concludes the paper with a summary of its findings and presents the potential future directions to enhance the digital ecosystem for coastal fishing communities.

2. Methods

To tackle the research questions outlined in Section 1, the study employed three main categories of methods: desk literature review, co-design process, and a sustainable social change model. Fig. 1 provides an overview of these methods, presented in the order they were utilised in the study.

Below, a detailed overview of the research community and the methodologies used in this study is provided.

2.1. Study area

As illustrated in Fig. 2, the selected study area for the proposed ODE implementation is the coastal village of *Alappad* in the State of Kerala, India, with village coordinates at 09.0898° N, 76.4864° E. This village is a narrow stretch, approximately 17 km long, extending from south to north. According to the last census of India [31], the village is home to 21,655 residents, with an almost equal distribution between males and females. The community members in this study share a common set of socio-cultural standards and beliefs, forming a close-knit community characterized by shared socio-cultural values. Given that the majority of the male residents in the village are fishermen, this study area catalyzes nearby coastal communities to embrace new digital practices. These practices aim to support their livelihoods, enhance livelihood resilience, and provide disaster alerts and offshore emergency communication facilities. This focused study on Alappad offers insights that can be extrapolated to benefit neighbouring coastal communities, illustrating the potential for widespread adoption of digital solutions in support of sustainable livelihoods and improved resilience.

2.2. Literature review

The literature review for this study covered a broad spectrum of sources, comprising the UN and government reports, scholarly articles about ocean communication technologies, blockchain technology, technology adoption models, social change theories, sustainable development, the digital divide, participatory methods (e.g., Participatory Rural Appraisal tools), and co-design approaches. These sources were drawn from digital databases, including government official websites, Scopus, Google Scholar, United Nations reports, and private sector resources. The search results from these digital databases were evaluated within the context of the study's research community, and irrelevant findings were filtered out before further analysis of the articles.

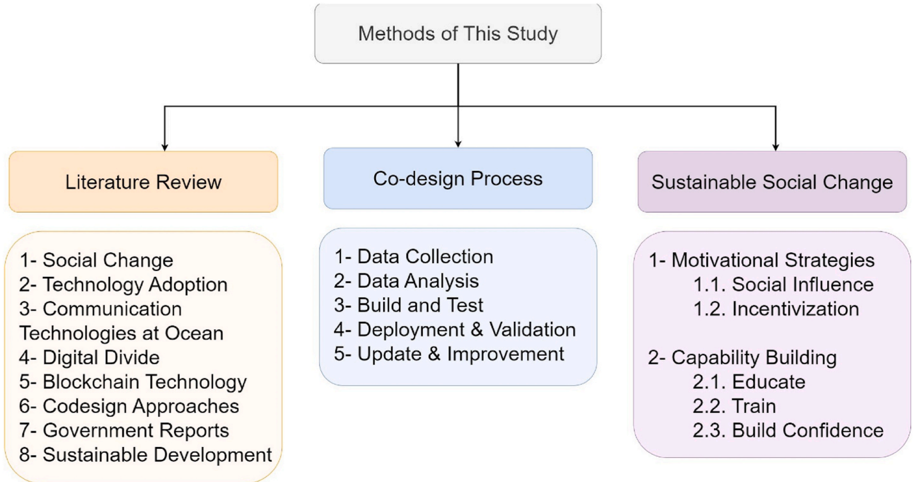

Fig. 1. Overview of the methods utilised in the study.

Fig. 2. Map of the study area.

2.3. Co-design process

The research employed a co-design [32,33] methodology to under-stand the community's characteristics, chal-lenges, and requirements, enabling the formulation of solutions for the identified issues. Fig. 3 illustrates the co-design process used in developing the OceanNet Digital Ecosystem (ODE) tailored for the fishing community. This method involves active engagement with community stakeholders throughout the design and development phases, ensuring alignment with their requirements and values. Such an approach facilitates a smoother technology adoption process. Extensive engagement with community members occurred during the requirement analysis and problem identification stages, providing a comprehensive understanding of their challenges and digital gaps. The gathered information served as the

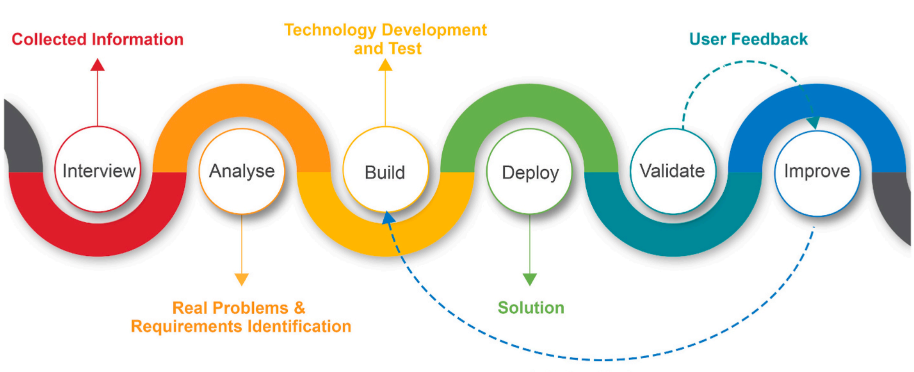

Fig. 3. Co-design process for a sustainable solution.

foundation for designing solutions to address the identified issues. Continuous feedback from the community played a pivotal role in refining the proposed solution, contributing to its ongoing improvement. This iterative approach significantly strengthened the capacity to design multiple sustainable solutions, thereby achieving the envisioned digital outcomes. The co-design methodology consists of six phases: issue identification, data analysis, solution development, product validation, solution deployment, feedback collection, and solution refinement.

2.3.1. Data collection

Taking into account the co-design process depicted in Fig. 3, the initial focus of the study was on gathering information from the community and identifying stakeholders for active participation in subsequent stages. This phase was enriched by qualitative, structured, and semi-structured face-to-face interviews, which served as key tools for community engagement. Initiated in 2014, the study has continued to evolve, with ongoing refinements to the solution.

Face-to-face interviews were conducted with over 200 participants, comprising boat owners, captains, crewmen, fishermen, fishermen's family members, and fishing vessel managers. Participants were provided with a detailed explanation of the study's purpose, and their consent was obtained for both interviews and the use of acquired materials. Employing a convenience sampling method, the research team obtained contact numbers from participants through their colleagues within the community. Interviews were conducted in the local language (Malayalam), with translators present for team members unfamiliar with the language. Semi-structured interviews with fishermen participants were conducted at their fishing vessels to gain deeper insights into their practices and daily routines. The interviews lasted a maximum of 30 min for family members and 50 min for other participants. Questions covered various aspects of the fishing process, including the technologies in use, the number of fishermen on each vessel, crewmen's roles and responsibilities, and communication methods used during voyages, both with their families and in emergencies. Additionally, business-related topics, such as fish catch procedures, conventional selling practices, influential stakeholders in the market, and methods to reach customers, were also explored.

This comprehensive process facilitated meticulous data collection, necessary for a profound understanding of the dynamics and needs of the fishing community. Interviews were documented in both audio and written forms, supplemented by captured images of existing technologies on fishing vessels and the stakeholders for further study. The amassed information was then leveraged to design a second set of interviews. The next round of interviews employed a structured qualitative approach based on various indicators related to their occupational, emergency, and personal requirements, as illustrated in Table 1. When conducting interviews with the fishermen's family members, the questionnaire aimed to capture the perspectives of the females within the community. Research volunteers obtained contact information for the fishermen's families through the local Panchayat member (the local self-governance structure) and conducted the interviews based on his recommendations.

2.3.2. Data analysis

The interviews were concluded upon reaching a point of repetitive responses from participants. Subsequently, the interviews were transcribed verbatim and stored as documents for further analysis. The information gleaned from these interviews underwent analysis using a manual technique [34,35]. The research team meticulously reviewed the data multiple times, focusing on addressing the research questions and gaining insights into the community's characteristics, capabilities, challenges, and motivations. The outcome of this phase was an understanding of (a) the community's needs, (b) existing communication methodologies prevalent in the community, (c) emergency scenarios,(d) fishing practices, (e) fishing trip patterns, (f) livelihood opportunities, (g) climate change impacts, (h) seasonal impacts on fishing, (i) perceived usefulness of existing solutions, (j) motivational aspects for digital solutions catering to entertainment, infotainment, business, etc. Through this inductive data analysis, a profound understanding of the community was achieved, identifying different problematic themes and establishing various categories to conceptualise a solution for empowering the fishermen's community. The insights from this stage were then applied to formulate the initial design of the OceanNet Digital Ecosystem (ODE).

Table 1
The questionnaire set for collecting information from the study community.

SI No	Question indicators	Interview questions
1	E01	Would you like to receive alerts and notifications for weather changes?
2	E02	Do you want to receive alerts on cyclones and tsunamis in advance?
3	E03	What are the early warning systems you currently use at sea?
4	E04	Would you like to receive real-time updates in case of a family emergency? Would you like to be informed about a potential collision with another ship while on a shipping route as a fishing vessel?
5	E05	Would you like to be informed about a potential collision with another ship while on a shipping route as a fishing vessel?
6	E06	Have you experienced any health emergencies at sea during fishing?
7	O01	Would you like to be informed about nearby fishing vessels to assist you in the case of food or fuel shortage on your fishing vessel?
8	O02	How is fishing done during a single trip? Is the fishing vessel anchored in one place, or does it move? If it moves, what is the movement pattern, frequency, etc.?
9	O03	How many crewmen are typically working on a fishing vessel?
10	O04	Do you want to know in advance when there are whirlpools around when you're fishing?
11	O05	Would you like to receive advanced information on high and low tide?
12	O06	What types of alerts and alarms are received on communication equipment?
13	O07	Would you like to receive information on the potential fishing zone (PFZ) while fishing?
14	O08	Do you want a technology that will inform surrounding fishing vessels in case of battery or engine failure?
15	O09	What is the maximum distance and number of days spent in a fishing run?
16	O10	What is the average and maximum speed of the fishing vessel, and is there a difference in speed while fishing or searching?
17	O11	What are the expected challenges and concerns with installing new communication equipment on the fishing vessel, and are you worried about your job?
18	O12	What kind of real-time information do you need to share while fishing?
19	O13	What kind of fishing vessel is used for fishing expeditions?
20	O14	What are the strategies for maximising profit when selling fish at the shore?
21	O15, P01	How far are you getting cellular coverage at sea?
22	P02	Does your phone support 2G, 3G, or 4G cellular technology?
23	P03	Is it possible to have a video call with family while on a long fishing trip?
24	P04	Do you have the desire to communicate with family and others in coastal regions using specific instant messaging apps?
25	P05	What is the method for communicating emergencies to family and how can they reach you while at sea for fishing?
26	P06	What do you do during your leisure time while fishing at sea?

*E – Emergency, O - Occupation, P - Personal.

2.3.3. Build and test

Before conceptualising and designing an actual solution for the pressing challenges identified in the community, an detailed literature review was conducted to identify available communication technologies at sea, along with business-related solutions, their feasibility, and challenges. The literature review on communication technologies specifically focused on those suitable for providing long-distance communication, as well as on blockchain technology for addressing business-related issues.

Furthermore, a review of the literature on various technology adoption methods and social change factors, which would play a pivotal role in the design process, was also conducted. Based on the identified requirements, a feasible technological solution was designed *(the ODE)*, and the communication solution was developed, as discussed in Section 4.2.1. The designed solution addressing communication issues, including components such as nodes and antennas, was implemented in a laboratory environment. In the subsequent phase, the research team tested the implemented solution to ensure it performed as expected.

2.3.4. Deployment, training, and validation

The solution underwent an initial pilot deployment on three fishing vessels for extensive testing in the ocean environment with the fishermen's help. Researchers accompanied fishermen on these trips, providing guidance on system usage and assisting with rotating the vessel's antenna to establish connectivity. Careful consideration was given to the deployment of various modules on the vessels to minimize disruption to the fishermen's work. Following numerous rounds of testing, the solution's equipment was installed on an additional ten fishing vessels over a two-year period to assess user adoption. During this phase, fishermen with the installed equipment received comprehensive training sessions to enhance their understanding of the system's benefits. These sessions ensured user familiarity and efficient use of the equipment, contributing to the social change model detailed in Section 4.4. The specific training methods employed are as follows.

1. **In-vessel Training:** Researchers visited fishermen on their fishing vessels before they embarked on fishing trips. They explained and provided training to the vessel captain and other crew members on how to use the ODE communication system and mobile application, outlining the necessary steps to ensure the system functions effectively.
2. **User Manual:** Recognising the need for users to remember the steps for system operation, a user manual in the local language (Malayalam) was prepared and distributed to each fishing vessel for user convenience.
3. **Outreach Activities:** Several outreach activities were conducted to update and raise awareness about the developed solution and its advantages. This included visits to fisheries schools, to educate the new generation of the community, and outreach to fishermen's families as well as the self-help group members to provide a deeper understanding of the solution.

In the subsequent validation phase, three focused group [28] discussions, each with a minimum of ten participants, were conducted to gather feedback on the solution. This phase was crucial for refining the solution in the next stage.

2.3.5. Update and improvement

Besides the sessions conducted during the validation phase, an additional six rounds of focused group discussions with users of the solution assisted the research team in continuously enhancing the solution. These discussions took place in various settings based on the situations: some meetings were held on the fishing vessels with the captains and crewmen, while more formal meetings occurred between the entire research team and stakeholders such as fishing vessel captains, business managers, boat owners, etc. Each discussion session involved between four to ten participants cooperating with the research team. The participatory approach also helped the team understand the additional requirements of the fishermen, focusing not only on technological aspects but also on user-friendliness and ease of use. The update and improvement processes were particularly crucial for the community to adopt the proposed solution.

During the pilot deployment phase, nine focused group discussions were conducted with fishing vessel captains to gather feedback on the challenges faced while utilising the proposed solution and to receive suggestions for making it more convenient for them. The close interaction with the stakeholders helped to improve the design on antenna placement, antenna rotation, finding a suitable location for the controller box inside the boats' wheelhouse, and efficiently wiring the required cables. In the re-design process of the solution, the team benefited from more frequent focused group discussions with selected fishermen and fishing vessel owners who participated in the initial deployment and testing phases. These focused group discussions also aided in assessing the community's digital literacy, digital capacity, and alternative skill sets. Fig. 4 illustrates the methods employed by the research team during the various phases of the study. It also depicts the achieved objectives of each method. The figure delineates the process sequentially, starting from gathering information about the community to delivering a solution based on the identified requirements. It provides a different perspective on the ODE development, showcasing where in the process digital capacity-building was delivered.

2.4. Sustainable social change

This study complies with the three pillars of sustainable development, environmental, economic and social pillar from different perspectives [36]. To comply with the environmental pillar, the reliable and transparent data records on the blockchain database (ledger) enable the policymakers and environmental activists to have an accurate picture of the exploitation of the marine ecosystem at any time so they can make informed decisions when needed. The ODE significantly bolsters the social aspects of sustainable development through several key strategies. First, it empowers fishermen by reducing their vulnerability to exploitation by middlemen, fostering a more equitable fishing environment. Second, ODE prioritises active engagement and participation from the community, recognising their role in its success. Knowledge sharing is also central to ODE's approach, as it actively works to improve knowledge and awareness among community members. Furthermore, social inclusion is a core principle throughout the entire co-design process of ODE. Ultimately, by empowering fishermen, ODE contributes to increased livelihood resilience for the entire community. Additionally, the system has the potential to reduce health risks encountered by fishermen during voyages.

Following an in-depth examination of the community's challenges and an analysis of their unique needs and characteristics, a comprehensive suite of technological solutions has been developed. This digital ecosystem is tailored to facilitate their digital empowerment. To ensure the sustainability of the proposed digital ecosystem, it was crucial to cultivate motivation for technology adoption within the community and enhance the digital proficiency of stakeholders, such as fishermen. This would enable them to effectively utilise the system to enrich their livelihoods and ensure safety during their voyages. The sustainable social change model applied in this study comprises two main sets of strategies. The first is aimed at motivating the community to accept the necessary social change, while the second focuses on enhancing their capacity and confidence to adopt and utilise the proposed solution for addressing their safety and livelihood issues. The methods employed to boost motivation included.

- Social Influence: Social influence, broadly defined as the impact of others on our behaviour and choices, is a key factor in technology adoption among the fishermen. In this case, it includes their

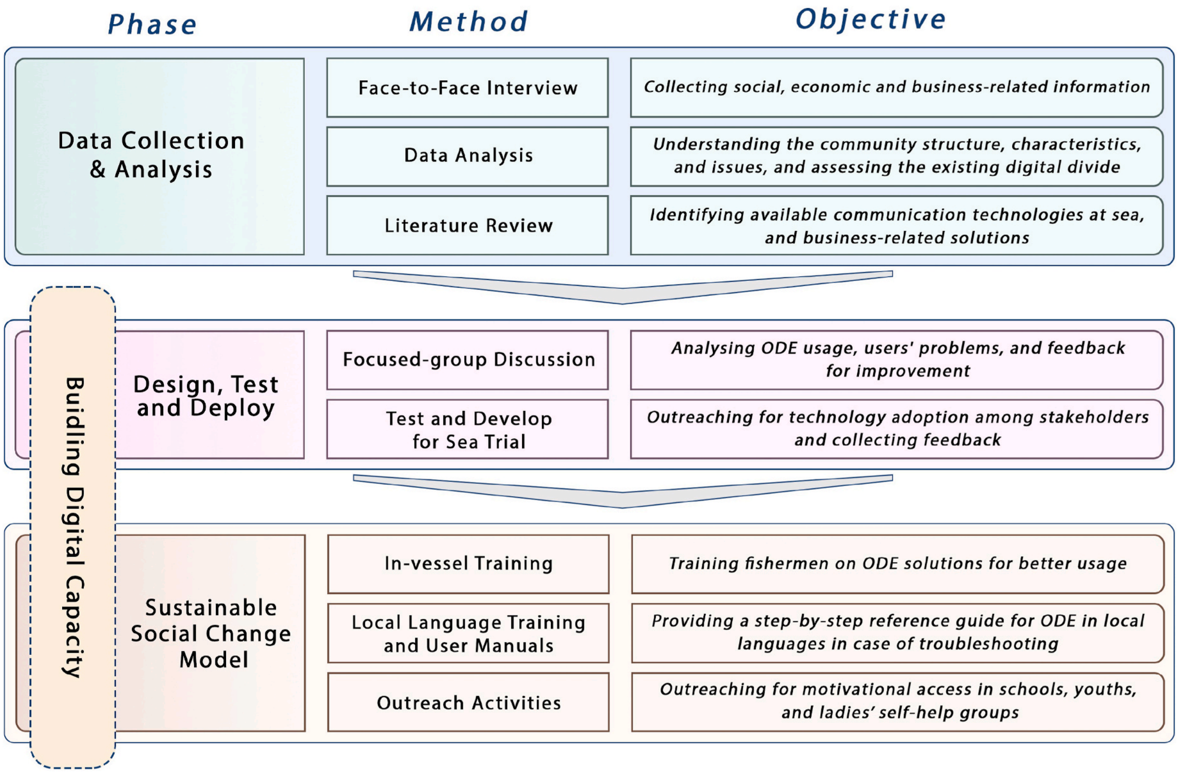

Fig. 4. Methods used for requirement collection and digital capacity building based on the different phases of the study.

perception of their peers' technology use [37,38]. This project leveraged social influence to enhance the motivation of fishermen by involving family members, peers, and community leaders. Community leaders were particularly effective in persuading fishermen to try the proposed system during their voyages. To further bolster trust and encourage adoption, the highly respected chancellor of the university, who himself hails from the fishing community, played a key role in communicating with local leaders and fishermen about the system's purpose and capabilities. Additionally, several other researchers and staff from the university, with roots in fishing communities, were involved in encouraging stakeholders to utilise the proposed technological solution.

- Incentivisation: Researchers provided incentives such as real-time communication while at sea, free Internet access, access to market information for informed decisions, and availability of infotainment to encourage stakeholder system usage. Additionally, the research team conducted video calls from the ocean to the fishermen's family members on shore to boost their motivation. This was especially impactful since the fishermen typically have no means of communication with their families for an average of a week while they are at sea.

Studies show that a community's belief in their ability to use a technological solution – possessing the necessary skills, knowledge, and tools – is crucial for adoption and utilisation [38]. Furthermore, sustained use fosters habit formation and reduces user anxiety, ultimately increasing the likelihood of long-term adoption [38]. The research team focused on enhancing the users' mental capabilities and technical proficiency to achieve this sustained adoption of the proposed digital ecosystem.

Methods utilised to enhance these capabilities and proficiency in the required skill set of the users include.

- Educate: Researchers conducted several awareness sessions on the benefits of technology use and the advantages it brings to fishermen, their families, and vessel owners. Researchers have done several vessel visits and one-on-one discussions with fishermen on the benefits and incentives they receive from learning how to utilise the system. The interaction was also used to understand their underlying beliefs, the skill sets to be built to operate the system, and the proper utilisation of the technology.
- Train: To ensure stakeholder proficiency, training sessions were conducted in two phases: onshore before fishing trips and offshore during voyages. These sessions focused on equipping participants with the skills to operate the communication equipment on their vessels and utilise the OceanNet mobile application on their smartphones. The researchers meticulously covered a range of topics, including operating the communication device, remotely controlling antenna rotation, interpreting signal strength readings, identifying optimal antenna positioning times, recognising base station locations, and maintaining the system onboard. These comprehensive training sessions were repeated multiple times before the fishermen embarked on independent fishing trips, ensuring they could operate the technology without researcher accompaniment.
- Build Confidence: Training fostered a supportive environment where researchers were impressed by the fisher-men's eagerness to learn the new technology. They actively encouraged independent use of the communication equipment and software, assuring participants of ongoing support whenever needed. To further empower the fishermen and address any technology anxiety, researchers embarked on several fishing trips alongside them. During these voyages, the fishermen were guided through using the system for communication, including services like Skype, social media, and instant messaging. Researchers provided clear demonstrations and explanations, ensuring the fishermen felt comfortable and confident utilising the technology.

The result of this social change model implementation for the adoption and usage of the technology, their feedback and the detailed observed changes in users over several months have been explained in section 4.4.

3. Literature review

Bridging the digital divide remains a significant challenge for empowering coastal fishing communities. Several factors contribute to this challenge, including the lack of long-range communication systems, solutions for inclusive stakeholder engagement, and successful interventions to enhance technology adoption. This section delves into these key challenges and explores existing literature to identify multidimensional factors and critical research gaps.

The digital divide refers to the disparities in Information and Communication Technology (ICT) access, usage, and outcomes, posing a major societal challenge [39]. This issue significantly hinders the sustainable development of communities. The digital divide can be addressed at three key levels [40].

- Level 1: Digital Access and Internet Attitudes: This level focuses on disparities in access to the internet and the general attitudes towards its use within a community.
- Level 2: Digital Capacity, Skills and Usage: This level deals with the skills gap related to technology use and the actual use of technology within the community.
- Level 3: Beneficial Digital Outcomes: This level addresses the disparities in the positive outcomes derived from technology use within a community.

3.1. Digital access

The lack of digital connectivity has a significant impact on the economies of rural communities, particularly regarding communication at sea and its effect on the competitiveness of small-scale businesses [41]. Fishermen rely on various communication technologies depending on the communication scenario: (a) connecting with families or vessel owners on shore; (b) communicating with nearby "buddy vessels"; and (c) long-distance emergency communication. Unfortunately, no single affordable technology effectively addresses all these needs. For communication between buddy vessels at sea, fishermen currently utilise VHF (Very High Frequency) and UHF (Ultra High Frequency) radio communication systems [8,42]. These technologies are suitable for short-range communication, typically within a few kilometres of the shore, but are susceptible to interference from various sources like other radios, electrical equipment, and even the metal construction of the fishing vessels themselves. Additionally, the Earth's curvature and obstacles like the sea surface can limit their range. Furthermore, bad weather conditions such as heavy rain or lightning can disrupt their performance, rendering communication unreliable or even impossible [43,44].

Existing solutions for communication with families and boat owners on shore, such as 4G/5G cellular networks, are limited by range, typically reaching a maximum of 15 km from the coast [45]. Cellular operators are hesitant to invest in expanding coverage due to the low population density in these coastal villages, resulting in a poor return on investment (ROI) [45,46]. While technologies like maritime satellites, the Automated Identification System (AIS), and Starlink offer high-throughput communication capabilities, their high costs render them unaffordable for many fishermen. Additionally, Starlink satellite services face limitations in remote areas due to the high cost of the solution and, as of December 2023, regulatory hurdles [47]. These regulatory challenges, coupled with the need to install user terminals (UTs) on fishing vessels, further restrict the feasibility of Starlink for a significant portion of the fishing community.

UAV (Unmanned Aerial Vehicle) drones have also been explored as potential solutions, acting as relays or aerial base stations to connect to satellites [48]. However, the high costs associated with purchasing, operating, and acquiring the skills necessary to operate these drones for communication purposes pose a significant barrier. Furthermore, bad weather conditions can disrupt their functionality, and commercial use of drones often requires special licenses or permits. Since typical fishing voyages exceed 100 km, existing affordable technologies struggle to provide connectivity beyond cellular coverage areas. This results in a communication blackout for several days during each fishing trip, which contributes to the heightened risks associated with being at sea. Consequently, there is a pressing need for the development of low-cost, low-power, long-range communication systems that enable real-time communication for fisherfolk communities [8].

3.2. Digital capacity and usage

Research indicates that digital technology use can improve people's quality of life [49]. However, the digital divide creates inequality in Information and Communication Technology (ICT) use within rural communities. Digital capacity, the second level of the digital divide, refers to the skills required for tasks such as information searching, using collaborative software like WhatsApp and Skype, basic internet navigation, and overall ICT experience and use [50]. These digital skills are crucial for maximising the benefits of available services and technologies. Unequal skills and knowledge in handling internet devices are termed *'digital inequality'*. This inequality encompasses a user's autonomy (referring to the user's ability to make independent choices regarding the use of digital technologies), usage patterns (meaning the frequency of digital device usage), and overall skill level. Additionally, factors such as low self-efficacy, computer anxiety, and other psychological influences are considered to contribute to digital inequality [39].

Motivational access, another key factor, refers to the desire to have a device and connect to ICT [51]. Similar to the previously mentioned factors, motivational access inequality can hinder users from adopting specific technologies. Motivational access is considered to be influenced by social, cultural, mental, or psychological factors, and can be rooted in early social experiences that may make the internet seem unappealing to low-income and low-educated individuals [52]. The motivational access divide includes a lack of motivation to access ICT, learn new technologies, or have any interest in IT-related topics. However, even with limited physical access to ICT, high motivational access can encourage individuals to develop stronger skills in using digital technologies [53].

Varma et al.(2021) pointed out that the critical challenge in designing a solution is to engage the community freely, understand the challenges faced by the community, such as water scarcity in the summer, and then decide on appropriate technological solutions [54]. They have used a participatory co-design approach for enhancing digital capacity, and this method is used to identify and solve their water crisis collectively, involving ice-breaking sessions, mind maps, group sketching, and brainstorming. The study conducted by Ajith et al. (2022) pointed out the need for a phased approach for implementing the *Jivamritam* - drinking water solution in rural areas, through capacity development and technology transfer [55]. The study addresses challenges such as imparting knowledge, resource allocation, technology selection and provisioning, community empowerment, water governance, and local government support. They addressed these issues by establishing a Community Empowerment Model through engagement, co-design, and ownership at individual, collective, and practical levels, aiming for a sustainable outcome of pure drinking water for the community. Their interventions lead to raising awareness, designing a user-friendly solution with minimal interventions, instilling a sense of ownership, and also making them aware of the solution's constraints and cost implications.

3.3. Digital outcome and technology adoption

According to the International Telecommunication Union (ITU), the assumed outcomes of digital skills for the global population are the ability to use ICTs to achieve favourable outcomes in the day-to-day life of themselves and others [56]. However, the outcomes in one domain may not necessarily correlate with outcomes in another, highlighting the need for more research to draw conclusive results from existing studies and their impact on intended outcomes [56]. Additionally, inequality in users' capacities to exploit ICT can significantly affect individual outcomes and benefits [39]. For instance, a study focusing on students' performance in rural and urban communities in the context of e-learning revealed that the difference in the digital divide is mainly due to a lack of parental support and intrinsic motivation [40]. This lack of support and motivation decreases the intended benefit of ICT, affecting the digital outcome. In another study, a community engagement approach based on the theory of change was successfully adopted, using peer educators as mediators of knowledge transfer to create a supportive environment at both household and community levels for a better digital outcome [57].

Adopting digital solutions and moving toward digitisation play a crucial role in achieving sustainable development goals across multiple sectors [58]. The lack of knowledge or skills to use technology leads to poor adoption of technology [41]. According to the research by Al-Emran et al. (2023), adopting technology is not an immediate process, as it requires non-technological behaviour changes [49]. The study presented by Hwang et al. (2023) explores the roles of critical factors based on social cognitive theory such as social, personal cognitive, and the commitment to change approach in e-vehicle adoption by the community [59]. This study highlights that social transformation requires a change in individual perceived motivation. However, individuals often exhibit inertia in adopting new services or products and tend to stick to familiar ones. The study also reports that resistance to change, lack of understanding, and trust issues act as significant barriers to the adoption of AI in the supply chain area [60].

An extended version of the Technology Adoption Model (TAM) for mobile health services has been proposed [61], incorporating six new variables. These variables encompass technology anxiety, social influence, trust, perceived risk, perceived physical condition, and society's resistance to change. Technology anxiety pertains to the extent individuals experience problems while adopting a new technology [61]. Social influence plays a significant role in shaping the decision to adopt the technology and also impacts the perception of usefulness (PU). Research has shown that social influence fosters positive attitudes and behavioural intentions. For instance, in a study by Yu et al. (2017), it was found that observing individuals within one's social circle using an interactive communication tool strongly motivated others to adopt the same ICT tool [62]. Social innovation studies recognise innovation as a driving force for societal improvement and positive change [63]. Additionally, social influence plays a crucial role in technology adoption, enabling individuals and society to embrace new technologies [64]. Consequently, Internet and communications technologies are widely embraced in individuals' daily lives due to social influence.

Creating new technologies for low-literacy groups requires in-depth research into their lives, relationships, and concerns, and a continuous partnership with primary users. For mobile technology targeting older people, consideration of their physical and cognitive profile is essential [65]. Involving users throughout the design process allows for progressive testing of the solution and facilitates fine-tuning of the system, thus strengthening the design [66]. One of the major barriers to the success of any new information technology solution is the lack of user acceptance [30,67,68]. User acceptance refers to the readiness of a user group to use Information Technology (IT) for the task it is meant to support [69]. Therefore, user acceptance is considered a crucial factor in deciding the success or failure of any information system project [30, 70].

Various technology acceptance methods and their limitations have been discussed in several studies [68,71–75]. Among the key factors contributing to user acceptance of technology is the user's confidence and the ease of use of the product [76]. Previous research indicates that users are sometimes hesitant to adopt information systems that promise impressive performance gains [77]. Researchers have explored a wide range of issues related to this topic, covering individual user characteristics, their cognitive styles, internal beliefs, and impact on user behaviour [78]. User acceptance has also been viewed as a function of user participation in system development [79]. Perceived Ease of Use (PEU) and Perceived Usefulness (PU) play significant roles in developing attitudes towards technology adoption [67,80–82]. PEU encompasses various factors, including the user's self-efficacy and the complexity of the interface [83]. The impact of technology can be measured based on its acceptance [83].

Studies have demonstrated that digital habits and digital skills help to move with the current digital era, and they have the potential to transform the community [84,85]. Because digital transition impacts humans on their cognitive level, individual level, and social level [84], Internet skills and experience even protect people from digital exclusion. The current digital technologies are changing individuals' social, behavioural, and cognitive development due to their highly digital habits [85]. Additionally, technologically enabled social structures are emerging, facilitating fundamental changes in business practices.

Another study explored different factors that affect the user's intention to adopt new consumption behaviours required for adopting smart grid technologies through the use of the Theory of planned behaviour (TBA) framework, which is an extended model of the Theory of reasoned action (TRA) [86]; both models affirm that individuals' behavioural intention generally leads to their particular behaviour. Similarly, any change imposed on users can induce resistance, and it is a normal response to any innovation. The study also suggests that behavioural beliefs and attitudes can increase positive attitudes and facilitate adoption, as attitude is a factor that leads to adoption intention. The study suggests three interventions: education, communication, and information initiatives. The findings highlight that communication and information initiatives must focus on content related to specific beliefs [86].

A study reported factors influencing the acceptance of telemedicine services by the rural population of Pakistan. They have used TAM as the framework and derived factors linked to the usage intention [87]. The research team adopted a face-to-face interview method and used the Partial Least Squares (PLS) method to analyse the collected data. Research suggests that usage intention is a function of several factors, including PU, PEU, social influence, facilitating conditions, and factors such as trust, technological anxiety, perceived risk, and resistance to technology [87]. Another research focused on adoption intention, highlighting the importance of three types of access, mental access, material access, skill and usage access as the significant contributing factors towards the adoption of ICT among rural women [88]. They point out that adopting ICT can lead to innovation, and adoption intention will boost their entrepreneurial orientation. They used a Structural Equation Model (SEM) to validate and test the model.

Furthermore, in addition to considering the perspective of technology adoption, it is crucial to take into account the dimensions and factors necessary for facilitating social change towards technology adoption. According to the literature, there are several dimensions to social change such as the pace of change [89], the scope of change [90], the direction of change either progressive [91] or regressive [92] directions, the level of disruption, revolutionary [93] and evolutionary (gradual) [94], the intentionality of change, planned and unintended changes [95,96], and distribution of benefits of change [97] to name a few. There are also several key factors to social change realisation such as education level, social influence, and capacity building [98–100], time and duration of engagement with the community, participative action, and local social networks [101,102], human tendency to change [99].

3.4. Identified research gaps

The key research gaps derived from the detailed analysis of the existing literature are.

- Limited long-distance communication solutions hinder real-time offshore connectivity for fishing vessels, restricting their digital access and hindering the full potential of digital technologies for these communities.
- Existing research on digital inequality often overlooks the specific challenges faced by fisher communities. A more in-depth assessment is needed to understand the factors that hinder digital capacity building within these communities.
- A critical gap exists in understanding how enabling access to tailored digital services can enhance technology adoption for improved safety and livelihood outcomes.
- The literature extensively explores how technology shapes social structures. However, a gap exists in investigat-ing the role of community stakeholders as technology adopters in this process.

This section presents the findings of the study, including the analysis of data collected from the coastal fishing community. It details the architecture of the designed digital ecosystem, which aims to empower fishers through digital access and the ability to utilise digital services for enhanced safety, communication, and livelihood opportunities. Finally, the section explores the implementation of the proposed solution and the sustainable social change model employed in the study.

4. Results

4.1. Data analysis outcome

The community in this area is more susceptible to ocean-based disasters such as coastal floods and tsunamis [103]. The local people in this coastal region exhibit distinct behaviours, norms, practices, and cultural characteristics, reflecting their unique relationship with the ocean environment. They frequently face the unpredictable behaviour of nature, leading to significant challenges and hardships. During the initial assessment of the community's engagement process, the research team discovered the profound digital divide specific to the fishing community in Kerala, India. Most of the fishermen and their families are not digitally empowered to use the Internet, smart devices, and applications for their daily communication, information retrieval, and entertainment. Several factors such as mixed level of education, lack of smartphone usage, lack of interest in ICT, technology anxiety, and lack of digital skills contribute to this divide, with the primary issue hindering the safety of fishermen at the ocean being the lack of communication and internet facilities beyond a certain distance from the shore. Existing communication opportunities are limited to only a few kilometres or are economically infeasible for the fisher community. Some other solutions may require special licenses, and many are not viable in the harsh ocean environment. The detailed findings from the conducted interviews with the community members are as follows.

- *Fishing vessel operations*: The face-to-face interview findings revealed that fishermen typically embark on fishing expeditions, sometimes lasting for up to fifteen days and, in rare cases, up to one month, depending on their catch and available fuel. These journeys involve a crew comprising the captain or *'srank'* (driver), and workers assigned and tasked with capturing fish using the net and sorting various catches and bycatches. It was observed that a few vessels have a single individual who fulfils the roles of both captain and driver. The decision-making process during fishing operations rests primarily with the captain, including trip duration and contacting the manager or seller at fish landing centres. Additionally, they are responsible for navigation, locating fish types, and communicating with other fishing vessels using the VHF (Very High Frequency) radio within short distances. Usually, the crew size varies between 10 and 12. The size of the fishing vessel also varies between 80 feet and 110 feet. There are two types of fishing vessels, one made of wood and fibre and the other one made of metal. They fish below the Arabian Sea area and the fish gears they use are primarily of two types such as *bottom trawl* and *midwater trawl.* However, based on the mouth opening of the trawl they are grouped into beam trawl, otter trawl, and bull trawl.
- *Communication challenges:* The face-to-face interview findings revealed that fishermen typically embark on fishing expeditions lasting up to fifteen days, and in rare cases, up to one month, depending on their catch and available fuel. These journeys involve a crew comprising the captain, also referred to as the *'srank'* (driver), and workers tasked with capturing fish using nets, sorting catches, and bycatches. It was observed that some vessels have a single individual fulfilling both captain and driver roles. The decision-making process during fishing operations rests primarily with the captain, including trip duration, contacting managers or sellers at fish landing centres, navigation, locating fish types, and communicating with other fishing vessels using Very High Frequency (VHF) radio for short-distance communication. Crew size typically varies between 10 and 12 members. Fishing vessels range in size from 80 to 110 feet and are constructed from either wood and fibre or metal. The primary fishing area is the Arabian Sea, and the main fishing gear types are bottom trawls and midwater trawls. These trawls can be further categorised into beam trawls, otter trawls, and bull trawls based on the mouth opening design.
- *Smartphone usage and technology gaps*: The study revealed that the majority of fishermen operating fishing vessels are middle-aged or older men who are unfamiliar with the benefits of using smartphones. Currently, smartphones are primarily used for making voice calls and sending text messages. Among the younger generation of fishermen, some carry smartphones, but these are often encased in plastic bags once they reach the limit of cellular coverage, as the phones become unusable beyond this range. The interviews further indicated that most fishing vessels lack Automatic Identification System (AIS) support or satellite communication due to the high costs associated with acquiring and operating such technology. Fishermen expressed a strong desire for alternative communication methods to ensure more reliable and efficient communication at sea. Additionally, a few fishermen expressed interest in using communication methods to connect with their families while at the ocean, with children in their families particularly keen on maintaining communication during their fathers' absences.
- *Digital divide and lack of access to digital services*: The study highlighted the fishermen's struggle to access information from the Indian National Centre for Ocean Information Services (INCOIS), particularly regarding Potential Fishing Zones (PFZs) and other relevant alerts. This lack of connectivity often results in receiving such information too late to be practically useful. Furthermore, the research revealed that many fishermen expressed a need for awareness about the digital services provided by INCOIS, including weather forecasts, high sea wave alerts, temperature updates, and fishing zone information. The absence of connectivity at sea creates a distinct lifestyle for these fishermen compared to nearby villages. The majority of fishermen lack experience using smartphone applications such as internet banking, mobile banking, UPI transactions, instant messaging, and social media for connecting with family and friends. Similarly, they have no prior experience using safety-related services like INCOIS alerts and other weather information. This lack of digital access creates a sense of isolation from the outside world and contributes to a different way of life compared to those residing across the lagoon that separates this community.
- *Secrecy and competition*: During a closed group discussion, a fisherman emphasised the need for confidentiality regarding certain

fishing information, such as the location of identified fish schools, to avoid competition with other vessels. VHF channels currently used for communication present a challenge in maintaining secrecy, as others can easily overhear such information. The fishermen also highlighted the difficulty in conveying catch information to fishing vessel managers in a timely manner. This information is crucial for facilitating the selling process to third-party buyers in fish landing centres, where auctions determine the final price. The lack of timely communication between managers on shore and fishermen at sea limits their ability to capitalise on these auction opportunities. Furthermore, the absence of real-time information on fish market demand from the shore makes fishermen entirely reliant on intermediaries for the fish-selling process. This reliance can negatively impact their profit margins. Access to communication and internet connectivity would empower them to directly communicate critical information with various stakeholders throughout the process, potentially increasing their profits. The fishermen in this area typically catch over 30 different fish species. Some of the most common and commercially valuable catches include various types of Sardinella, Mackerel, Seer fish, Black Pomfret, Tuna varieties, Pink Perch, and Indian Anchovy.

- *Community structure and influence*: The various stakeholders involved in fishing, from processing and selling to distribution, exhibit a strong interconnection, working collaboratively to sustain their livelihoods. This collaborative spirit extends beyond the immediate community, as evidenced by the shared use of fish landing centres with nearby villages. A strong sense of community is evident, with daily interaction among members and engagement with nearby villagers to make occupational decisions.
- *Safety concerns*: Safety emerged as a paramount concern during fishing expeditions. Fishermen reported facing significant risks from large cargo ships traversing their fishing grounds and resting areas, potentially leading to accidents and chaotic situations. The current AIS and VHF systems appear inadequate in effectively preventing collisions or providing timely warnings. Compounding this issue, many fishing vessels lack AIS entirely, leaving them vulnerable to the lack of emergency notifications during situations like cyclones, due to the absence of connectivity. Fishermen further highlighted recurring concerns such as vessel engine troubles, fuel depletion, capsizing incidents, and unintentional straying into shipping channels, all of which pose significant risks.

Table 2 outlines the specific digital access needs identified through interviews and other methodologies. Addressing these needs and providing suitable technological solutions has the potential to significantly improve the fishermen's efficiency, safety, and overall fishing experience. The findings from these methodologies form the foundation for designing and developing the proposed digital solution. Recognising the existing digital divide, a co-design approach was employed to create the solution. The objective is to empower the fishing community by enhancing their livelihood opportunities and resilience while bridging the digital gap. This research introduces a comprehensive integrated digital ecosystem called the OceanNet Digital Ecosystem (ODE). This digital ecosystem is meticulously tailored to meet the digital access, digital capability, and digital outcome requirements of the fishing community, ultimately aiming to foster sustainable and resilient fishing communities. The following section elaborates on the various aspects of this unique digital ecosystem.

Table 2
Digital access requirements of the community.

Emergencies	Occupational	Personal
- Real-time localisation and tracking for rescue	- Sea state information	- Daily phone calls or messaging
- Remote health monitoring for emergency in case of illness and injury	- Potential fishing zone	- Internet and infotainment solutions with adequate bandwidth to the shore
- Critical weather, sea information and disaster alerts	- Disseminate fishing market price information for auction	- Emergency information contact
- Communication with port authorities	- Disseminate fuel and fish storage information	- Personal communication to the crew members of other fishing vessels
- Country border crossing alert	- Navigational and mapping information	- Communication with family members
- Peer-to-peer vessel communication	- Peer-to-peer vessel communication	- Communication with fishing vessel owner
- Ship to fishing vessel collision	- Logging of fish catch	- Communication with fishing vessel manager

4.2. Architecture of the proposed digital ecosystem

To empower the fishing community by enhancing their livelihood opportunities, and resilience, this research proposes a unique integrated digital ecosystem called the OceanNet Digital Ecosystem (ODE). The significant regional variations in digital service demand and supply highlight the importance of effective digital ecosystems [104]. The ODE integrates three key solutions to enhance safety at sea and strengthen community resilience.

4.2.1. Internet over ocean: a hybrid communication network

During fishing voyages, fishing vessels travel vast distances remain at sea for extended periods and lose connectivity from the shore. To overcome this challenge, the solution leverages the fishing vessels themselves as relay nodes in the ocean, effectively extending the communication reach. To achieve this, a heterogeneous multi-tier ad hoc network architecture has been integrated to expand the limitations of existing communication networks and establish the foundation of the OceanNet solution. The OceanNet communication system utilises long-range Wi-Fi to establish both Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) networking, enabling network access deep within the ocean. Fig. 5-(a) illustrates the network architecture of the fishing vessel communication system. Based on a detailed technical evaluation [45], Long Range Wi-Fi (LR Wi-Fi) was chosen to provide backhaul internet connectivity, making the V2I network possible. Wi-Fi technology is also used for communication between fishing vessels via V2V networking, allowing fishermen to access the internet through their smartphones.

The implemented network architecture consists of three distinct tiers, each offering varying communication capabilities and incurring different installation costs. This tiered structure allows boat owners to select the equipment that best suits their financial situation and vessel size. The *Supernode (SuN) tier* represents the most resource-intensive node configuration, featuring an AR and two ABEs installed on the vessel. *The Adaptive Node (AdN) tier* equips vessels with both an AR and Adaptive Backhaul Equipment (ABE). While the ABE is more expensive than the AR, it offers a significantly extended communication range. The last one is the *Access Node (AcN) tire*, which utilises a relatively inexpensive Access Router (AR) installed on smaller vessels. The AR functions as a Wi-Fi router with a communication range of 100–200 m. All these nodes leverage extended communication capabilities by integrating V2V and V2I networking concepts. The V2V network provides internet connectivity among fishing vessels in the ocean. V2I communication is established between SuNs and AdNs, while V2V communication occurs between AcNs and both AdNs and SuNs. The V2I network provides offshore connectivity by strategically placed base stations with elevated heights. These elevated base stations offer improved line-of-sight and extended communication range. Automated antenna reorientation systems and directional beamforming techniques are employed to continuously track the location of the base station for optimal connectivity. The dynamic and evolving nature of fishing vessel locations creates a hybrid, self-organising network topology, facilitating

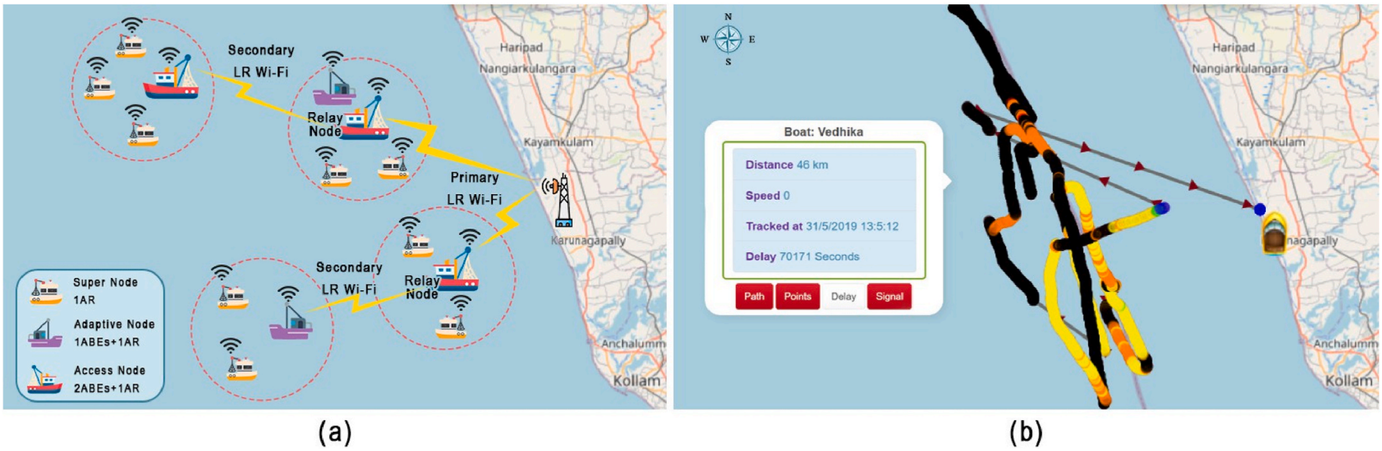

Fig. 5. (a)OceanNet network architecture for fishing vessel communication [105] (b)Web Application for localisation and tracking.

extended communication coverage across the ocean.

4.2.2. Mobile application for real-time fishing vessels tracking

Community engagement revealed the need for real-time vessel localisation and tracking when fishermen are at sea. Additionally, the fishing community expressed a strong desire for access to information on potential fishing zones (latitude and longitude information of fish availability) provided by INCOIS while at sea and showed interest in voice-over-IP calls, information gathering, and entertainment. All these user needs and functionalities have been integrated into the upgraded OceanNet Digital Ecosystem (ODE). This was specifically designed to foster motivational access, aiming to generate increased interest among community members in utilising the ODE.

Recognising the importance of perceived usefulness, the system prioritises real-time vessel tracking. A device installed on each vessel continuously transmits its GPS location, enabling the monitoring of the vessel's live position and associated connectivity parameters as shown in Fig. 5-(b), allowing visualization of a vessel's location and distance from shore. The web application user interface (UI) leverages the OpenStreetMap API to visualise these real-time location updates. Currently, both fishermen's families and vessel owners can utilise the software to track the live location of their vessels. Incorporating user feedback led to the development of characteristic features like icon-based design and multilingualism in later stages. This mobile application serves as a significant driver for digital skill development and motivational access.

4.2.3. Blockchain-enabled e-commerce platform for livelihood enhancement

Fishing communities face constant challenges from climate change (cyclones, floods, tides) and disasters (tsunamis). The 2004 tsunami devastated the Alappad community in India, causing social and economic hardship, highlighting the need for livelihood support [106]. Given the susceptibility of the fishing livelihood to climate change and market swings, building resilience is crucial to absorb these shocks and prevent further hardship [107]. The current fishing livelihood faces several challenges that limit their income and decision-making power.

The lack of communication and traditional first-come-first-serve auction system demands a physical presence at the port, limits their role in the process and makes them vulnerable to non-inclusive practices. The lack of digital skills and digital literacy restricts access to broader, potentially more profitable markets. Also, the current fishing industry lacks transparency and control for fishermen. Middlemen dominate the process, influencing prices, limiting market access (due to trust issues and reliance on intermediaries for information), and restricting fishermen's roles in decision-making and auctions. This dependence weakens their livelihood security and limits their ability to adapt to market fluctuations and access a wider customer base. A solution is needed that empowers fishermen by fostering inclusivity in decision-making, providing real-time market information, eliminating the need for intermediaries, and allowing fishermen to access a wider market while at sea.

To address these requirements, a blockchain-enabled solution has been devised to enhance engagement, inclusivity, and profit for fishermen. A blockchain-based digital bidding process (digital auctioning function) has been proposed to transform the centralised, middlemen-controlled auctioning process by providing crucial market fluctuation information on a tamper-proof blockchain ledger, ensuring high reliability and transparency [108–110]. All transactions will be managed by smart contracts through a decentralised mobile application (DApp). Unique digital identities track the sellers' and buyers' activities over the platform. Instead of cryptocurrencies, existing digital payment systems like UPI and bank transfers will be utilised for a better user experience, connecting with a wider range of customers and enhancing profit margins and livelihood opportunities. This approach mitigates over-dependency on intermediaries. Fig. 6 depicts the benefits of the proposed solution and the place of improvement in an auctioning process (green boxes).

The study revealed that several fishermen lack sufficient digital literacy or financial means to own smartphones. To overcome these challenges, dedicated smart warehouses need to be established at each harbour to facilitate trades via a digital platform [11]. Operators of these smart warehouses, known as Oracles, will input data about available fish products into the blockchain, shaping the supply chain management system for the fish market. The oracles can be selected from among the women within the community, promoting gender equality. The proposed solution provides fishermen with Internet access through a centralised approach and offers a decentralised digital market and supply chain management system, creating a hybrid design serving users via a smartphone.

In summary, the proposed blockchain-enabled e-commerce platform offers numerous benefits to fishing communi-ties. It revolutionises the traditional auction process, empowers fishermen to conduct real-time auctions at sea, reduces dependence on intermediaries, ensures transparency, and eliminates exploitation risks. The digital ecosystem provides comprehensive information on fish product availability, prices, and climatic conditions, enabling stakeholders to make dynamic and informed decisions. The integration of smart warehouses as Oracles enhances information inclusivity and shapes the supply chain management system, benefiting the fish market.

4.3. ODE implementation

The core of the project's design and implementation revolved around enhancing the community's digital capabilities and overall digital well-

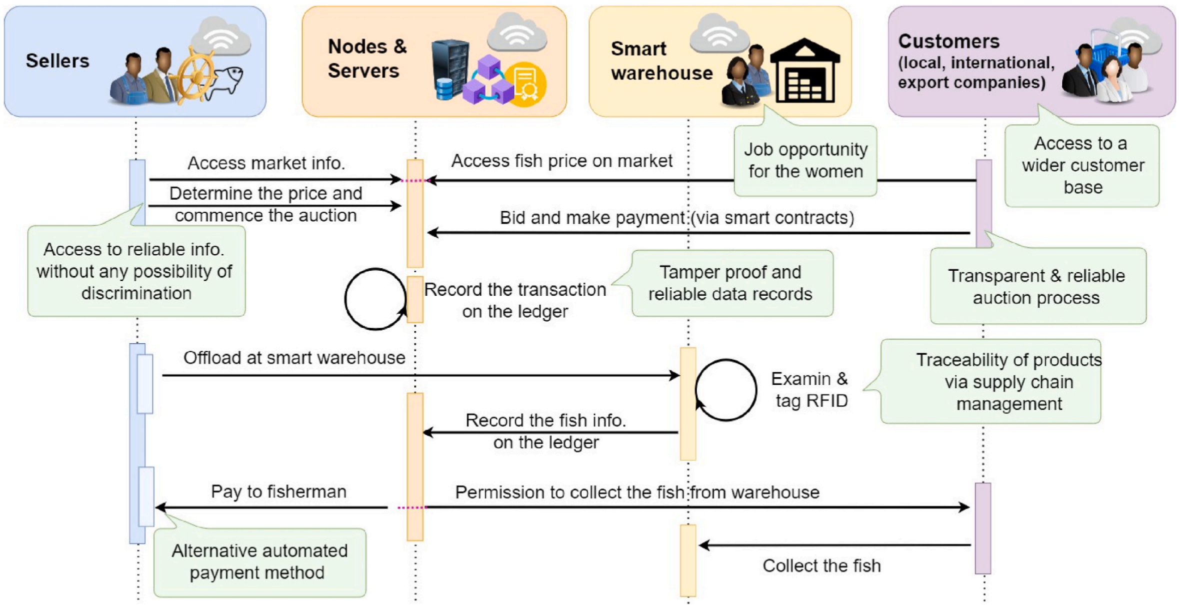

Fig. 6. The auction process, after the intervention via ODE.

being through an IoT-based digital ecosystem. Emphasis on solution acceptance, frequent usage, and ongoing community interaction was prioritized from the outset. During the community analysis phase, the research team conducted a comprehensive assessment to understand the stakeholder landscape. This included evaluating their current level of digital access and capacity, existing business practices, identification of influential stakeholders, and understanding the personas and challenges faced by the fishermen. This holistic approach ensured the solution would be aligned with their actual needs. Furthermore, the initial investigations also focused on identifying the various factors that contribute to the community's vulnerability to ocean-related disasters. Frequent engagement with community stakeholders proved instrumental in highlighting the need for a sustainable social change model. To ensure successful adoption of the OceanNet digital ecosystem, the project implemented capacity-building programs tailored to the community. These programs included in-vessel training sessions, the development of user manuals, and the strategic involvement of women's groups within the community.

4.3.1. Deployment

The solution deployment unfolded in stages, acknowledging the need to persuade the community of the system's benefits. Initially, three fishing vessels were equipped, targeting owners who recognised the value and importance of a vessel tracking system. The second phase expanded to four additional vessels, with referrals coming from satisfied owners and captains involved in the initial deployment. Positive feedback from these early adopters, particularly regarding instant messaging apps and voice/video call services, fueled discussions within the fishing community. This positive word-of-mouth ultimately led to the solution's adoption by the newly included vessels. Over the following year, the project expanded once more, bringing the total number of equipped vessels to fourteen.

The majority of vessels in this project are mid-sized, under 30 m long. Representing a significant financial investment for owners, the potential loss of a vessel can be financially crippling. Recognising this reality, some owners adopted the proposed vessel tracking system to enhance safety and security at sea. They perceived the system's ability to track vessels during routine voyages and provide crucial location information in case of emergencies.

Fishing vessel owners play a pivotal role in driving change, as their investment is on the line and they hold the ultimate decision-making power regarding system implementation. However, even with owner buy-in, securing the fishermen's active participation remains crucial. Several factors contributed to initial resistance among some fishermen, including concerns about privacy, technology anxiety, and the perceived complexity of using smartphones and the system itself, particularly among older crew members.

4.3.2. Field trials to validate the architecture

To test and evaluate the communication solution and its architecture, testbed-based experiments were conducted over the Arabian Sea. The equipment were integrated into a total of fourteen fishing vessels for pilot testing as shown in Fig. 7.

The experiments were conducted under various Douglas sea states (a system for categorizing wave heights and sea conditions) [111]. Table 3 and Fig. 8 depict the range at which communication was successful: over 50 km for V2I communication (vessel to shore station) and over 15 km for V2V communication (vessel to vessel).

The pilot test phase achieved a successful communication range of over 65 km between a vessel and the shore using the designed communication architecture. This performance held true even under extreme weather conditions. Currently, the system is implemented and functioning well in fourteen fishing vessels, with real-time data collection enabling the monitoring and analysis of fishing vessel activity [45].

Initially, the solution relied on a manually operated rotating antenna to establish communication with the shore. Since the base stations utilised directional antennas, optimal connectivity required the captains to physically rotate the vessel's antenna towards the base station. The research team trained the captains on this procedure, and the maximum achievable angular connection range was approximately 17 km. In response to user feedback, the system was upgraded to incorporate a remote-controlled rotating antenna system. This significantly improved user experience and ease of operation. To further simplify antenna positioning, a fully automated antenna rotation platform was designed and integrated into the solution. This upgraded system utilises GPS location data to automatically adjust the fishing vessel's antenna orientation towards the shore station, eliminating the need for manual or remote control. Upon gaining internet access, the fishermen explored various digital services. These included messaging applications like WhatsApp and voice/video calls through platforms like Skype. Additionally, they utilised web browsers like Google Chrome to verify their connection quality. Twelve fishermen participated in this testing phase,

Fig. 7. Testbed setup for the network architecture: (a) Base Station setup at the shore, (b) Fishing vessel as a node,(c) SuperNode acts as mobile BS and ABE, (d) Adaptive Node or ABE.

Table 3
Summary of six field trials conducted at the Arabian Sea during high tides.

Field trial date	Frequency (GHz)	# of Trawlers	Douglas seastate code (0–9)	Range (km) (shore to fishing vessel)	Range (km) (fishing vessel to fishing vessel)	Noise floor (dBm)	Signal strength (dBm)	Channel bandwidth (MHz)	Minimum Tx/Rx rate (mbps)
25/12/14	5.8	1	3	17.7	–	−92	−73 to −88	5	1.725/1.625
01/06/15	2.4	2	3	45.6	16	−99	−58 to −86	5	3/3
06/01/16	2.4	3	3	43.7	22.6	−98	−62 to −82	5	4.9/1.6
06/01/16	5.8	1	3	41.1	–	−98	−61 to −87	5	1.8/1.53
15/09/16	2.4	2	4	51.3	–	−98	−53 to −85	5	2/5
23/09/16	2.4	2	4	52	–	−98	−51 to −82	5	3/5
26/09/16	2.4	4	5	45	–	−96	−61 to −83	5	3/5

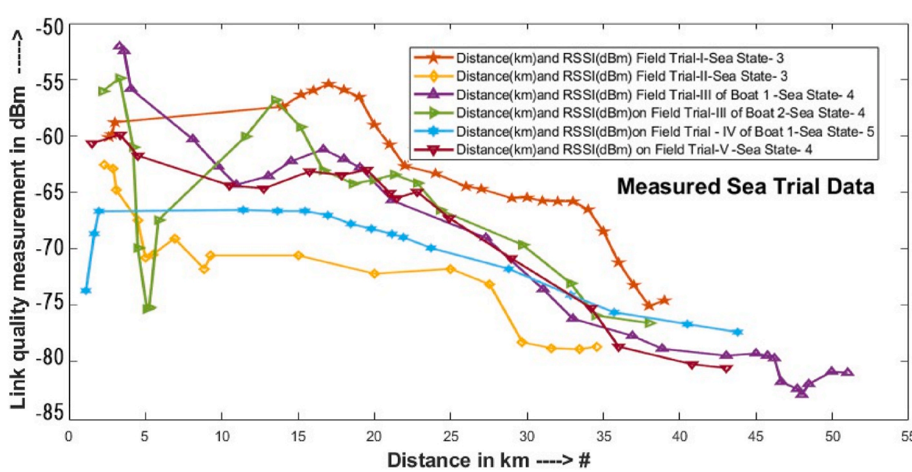

Fig. 8. Field trials summary (6 trials, 14 fishing vessels).

actively using voice and video communication services.

The project is currently in the process of deploying the communication solution to a wider range of fishing vessels, aiming to scale up its utilisation. Encouraging fishermen to adopt this system for safety and business improvement has proven to be a challenging but rewarding endeavour. The research team recognised from the outset that the success of this technological solution hinges upon ongoing community engagement throughout the design, development, and operation phases. Therefore, they committed themselves to fostering awareness at the community level. However, interactions with community members revealed several challenges hindering the project's goals. These included a lack of awareness about the benefits of digital services, limited digital access, and difficulties in forming habits of continuous usage. Additionally, the project encountered resistance due to a lack of social influence within the community to adopt new technologies. In general, rural communities often exhibit a lack of awareness and motivation to use digital solutions.

Designing a social change model for transforming this rural fishing community into a smart, digitally enabled one proved to be a crucial, yet highly challenging, phase of the project. Factors such as broad stakeholder involvement, community awareness-raising initiatives, and aligning the solution with the community's specific characteristics laid the foundation for the development of the sustainable social change model proposed in this research.

4.4. Sustainable social change outcome

The adoption of the proposed digital ecosystem relies on the continuous interaction of stakeholders with the technological solutions and systems developed for them. According to Dashkevych et al. (2023) [112], smart technologies are perceived as tools to achieve sustainability and improve the quality of life. Sustainability can be achieved when the proposed technology empowers the community by bridging the gap in digital capacity and digital outcomes. Community empowerment needs a holistic staged approach emphasising the digital capacity building of all the stakeholders involved in the community transformation. To achieve this goal, the study proposes a sustainable social change model for the adoption of the ODE for long-term community transformation through digital empowerment. Social change in this study refers to the transformation of the target society in terms of their conventional communication and business practices [113]. The digital outcome of the community is dependent on their utilisation of digital services for emergency communication, enhancing business opportunities, skill development, digital capacity, increased motivational access, and increased awareness. To achieve the community's digital outcome, a social change model was introduced.

The detailed analysis of the community helped to structure the social change and the ICT integration model envisioned to digitally empower the community which is shown in Fig. 9. The community stakeholders are at the core of the model, who had to be persuaded through various levels of engagement to appreciate the numerous opportunities they would benefit from the solution. The model has three major sections, and the outcomes of each are as follows.

- **Digital access** to various services over the Internet benefits the community whenever they need them. For instance, Internet access at sea provided them with real-time communication opportunities during their occupational voyages, such as VoIP and instant messaging. It also provided different services such as potential fishing zone identification (using satellite images), remote health monitoring services, weather forecasting, sea-state information, disaster alerts, localisation and tracking of fishing vessels, etc.
- **The collective digital outcome** achieved through various methods aimed to enhance user motivation and capability. Short-term outcomes observed in the community included their willingness to cooperate with the research team in installing the equipment on their

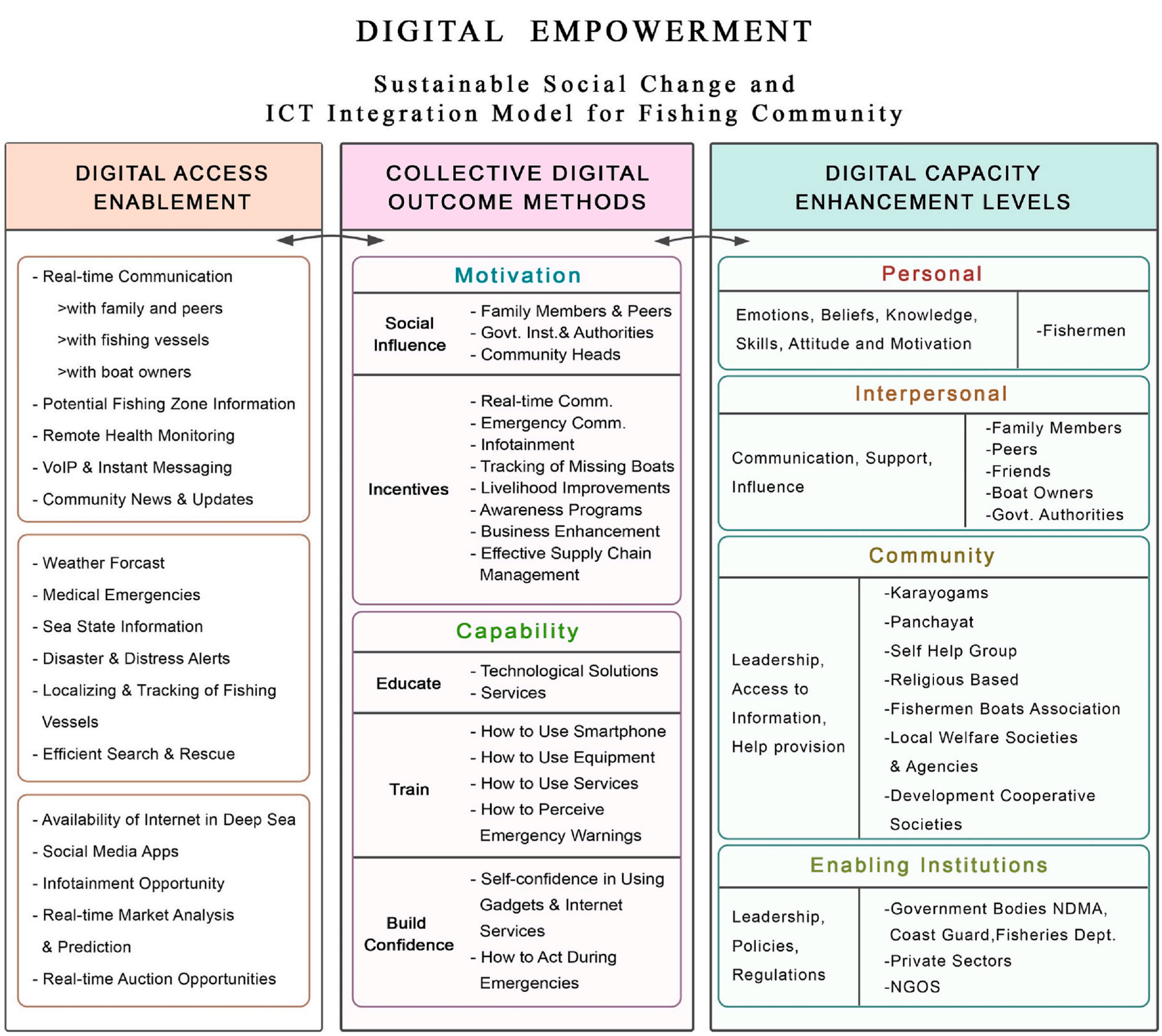

Fig. 9. Realising digital empowerment through sustainable social change model.

fishing vessels, as well as their participation in training sessions and testing the equipment during voyages. However, initially, the team noticed that fishermen would turn off the equipment when researchers were not present. One reason for this was their concern about power consumption of the equipment. They also raised questions such as, *"Will this system record our voices or listen to us if turned on?"* indicating a need for assurance regarding privacy while using the system. In the short term, a lack of experience with digital systems and services, along with a lack of trust in the proposed solution, were evident, resulting in minimal confidence among individual fishermen. Over the medium term, spanning eighteen months of usage, there has been a significant increase in their utilisation. Fishermen have begun accessing instant messaging services and providing feedback for improvements, indicating their growing acceptance of the solution and recognition of its usefulness. Their feedback and usage patterns demonstrate trust in the system and an understanding of its benefits. Based on the received feedback, the research team updated the user interface, adding features such as auto antenna rotation, resulting in increased usage. Users have expressed a positive perception of the system's utility, leading to more frequent use. Moreover, they have begun sharing their experiences, both positive and negative, with other fishermen and vessel owners, indicating development of a sense of ownership among them. With over 1000 h logged across 41 fishing trips, there is a clear trend of increasing digital utilisation and motivation to engage with the system while at sea. This transition from initial hesitation to embracing the solution and recognising its value is evident compared to the initial phase. The long-term outcome is yet to be studied and the research team is planning to perform it soon.

- **Digital capacity enhancement** within the fishing community proved to be a gradual process. While the research team didn't observe immediate and significant improvements in digital skills among fishermen and other stakeholders, their commitment and perseverance paid off over time. Frequent, well-structured training sessions were instrumental in developing essential digital skills and fostering a perception of ease of use among stakeholders. Active participation in these sessions not only enhanced their ability to use the system but also facilitated knowledge acquisition. This ultimately boosted collective and individual motivation, leading to a greater appreciation of the solution's usefulness. The positive impact of the project was evident at multiple levels within the community. At the individual level, training and education sessions enhanced user perception of the system. Users demonstrated noticeable improvement in skill development, motivation to use the solution, and overall receptiveness to the technology. Over time, positive beliefs and emotions surrounding system usage also emerged. Interpersonal communication between fishermen and vessel owners improved significantly. This enhanced support network fostered greater system adoption. At the community level, technology awareness rose, and community leaders and family members expressed strong support for the communication system. They recognised the value it provided in facilitating communication between fishermen at sea and their families back home. The involvement of family members, peers, and community leaders leveraged social influence to further increase motivation among fishermen. Community awareness sessions played a vital role in

educating stakeholders about the communication platform's necessity and its potential to enhance both safety and livelihoods. These sessions resonated particularly well with women and children, who were more enthusiastic about adopting the solution than other community members. For them, the ability to stay connected with loved ones at sea provided significant peace of mind. Similarly, awareness sessions conducted in schools fostered technology acceptance among the younger generation. Looking towards the long term, the project envisions fostering enhanced leadership skills within the fishing community. This will be achieved by providing improved access to information, empowering them to make informed decisions. Ultimately, this is expected to strengthen support systems for fishermen during emergencies. The following quotes from fishermen's family members exemplify their strong support:

> " … It is good to have a device to alert the fishermen if their boat is anchored in the route of large ships to prevent disasters from collisions … (A family member)"

> " … We would like to be able to talk with our family members (at the sea) in case of any emergencies at home … (A family member)"

Table 4 showcases the current state of digital empowerment within the community, as measured by the specific indicators during the research. As the table illustrates, most envisioned digital empowerment metrics have been partially achieved, with some reaching full realisation. For instance, access to digital services at sea has been fully achieved, while motivation and consistent system access are yet to reach their full potential. Indicators like confidence in using the solution, trust in its effectiveness, increased online time at sea, and improved digital skills all point towards an enhanced digital capability among fishermen. Additionally, their use of instant messaging services, their willingness to suggest solutions to others, and internet usage at sea demonstrate progress in community-wide technology adoption. Overall, these positive indicators suggest that the digital empowerment of the fishing community is on a positive trajectory.

The OceanNet digital ecosystem (ODE) addresses various categories of the digital divide, as illustrated in Fig. 10. Aligned with several United Nations Sustainable Development Goals (SDGs), the ODE contributes to SDG 9 by embracing innovative solutions and fostering resilient infrastructure. Additionally, it supports SDG 8 by promoting sustainable economic growth, SDG 2 by advancing food security and market information, SDG 3 by promoting well-being and safety, SDG 4 by facilitating lifelong learning and specific skill sets t bridge the digital divide, SDG 5 by empowering women in the community through managing the smart warehouses, and SDG 14 by providing the means for sustainable use of the marine ecosystem [114].

The ODE ecosystem helped to address the lack of digital access that existed in the study fishing community. The lack of digital capacity of the selected fishermen and vessel captains was enhanced through digital skill training, frequent communication and collaboration with them during the co-design and by focusing on the system's ease of use by upgrading the system based on the feedback provided by the users. This

Table 4
Progress of the envisioned digital empowerment of the community.

Indicator	Digital Empowerment Index	Status
Access to digital services	Digital Access	Achieved
Motivation and attitude improvement	Digital Capacity	Partially achieved
Confidence in using the solution	Digital Capacity	Achieved
Improve in technology anxiety	Digital Capacity	Partially achieved
Trust in the proposed solution	Digital Capacity, Outcome	Partially achieved
Frequent usage of system	Digital Access, Capacity, Outcome	Partially achieved
User engagement	Digital Capacity	Achieved
Increased online time	Digital Access, Outcome	Achieved
Improved digital skills	Digital Capacity	Partially achieved
Internet usage beyond 15 km	Digital Access, Capacity, Outcome	achieved
Feedback provision for system improvement	Digital Outcome	Achieved
Use of instant messaging service	Digital Outcome	Achieved
Suggestion of the solution to others	Digital Outcome	Partially achieved

enhanced overall digital resource awareness and established new digital practices. This enhanced the overall digital outcome of the community by providing options (see. Fig 10) for increased safety, profit management, and increased resilience by enabling the adoption of the technology by the users.

5. Discussion

The first research question focused on building a digital ecosystem to achieve real-time disaster risk reduction and enhance resilience to ocean emergencies and this underscored the necessity for a communication system at the ocean, while the co-design process further elucidated the requirement for a digital ecosystem to facilitate real-time disaster risk reduction and bolster resilience to ocean emergencies. The ecosystem was tailor-made for the community, and their involvement throughout the design, development, testing, and deployment phases underscored the necessity for a social change model to drive the adoption and usage of the proposed solution. This endeavour also addressed the second research question: How can the fishing community be empowered to leverage the developed technologies for improved safety and livelihood? Addressing the second research question required focusing on integrating technologies such as IoT devices integrated with a Long Range Wi-Fi communication for enabling V2I and V2I networking, inclusive mobile applications and blockchain to enable the community to access the Internet in the ocean for digital service access and build business opportunities and livelihood resilience. Similar to the process for addressing the first research question, strategies such as co-design and active engagement strategies strengthen the target community's digital skills and enabled them to utilise the OceanNet Digital Ecosystem (ODE) during their voyages.

6. Limitations

This research, while demonstrating valuable contributions, has limitations due to its scope. The implemented solution was a trial version deployed in a single fishing village. This approach restricts the generalisability of findings, as specific challenges within that community may not be universal. One such challenge is the fluid nature of crews. Fishermen and captains often switch between vessels, necessitating repeated training for new crew members on equipped boats. Similarly, vessel ownership can change hands, and new owners may not be as cooperative as the initial participants. Furthermore, the widespread use of wireless technology hinges on obtaining special government permissions. This highlights the need for continued support from government authorities.

Scaling the project to encompass multiple villages across coastal regions requires tailoring the approach. While the core solution is adaptable to most Indian fishing communities, strategies for stakeholder participation, capacity building, trust building, and training intervals may need adjustments based on specific community characteristics. A more in-depth study of diverse coastal communities is necessary to refine the model and ensure it meets the varied needs of different villages.

It's important to acknowledge that the proposed technology offers support, but it's not a cure-all. For example, the system cannot provide information on seasonal fish availability. While it empowers fishermen with better decision-making tools and easier communication, their safety ultimately relies on their attentiveness to warnings (border crossings, cyclones) and their ability to take appropriate action. The Internet access for digital services on the ocean also presents potential downsides. Similar to trends observed among younger generations, excessive use of social media and entertainment services could distract from learning about the ocean and their profession, potentially jeopardizing safety during fishing operations. The e-commerce platform within the solution, while offering wider customer reach, might disrupt traditional business practices. This could force some individuals, like intermediaries, to adapt their business models.

7. Conclusion

Coastal fishing communities face a multitude of challenges, including natural disasters, emergencies at sea, and a significant digital divide. This lack of digital access and capacity acts as a major barrier, preventing them from fully utilising digital resources that could improve their safety and livelihoods. The consequences of natural disasters are often exacerbated by this limited digital access. This research directly addresses these issues by introducing the OceanNet Digital Ecosystem (ODE). ODE is a comprehensive suite of technological interventions designed to improve digital access, capacity, and overall well-being within the coastal fishing community. The solution provides internet connectivity and access to essential digital services through its innovative heterogeneous, multi-layered communication system. Additionally, a blockchain-based e-commerce platform offers new business opportunities, fostering greater livelihood resilience for the fishermen.

To ensure technology acceptance and maximize impact, all these technological solutions are integrated with a unique and sustainable social change model. This approach not only enhances disaster resilience but also improves the overall quality of life for the community. Co-designing the solution alongside the community was crucial. This collaborative process facilitated a deep understanding of their specific needs and ensured successful diffusion of the technology. It also allowed for the involvement of various stakeholders, both at the micro and

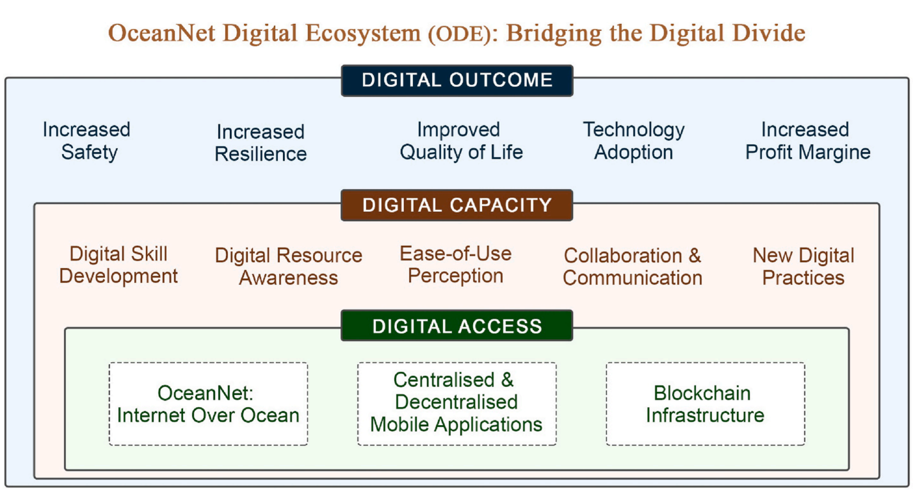

Fig. 10. Digital divide categories addressed by OceanNet digital ecosystem.

macro levels, who are vital for successful adoption within the community.

Frequent interactions with users played a vital role in shaping the overall system design and development. These interactions highlighted the importance of social cohesion in the project's success. Engaging with the community also facilitated capacity-building initiatives. This included school visits and educational sessions aimed at empowering the younger generation and fostering awareness about the solution. Regularly collecting feedback and suggestions from fishing vessel captains and fishers proved beneficial. This built trust and empowered them to provide clear and specific requirements and suggestions, ultimately aiding the research team throughout the deployment and training process. By employing various methodologies, this study has identified key factors and developed intervention strategies that contribute to successful technology transfer in such contexts.

Future endeavours aim to expand the mobile application's functionalities by incorporating additional modules that address various social and business needs within the fishing community. This will enhance the app's overall value proposition. Scaling the project is a key priority. Efforts are underway to deploy the communication system across over a hundred fishing vessels. This large-scale implementation will serve to test the system's robustness and reliability in real-world operational conditions. The team is actively working on the e-commerce platform, with the blockchain structure and its framework design already finalised. The next step involves identifying suitable entities to act as blockchain ledger holders, paving the way for full implementation. In a significant collaboration, the research team is partnering with the Indian National Centre for Ocean Information Services (INCOIS) to implement the Tsunami- Ready Recognition program [115, 116]. This program will equip fishing villages with various mitigation measures, ultimately reducing their vulnerability and increasing their resilience to natural hazards, particularly tsunamis.

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CRediT authorship contribution statement

Sruthy Anand: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Conceptualization. **Mojtaba Enayati:** Writing – review & editing, Software, Methodology. **Dhanesh Raj:** Writing – original draft, Validation, Software, Data curation. **Alberto Montresor:** Writing – review & editing, Supervision. **Maneesha Vinodini Ramesh:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

Data availability

The data that has been used is confidential.

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