sustainability

Article

Using IoT Sensor Technologies to Reduce Waste and Improve Sustainability in Artisanal Fish Farming in Southern Brazil

Ramakrishnan Ramanathan [1,*], Yanqing Duan [2], Joaquim Valverde [3], Samuel Van Ransbeeck [2], Tahmina Ajmal [2] and Silma Valverde [4]

[1] Essex Business School, University of Essex, Southend Campus, Elmer Approach, Southend-on-Sea, Essex SS1 1LW, UK
[2] Research Institute of Smart Cities, University of Bedfordshire, Park Square, Luton LU1 3JU, UK
[3] Instituto Federal de Educação, Ciência e Tecnologia Catarinense, Campus Camboriú, Rua Joaquim Garcia, Camboriú 88340-055, Brazil
[4] Department of Education, Universidade Federal do Paraná, Litoral Campus, Rua Jaguariaíva, 512, Caiobá Matinhos 83260-000, Brazil
* Correspondence: r.ramanathan@essex.ac.uk; Tel.: +44-1702328412

Abstract: Modern digital technologies have the great potential to improve the sustainability of fish farming in artisanal fisheries. However, in spite of the popularity of these technologies for fish farming in other parts of the world, Brazil still lags behind. To fill this gap, this study has conducted the first field study in implementing the IoT sensor technologies in Southern Brazil and documents the experiences in this paper. More specifically, it discusses developing sustainable artisanal fisheries infrastructure using these technologies with reference to southern Brazil, where the study explores the use of sensor technology in aquaculture and its effectiveness in reducing waste and improving productivity. The overarching goal of the project is to demonstrate how simple data collection using IoT sensors and its analysis can support artisanal freshwater fish farms in Brazil and beyond to increase production, reduce waste, and thereby improve their sustainability. The pilot implementation of these technologies has demonstrated the potential of increasing the productivity of the artisanal fisheries, reducing waste (e.g., loss of farmed fish, optimised feeding to reduce waste of feeds), and improving the sustainability of aquaculture. This paper documents the valuable firsthand experiences of selecting, adapting, and implementing the IoT sensor technologies with close cooperation from local research institutions and artisanal fish farmers. The paper describes the different implementation stages and use interviews with stakeholders as a testimony of the effectiveness of the IoT technology adoption.

Keywords: aquaculture; Brazil; IoT

Citation: Ramanathan, R.; Duan, Y.; Valverde, J.; Van Ransbeeck, S.; Ajmal, T.; Valverde, S. Using IoT Sensor Technologies to Reduce Waste and Improve Sustainability in Artisanal Fish Farming in Southern Brazil. *Sustainability* **2023**, *15*, 2078. https://doi.org/10.3390/su15032078

Academic Editor: George P. Kraemer

Received: 30 November 2022
Revised: 5 January 2023
Accepted: 7 January 2023
Published: 21 January 2023

1. Introduction

Modern digital technologies (MDT), such as the Internet of Things (IoT), big data, Artificial Intelligence (AI) robots, and mobile apps, have been used in many countries to improve fishing practices. Although some countries such as the UK and China are leading in this context, artisanal fisheries in Brazil are seriously lagging in exploiting the potential of these technologies. This is a serious research gap. To fill this gap, this study conducted field trials of these technologies in Brazil. This paper presents our experience of adapting the relevant IoT technologies and assessing their impact on the productivity of the Brazilian artisanal fisheries, reduction of waste, and improvement of overall sustainability.

Several modern digital technologies have been developed in the last few decades. These include the Internet of Things (IoT) sensors, cloud connectivity, big data analytics, and smartphone connectivity, which have been applied for multiple application domains [1–5].

The applications of these technologies have shown promise in helping the aquaculture sector as well. Although economic factors have always been an important factor, the recent transition to a new economic strategy means social and environmental factors are more prominent. In the Brazilian context, Valenti et al. [6] (p. 26) define sustainability in aquaculture as “the cost-effective production of aquatic organisms, which keeps a harmonic and continuous interaction with the ecosystems and the local communities”. The authors further highlight that sustainable aquaculture must be productive, use natural resources rationally, and should not degrade the ecosystems.

Existing research on sustainability in aquaculture tends to focus on measuring economic, societal, and environmental factors, mostly through the DPSIR (drivers, pressures, state, impact, and response model of intervention) framework. Although this research is an important tool in mapping the problems with aquaculture, our focus lies on providing a specific part of the solution by implementing low-cost IoT in aquaculture. The literature on modern digital technology implementations in artisanal aquaculture is relatively scarce and mostly addresses aquaculture in Africa and Asia, with very few applications in Brazil. A detailed literature review shows that there are not many in-depth studies that looked at the status of artisanal fisheries in Brazil and explored the applicability of modern digital technologies. Our study contributes to this literature gap by gaining valuable insights affecting smart aquaculture in Brazil by engaging and interacting with various stakeholders via workshops, field visits, and pilot implementation of appropriate modern digital technologies in selected sites in Brazil. Thus, the main contribution of this paper is that this is one of the first studies that presents the Brazilian context for the application of modern digital technologies in aquaculture.

This paper focuses on direct water quality monitoring in (semi-) permanent farm sites using sensor probes and does not discuss the use of satellite GIS technology, which is more commonly applied to track migrating fishes. In Section 2, it discusses the current state of aquaculture in Brazil; this is followed by a review of digital technologies in aquaculture. Section 3 explains the research methodology, research questions, and stakeholders. Section 4 gives details about the technology implementation, and Section 5 explains the results. Finally, Section 6 draw the conclusions.

2. Literature Review

This section provides a detailed literature review of the status of aquaculture in Brazil and the use of technologies for aquaculture in general, and it highlights the issues in the Brazilian aquaculture sector.

2.1. Current State of Aquaculture in Brazil

Aquaculture in all its forms has steadily been increasing its production in Brazil, reaching 179 million metric tonnes of fish in 2018 [7] (p. 2). In Brazil, in 2019, 758,006 metric tonnes of fish were produced, of which 57% were Tilapia and 38% were native fish [8] (p. 10). There is an opportunity to increase that production, but there are challenges that need to be addressed. One of the reasons that Brazil is lagging behind other countries is the high number of artisanal fishers which do not use technology to its full extent [9]. In the state of Santa Catarina, 34,000 artisanal farmers exist, of which only 9% produce in sufficient quantities to commercialise their production [10]. There is huge scope for increasing productivity, reducing fish waste, and improving the sustainability of these artisanal farms by applying modern digital technologies [11].

Artisanal fishing has many advantages over industrial fishing. Jacquet, J., Pauly, D. [12] state that the relative lack of waste, the lower amount of fuel used, and, overall, the smaller environmental footprint of artisanal fisheries (both onshore and maritime) are important factors to incentivise artisanal fisheries over industrial ones.

2.2. Modern Digital Technologies in Aquaculture

Several modern digital technologies have been successfully applied in the context of aquaculture in the last few decades [13–15]. Since they have so-called smart features (the ability to connect to the internet or cloud), the use of these technologies in aquaculture is also called smart aquaculture. A smart aquaculture system is characterised by a number of modern digital technologies: Internet of Things sensors, cloud computing, artificial intelligence, machine learning, big data, blockchain, analytics, augmented reality and virtual reality, robotics, additive manufacturing, smartphone apps, and more. Rowan, N.J. [13] presents a detailed description of modern digital technologies used in smart aquaculture systems. Yadav et al. [14] provide a review of such technologies and their aquaculture applications.

Although technology is widely used in large-scale fish production (for example at MOWI Scotland), artisanal aquaculture still limps behind in adopting technology solutions to build a path towards sustainability. Nevertheless, there are ample advantages of using IoT: for example, farmers can monitor the water quality continuously in real-time and adjust feeding and aeration patterns accordingly. Having access to continuous data reduces the labour time needed for manual monitoring, freeing up time for other activities. By continuously monitoring, the farmers can plan and improve their farming practice in the long term. If small farms collect and combine their data, machine learning and artificial intelligence can be used to further optimize best practices, even in these small-scale farms.

Espinosa-Faller, F.J., Rendón-Rodríguez, G.E. [16] developed a system using Zigbee in a recirculation system. Sung, W.-T., Chen, J.-H., Wang, H.-C. [17] developed a low-cost system to monitor water quality remotely using Zigbee for communication. The AquaTIC project [18] developed a monitoring system to be used in different types of fish farms (an oyster and mussel farm, a fish farm, and a spirulina (microalgae) farm). Real-time monitoring helped the farmers, especially with the dissolved oxygen parameter. Oxygen is critical for fish growth and survival, and having real-time data allowed the farmer to switch on the aeration machines very quickly. A further step is to aggregate monitoring data and cross them with other data like nutritional data of feed, expected biomass at the different life stages, et cetera.

Besides monitoring-only systems, some projects combine monitoring with automation. Ding et al. [19] implemented a system to measure dissolved oxygen and, based on the incoming data, activate the aerator to supply oxygen to the pond. Huan et al. [20] successfully developed and deployed commercially a more complex monitoring and automation system in south China. This system monitors more parameters (dissolved oxygen, pH level, temperature, water level, salinity, turbidity, nitrate, and the status of the machinery) and thus can give a more precise image to the farmer.

Prapti et al. [21] have analysed several systems developed in the last 10 years (2011–2020). However, in the evaluated project, only 11% effectively produced a prototype, whereas the other projects either produced a framework, got their results through experimentation, or got their results through simulations of IoT systems. Three parameters are the most researched: temperature, dissolved oxygen, and pH.

Whereas the literature referenced above looked for the technological solution, Zhang et al. [22] studies the economic impact of using IoT on crab and shrimp farms in China and found a significant cost decrease in the need for drugs and electricity, although the cost for feed went up because of a higher initial investment in seed. Even more significant was the reduction in labour costs: farmers could react quickly to changes in water quality and activate machinery, rather than having to do the testing manually and wait for results. The reduction in labour is especially important at night because farmers do not have to wake up to take care of the water. More than a cost-saving measure, it improves farmers' mental health. Moving from the expenses to the earning side, crab and shrimp produced with the help of the IoT system are bigger in size and number, leading to more generated income.

Despite of the developments in modern digital technologies and their promising applications in smart aquaculture, smart aquaculture practices are still in the nascent stages in Brazil [9]. In this context, this paper outlines the experiences related to introducing the modern digital technologies in artisanal fisheries in the state of Santa Catarina in southern Brazil. Interactions with stakeholders (farmers, government scientists, cooperatives, and academics) through workshops, field visits, and interviews were used to gather knowledge about the functioning of artisanal (small-scale) fish farms and the impact of introducing modern digital technologies. Based on the firsthand experience in technology implementation in Santa Catarina artisanal fishers, the paper presents the findings on reducing fish waste, increasing productivity, and improving the sustainability of artisanal fisheries.

2.3. Issues in Applying Technologies to Brazilian Artisanal Fisheries

A detailed literature review has highlighted the infrastructural, legal, social, and technological issues affecting the status of artisanal fishing in Brazil. These include:

1. Lack of infrastructure, both on a macro and micro scale [23,24], affects the productivity of artisanal fisheries in Brazil.
2. Legislation and enforcement: most literature on legal issues is focused on marine fishing [25].
3. Social issues: authors such as [26–29] highlight the difficulties faced by artisanal fisheries, which is usually a mode of survival rather than a means of making a profit.
4. Due to the lack of infrastructure and the need for survival, most artisanal fisheries in Brazil use rudimentary technology [25,28,30], with no funds to make big investments in technological upgrades like automatization, oxygen machines, and sensor technology. Specifically for water quality monitoring, if farmers use anything, they use chemical reaction strips, which are very time-consuming.
5. All the above issues are exacerbated by the general conservatism in aquaculture and the lack of trust in technology that results in farmers resisting innovation and new technology implementations [31].

However, there is very little literature on how Brazilian artisanal fisheries can be supported with the relevant digital technologies. This paper fills this literature gap. Based on multiple stakeholder interactions, this study explores options to help small-scale fish farmers to make their businesses sustainable. The study has identified appropriate technology and tried to implement the technology in the selected small scale fish farms. To minimise the risk of lack of trust, this research project adopted a new approach where decisions are made collaboratively with farmers on an informed basis. The project engaged with local artisanal farmers and innovation entities such as local educational institutions to identify, adapt, and implement appropriate smart aquaculture technologies.

3. Research Methodology

The main research questions that this study aims to answer are the following:

- What is the current perception of the use of IoT Sensor Technologies by artisanal fishermen in Brazil for improving their operations?
- What are the problems they have encountered in implementing IoT?
- What are the potentials of applying IoT Sensor Technologies to reduce waste in artisanal fish farming in Brazil?
- What are the benefits and challenges?

3.1. Research Method

To answer the research questions, this study adopted mixed methods research, which is a combination of qualitative approach and technology implementation. The qualitative research was conducted through interactions between stakeholders in the form of interviews with key stakeholders, workshops, and field visits. Technology implementation has been done in selected fish farms, including that of a large agriculture research organisation (EPAGRI—Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina, the research agency of the state of Santa Catarina). Valuable insights and answers to the key research questions are obtained based on the collection of empirical evidence, observation, and technology implementation experience.

3.2. Stakeholders

The project brought together academics and students, farmers, government researchers, and farmer cooperatives. Throughout the project, the knowledge exchange between these different stakeholders helped in better understanding the complexity of artisanal fisheries. Furthermore, the interactive workshop format brought these stakeholders closer together, benefitting cooperation to improve the fisheries sector beyond this project. The study has conducted 3 workshops and interacted with a total of 50 stakeholders (fish farmers, cooperatives, government researchers, academics, and students) for the data collection.

3.3. Research Participants

Several stakeholders mentioned above participated in multiple workshops and field visits. Field visits included visits to farms in Brazil but also successful examples of smart aquaculture implementations in the UK. In addition, three farms in Santa Catarina (see map in Figure 1) that were willing to experiment with a new IoT implementation were selected. Each farm has its peculiarities; one farm only cultivated Tilapia, another farm supplemented its fish cultivation with distilling Cachaça (a national liquor) and events, and yet another farm was an experimental fishpond at the IFC (Instituto Federal Catarinense—the institution of one of the authors). The project team was enthusiastically supported by Aquipar, a fisheries association bringing together 35 farmers around Gaspar, and is led by the owner of one of the farms where the technology was implemented.

Figure 1. The state of Santa Catarina in Brazil.

4. Technology Implementation

Although IoT sensors have great potential to improve aquaculture productivity and reduce waste, our technology implementation was driven by farmers' immediate needs and their affordability. Based on our discussions with fishermen who participated in three workshops, interviews with the key farmers and EPAGRI support officers, and our observations during the field visits, the study identified two application areas: (a) water quality monitoring, e.g., level of oxygen, and (b) optimization of feeding time and amount of feed. Farmers highlighted that the lack of oxygen is the key factor affecting fish growth. The real-time continuous monitoring of the oxygen level using sensors in artisanal fish farming could significantly help farmers to improve productivity and reduce fish death rate because farmers can be altered to take immediate action when the oxygen level is too low. Water quality monitoring can also be used to make feeding decisions.

For the technology implementation using sensors, the project has chosen a low cost and reliable sensor system after stakeholder consultation that was installed in selected fishponds in Brazil. The chosen sensor system (Figure 2) is manufactured by a British company *SNE* (pseudonym). The study choses this company because its system is easy to install, use, and maintain. Rather than using chemicals to calibrate the system, *SNE* relies on disposable membranes that are replaced every month. These sensors must be submerged for 24 h in a water sample before being inserted into the device. As soon as the device is connected, the outputs from the sensor system was connected remotely to computers and servers for cloud monitoring and analysis.

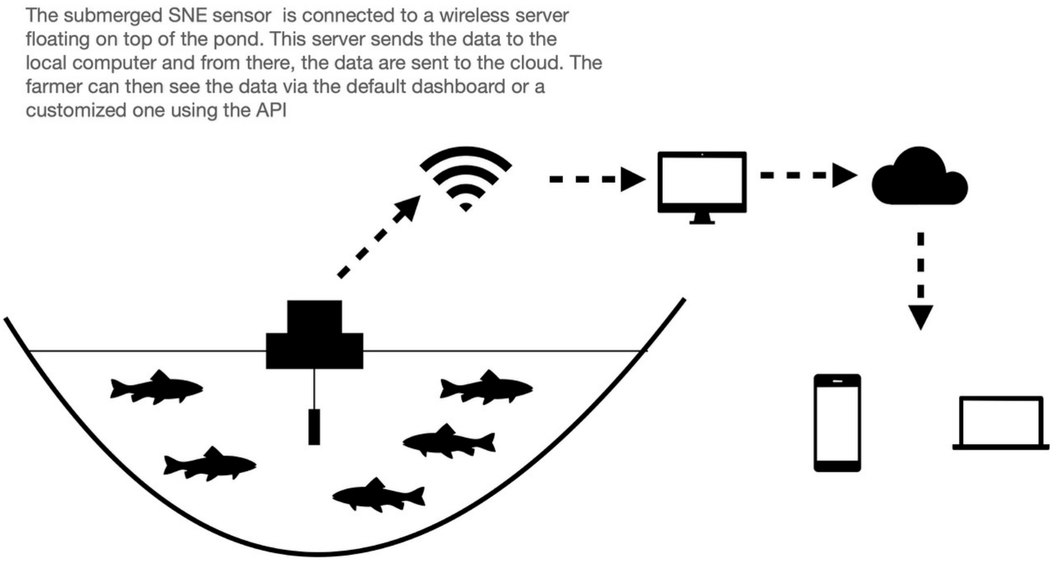

Figure 2. A schematic of how the SNE sensor system works.

Data Collection and Presentation of Results

The project involved the Brazilian researchers in the Instituto Federal de Educação, Ciência e Tecnologia Catarinense (IFC). They have developed technology resources with support from EPAGRI and made them available to artisanal fish farmers. Surveys have been carried out in stages, and they targeted activities typical of the real processes of production of edible aquatic animals and plants. Production can take from 6 to 12 months and hundreds of data are generated daily, manually recorded in different types of documents and media—paper, spreadsheets, photographs, etc.—during the entire creation cycle, from stand to harvest.

These are data related to the life cycles of the species (larvae, post-larvae, rearing, fingerlings, sexual inversion, breeding, fattening, harvesting, etc.); food (protein, energy; mineral vitamins, preservatives, additives for growth, flours, probiotics, organic acids, immunostimulants, etc.); nutritional stages (veal, microencapsulated egg, brine shrimp; zooplankton, feed, Kcal/Gross Energy, %CP etc.); water quality (Hydrogenionic potential (pH), temperature, transparency, salinity, oxygenation, etc.); diseases (infectious, bacterial, fungal...), and causative agents (parasites, stressors, etc.). The aforementioned data do not exhaust the combinatorial variables that can bring serious problems to production results, with consequences for economic sustainability (damage to the producer and the need to import); social (more expensive food and lower supply of quality animal protein), and environmental (wasted natural resources and pollution).

To ensure sustainable aquaculture growth, especially in small farms, it will be necessary to use a 'specialist' digital technological environment that enables: (i) management of knowledge about fish farming on a comprehensible basis anywhere and at any time and access to adequate scientific and procedural knowledge; (ii) use of reliable and personalized information in administration, production, marketing, and logistics; (iii) use of business intelligence (BI) applications (programs) in management and planning activities; (iv) Data Science to identify and understand the actual patterns of success and failure of the past and that are similar to what is happening in each production of the moment; (v) use of Big Data and Smartphones to access databases and Web services; and (vi) use of Digital Communication and Social Networks.

Figure 3 provides the architecture of data collection and analysis of the digital technology system for artisanal fisheries. The figure shows that data from aquaculture operations are stored using a specialized Management Information System (MIS) combined with big data from external sources (e.g., weather data) and then analysed using appropriate Business Intelligence tools such as neural networks, and the entire experience has been used to develop e-learning tools for curriculum development and training.

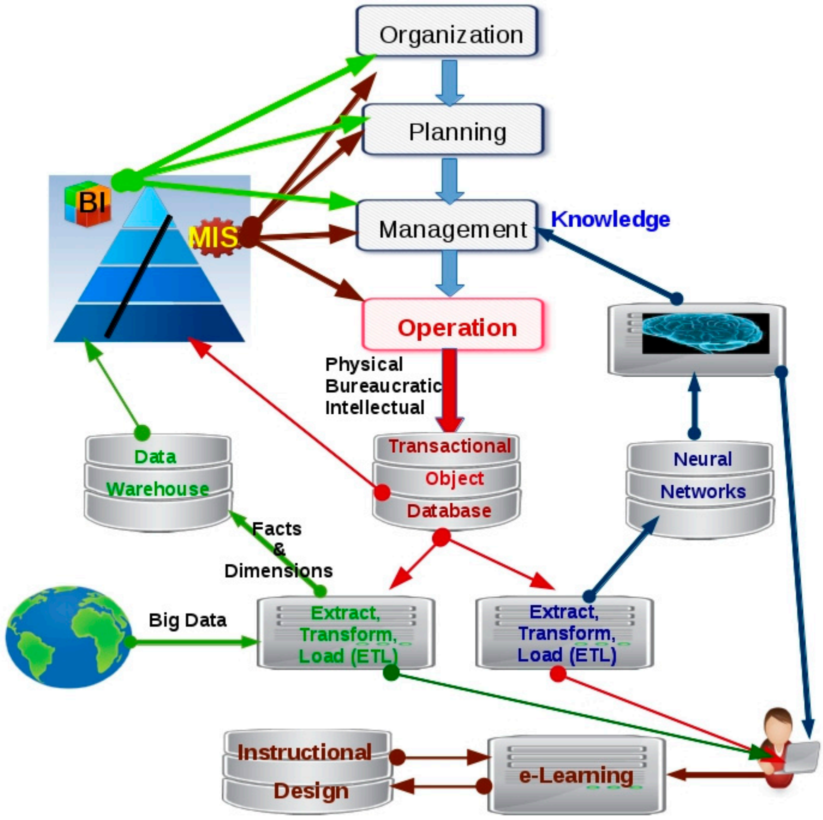

Figure 3. The architecture of the information system for technology implementation for artisanal fisheries. Legend: BI—Business Intelligence; MIS—Management Information System.

The details of the information system can be accessed by individual users using their login details. They can locate their pond from a list, update any details, register new equipment installed, see the details of food, medicines, hormones, etc. administered in the ponds, and look at the parameters measured using the IoT sensors (SNE). Figure 4 shows a sample screenshot from the administration screen system, where the user can plan automated actions and use linked data to get insights on the whole production process. On the left side, the farmer can select the tracked fishpond (propriedades in Portuguese), the production (produção) details, fish food and other consumables (insumos), financial information (financeiro), e-learning (educação a distancia), the knowledge database about fish species (organismos), and communication (informação e comunicação). In the main screen, we see the details of a production run at a pond. The list details feeding (alimentação) operations. The user can furthermore see the number of fish present in the pond (população), the catching process (despesca), medicine (medicinas), hormones (hormónios), biometry (biometria), and finally the sensor data (monitoramento IoT).

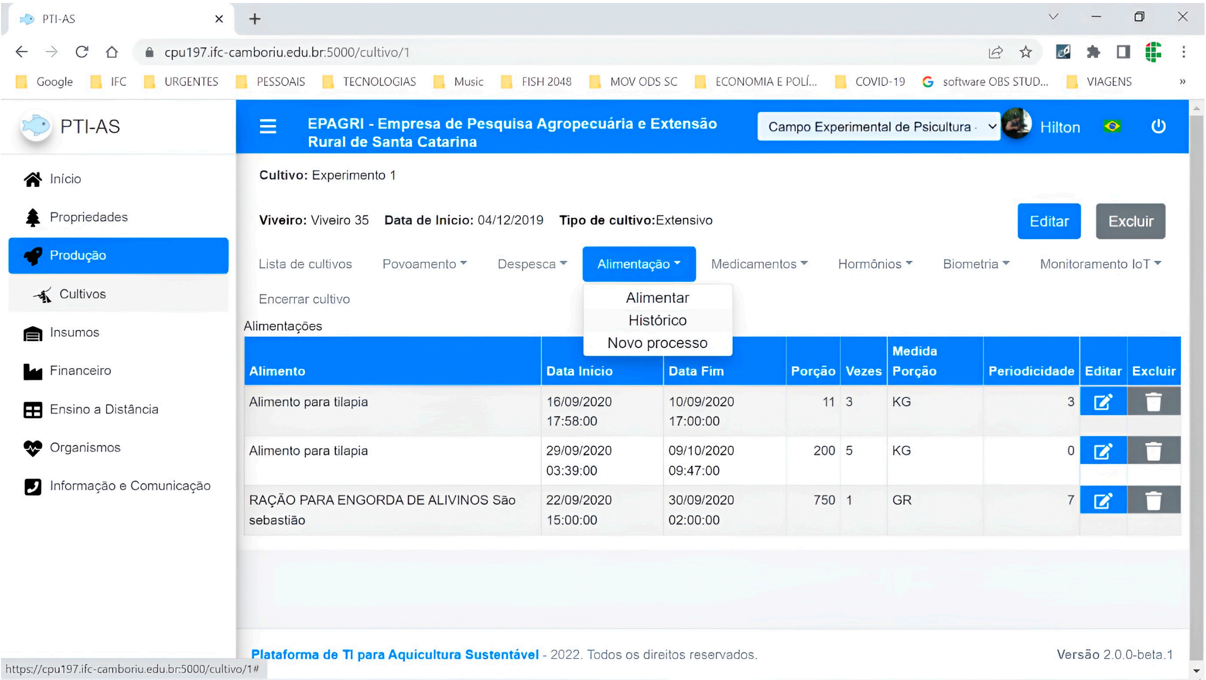

Figure 4. A screenshot of food menu showing the history of the operations carried out and registering information on feeding. The software is developed for Portuguese-speaking users; hence, the language is Portuguese.

This monitoring data is visualised as in Figures 5 and 6 and displays levels of ammonia, salinity, turbidity, depth of the water, et cetera. This figure furthermore shows minima and maxima. For most parameters, there is a safe range in which the aquaculture process can happen rather than an absolute value.

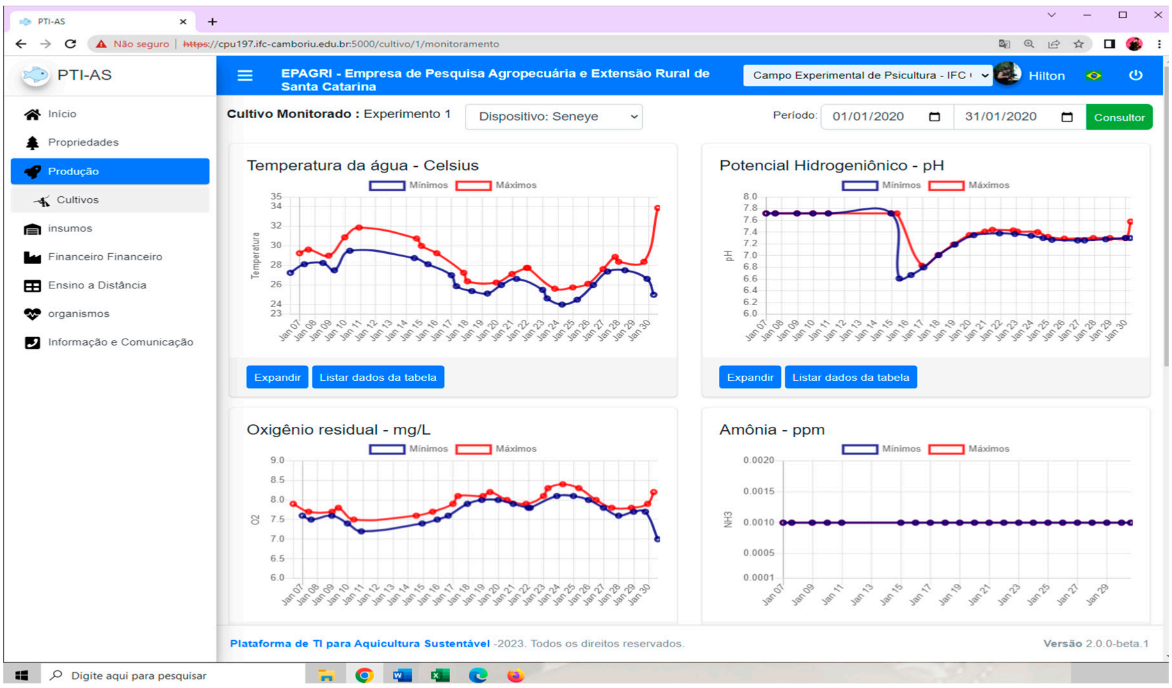

Figure 5. Data visualization from IoT SNE sensors. The system displays minima and maxima of each day for every parameter. (Amônio is Ammonium in English; Condutividade is conductivity; Salinidade is salinity; Turbidez is turbidity; Profundidade is depth).

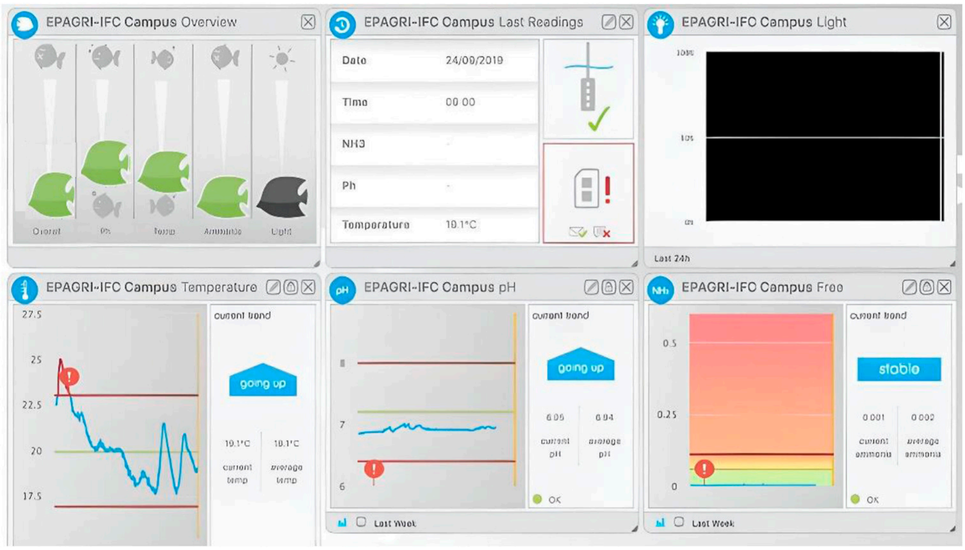

Figure 6. The dashboard showing the incoming data from the sensor. This early version, based on the sensor manufacturer software, is originally in English.

To facilitate easier access to farmers, the information system shown in Figures 4 and 5 can be accessed via a variety of devices: personal computers, tablets, and smartphones.

As mentioned earlier, the ability to monitor the water quality remotely was an important benefit of the smart aquaculture system. Using the Application Programming Interface (API), the data originally seen in Figure 6 through the manufacturers application, can be received in a custom-built dashboard as shown in Figures 4 and 5. This dashboard was developed to include general information about the fish (like the need for food at different life stages); it was sourced mainly from EPAGRI data and could calculate the amount of food to be dispensed based on the water quality and the age of the fish. Using this custom dashboard, the incoming data can be stored locally, and it is easier to access for offline data analysis. Monitoring of water parameters and the related automatization will benefit cost reduction and allow for more precise aquaculture. Thus, Figures 4 and 5 show a user (a fish farmer) dashboard that shows all the data of the pond in a single screen. This will help the farmer to look at all the data together and make decisions quickly whenever needed.

5. Results and Discussion

This section provides the results based on the interactions with stakeholders during interviews, workshops, field visits, and continuous learning during technology implementation. Qualitative data on stakeholder perception was collected and analysed.

5.1. Criteria for Successful Smart Aquaculture

The literature review in Section 2 has highlighted several infrastructural, legal, social, and technological issues affecting the status of artisanal fishing in Brazil. In line with these observations, our interactions with stakeholders in multiple workshops and field visits have highlighted that several key criteria were considered important for a successful implementation. More importantly, economic issues, trust, and ease of use emerged as key criteria, as described below.

1. Ease of Use: during interviews and workshops, several stakeholders stressed the need for ease of use of these technologies. They highlighted that they tried to implement a technology some years earlier but could not continue due to the complex daily procedures. Ideally, products available locally from the market that can be directly used without additional changes are preferred.
2. Affordability: given the small scale of the farmers' production, the available investment budget is low as well. As such, any technology should be cheap to acquire.

3. Continuous monitoring: the system should be able to detect problems as soon as they occur for immediate corrective action and should also be able to collect data for long-term analysis.
4. Reliability: if farmers rely on technology for critical decisions that can impact their livestock significantly, the system needs to be reliable; breakdowns are unacceptable. If the system fails and a pond is left without proper aeration due to the failure, the whole fish population can die and seriously impact the farmer's livelihood. Several participants mentioned that the proposed sensor technology in their ponds is a welcome initiative but also warned about the impact of disasters such as frequent power cuts, storms, and floods, which in the past killed huge quantities of fish. Even if sensors are fitted, local fish farmers should be supported to build resilience considering these disasters.
5. Continuity: after the system is installed, it should be used for a long time. Support should be available so that farmers do not have to buy a different system within 5 years. Having used another technology from a company that went out of business had damaged the trust of farmers who invested in the equipment.

5.2. Potentials for Reducing Waste and Increasing Productivity

During our implementation, the following benefits were observed based on the interactions with the stakeholders.

1. Reduce fish death and food waste: the pilot implementations have shown that there is a strong potential for timely reduction of issues causing death of fish. Before the implementation of modern digital technologies, there were incidents that oxygen levels were reduced in the pond during the night when there is no monitoring, which meant the death of fish the next day. With the implementation of modern digital technologies and smartphone connectivity there is continuous monitoring, and any reduction in oxygen level affecting fish life can be spotted quickly and alarms sent on the smartphone. There are options to switch on the oxygen generator remotely, thereby reducing the possibility of the death of fish. For example, one of the fish farmers opined the following during an interview by our team: "The sensor will enhance productivity because the fish will feel comfortable with the right oxygen level. The fish will not waste energy to get oxygen so he gets heavier." Similarly, technologies help reduce the waste of fish feed [13]. By ensuring the right quantity of fish feed is released into ponds at the right intervals, the chance of releasing excess feed, which would then become waste, is reduced. Further, the excess feed causes sedimentation and algae problems in the pond, which will in turn affect the growth of fish. These issues are also avoided using technology [32]. Further, by operating aquaculture machinery (e.g., oxygen generators and feeders) only when they are needed, there is also energy saving [32,33]. Before using modern digital technologies, fishermen usually switch on their oxygen generators overnight to ensure adequate oxygen supply. This causes unnecessary energy consumption, which can be avoided if these machines are operated only when needed. Our mobile phone apps have shown their utility, especially when there is a need to visit ponds during adverse weather (e.g., at night or during heavy rain). If there are issues with oxygen levels in the pond, for example, smartphone apps can feature alerts to this effect for immediate attention by the fishermen. More advanced smartphone apps developed by the team had options to remotely switch on the aerators instantly, thereby avoiding the need for a physical visit to switch the aerators manually. This is certainly handy in adverse weather conditions and helps not only avoid waste and increase productivity but also improve morale and social activities. These observations are consistent with the previous literature that highlighted the need for improving infrastructure [23,24] in Brazil. Improved infrastructure helps in large-scale adoption of even simple technologies and can go a long way in reducing waste in artisanal fishing. This reduced waste

helps in improving the availability of food, thereby increasing revenues, and thus further helps improve social fabric as observed by the authors of [26–29].

2. Increase in productivity: via continuous monitoring of various parameters and taking corrective actions, the smart aquaculture system can ensure the right quality and quantity of feed and oxygen for maximum fish growth. This increases productivity. Further, the use of modern digital technologies will help automate the system using smartphone applications. Using technologies can also help farmers to make quick and better decisions. Thus, the productivity issues highlighted by the previous literature (e.g., [26–28]) in the context of artisanal fisheries in Brazil can be avoided by the appropriate use of technologies.
3. Reduce costs: the use of technologies will eventually help farmers to reduce costs. For example, using sensors to automatically monitor and control the aerator will reduce electricity costs. The combination of monitoring with automation offers great advantages. The farmer does not have to be on-site permanently, as they can use remote monitoring and machinery control. This can save considerable labour and improve labour productivity too. Artisanal farms work with a small staff, often only composed of family members. Hence, any reduction in labour will positively impact the farm [34].
4. Improve sustainability: reducing fish death and food waste is an example of sustainability benefits from the use of modern digital technologies in smart aquaculture. In addition, there are several other benefits related to economic, environmental, and social sustainability. The economic pillar of sustainability is achieved in multiple contexts. For example, reduced waste, increased productivity, and reduced labour costs directly translate to economic benefits in terms of cost saving and increased revenues. Aquaculture with modern technologies will reduce the "manual" effort of recording and controlling management conditions and will intensify the dedication to planning, management, logistics, commercialization, professional qualification, and communication with peers. Better organized, the sector can take advantage of the benefits of collective purchases and sales and cooperate to increase the quality, productivity, and profitability of Santa Catarina and national aquaculture. The financial results of an increase in productivity will strengthen the sector, generate more jobs, and contribute to the improvement of the state's balance of payments. The environmental pillar of sustainability is also achieved in different ways. Modern digital technologies help optimise the consumption of energy and other resources (e.g., feed). With the help of sensor data (e.g., oxygen levels and alerts when the levels are low), the aerators can be switched on exactly when needed. Otherwise, it is a common practice to switch on aerators for the entire night. Thus, sensors help save energy. This results in significant environmental benefits with reduced carbon emissions and footprint. In addition, aquaculture with these new technologies can expand the knowledge of producers and improve the management of the means of production and protect the ecosystem from inappropriate actions and practices, misuse of water resources, and polluting actions. With more knowledge, producers will be able to invest better in technologies for waste treatment and water use. These precautions will make it easier to obtain governmental environmental licenses and increase productivity and product quality. There are significant achievements for the social pillar of sustainability too. Since artisanal fisheries constitute a majority of aquaculture business in Brazil (as in other countries), any improvement in the quality of life (e.g., improved revenue) of artisanal fishermen helps promote social cohesion, reduce social unrest, and improve economic growth. Improved social cohesion and reduced crime helps in improving social sustainability of the region. More social benefits arise due to the increased availability of fish as food and provide better nutrition and food security for populations at more affordable prices. Scientific publications from the Harvard University Institute of Medicine show that fish consumption improves the prevention of chronic cardiovascular diseases, diabetes, cancer, osteoporosis, and obesity, among others.

Though the progress of continued implementation of the smart technologies was significantly affected by COVID-19 lockdowns, the experience listed above highlighted several useful findings on the promise of modern digital technologies for smart aquaculture in Brazilian artisanal fisheries. It is understood that bringing IoT solutions would help to improve the sustainability of the production process in various ways. The insights into the water quality in a fast and continuous way allow farmers to adapt feeding and aeration to reduce costs. The continuous monitoring and easy maintenance significantly reduce labour time, allowing the farmers to work on other activities. For the cooperatives, stakeholders have been brought together, making it easier to network and create new collaborations. For EPAGRI, the state agricultural agency, large-scale deployment of a monitoring system would allow them to analyse the fisheries sector in-depth and purpose large-scale changes in land and water use and regulations. For the students, this project offered a first foray in applied research: rather than just studying at their desks, they could put research into practice. Finally, for local communities, it would strengthen their economy and unlock new potential.

6. Conclusions and Future Work

The literature review shows that there is a serious lack of research on using technologies in small-scale fish farming. This is particularly evident in artisanal fish farms in Brazil. Therefore, this paper aims to address this gap by demonstrating how IoT sensor technologies can benefit artisanal fish farms by transforming their low-productivity conventional fish farming practice into modern smart fish farming that is commercially viable. It describes the unique experiences in implementing modern digital technologies for smart aquaculture in artisanal fish farming in Brazil. The literature review has further highlighted that there are initiatives in improving sustainability, and that the use of modern digital technologies has positive impact on all aspects of aquaculture. Through interviews, field visits, and workshops, this research was able to corroborate those findings in Brazil. For the future development of applying IoT sensors to reduce waste and improve sustainability in artisanal fish farming in Brazil and other developing countries, the following recommendations are offered:

1. Technology applications should be driven by farms' imperative needs. The top priorities for technology implementation using IoT sensors and remote control digital technologies should include: first, improving the monitoring and control of water quality for better productivity and waste reduction, such as oxygen and temperature; second, optimising and managing the fish feed to improve resource efficiency; third, enabling fish farmers to have better access to information (e.g., suppliers information, weather, market demand and prices, etc.), knowledge and technical support and expert advice via mobile Apps. Mobile apps can also help in remotely switching on machinery (e.g., aerators or feeders) when required, which will come in handy, especially during adverse weather conditions.
2. New technologies should be developed with local culture in mind. It can be automatic, resulting in fewer labour requirements, but should be supplemented with proper user support. Working with local knowledge centres and government support agencies is crucial for the continued diffusion of these technologies to all beneficiaries.
3. Artisanal fisheries tend to work with traditional models of fishing. More training on new business models (e.g., (i) linking directly to the market as there is a lack of awareness of the fish supply chains, as most farmers do not directly deal with supermarkets or final consumers, (ii) using cooperative structures to ensure large supplying power and consequently winning bargaining power, and (iii) developing future contracts for the supply of fish to the market to ensure all fish produced are sold on time) will help the entire AF industry.
4. Significant effort should be made to raise sustainability issues among fish farmers, as there is a serious lack of understanding of environmental sustainability. For example, in Brazil, since the water supply is abundant, they tend to think pollution is not an

issue. It is true that, at current levels of production, the waste from ponds reaching local rivers does not appear to be a significant problem, but without adequate efforts in treating the wastewater before it leaves aquafarms, pollution issues will be the most significant limiting factor for future expansion of smart fish farms.

5. Government should improve the supporting infrastructure for aquaculture development, e.g., regulations, local government support networks, legal frameworks, financial incentives, better access to banks and financial support, etc.

This research is one of the first studies in Brazilian context. Our work can be improved in different ways. Future researchers can collect quantitative experimental data to assess the improvement in productivity or reduction in waste numerically and compare the results with similar experiences in other comparable countries. Numerical data on fish production can be collected to quantitatively prove the benefits of smart fish farming. Future work can also conduct similar experiments in multiple parts of Brazil and compare the results. Researchers can extend the applications to multiple sites and study the issues arising from scaling up. Numerical data on fish production can be collected to quantitatively prove the benefits of smart fish farming. Given that the technology landscape keeps evolving continuously, newer and more relevant technologies can be introduced in Brazil as and when they become available. Newer business models (e.g., startups) can be explored to commercialise these technologies. It is hoped our work provides the basis for future researchers to explore these interesting possibilities.

Author Contributions: Conceptualization, R.R., Y.D., J.V. and T.A.; methodology, R.R., Y.D., J.V. and T.A.; software, J.V. and S.V.R.; validation, All; formal analysis, R.R., Y.D. and T.A.; investigation, J.V. and S.V.R.; resources, R.R., Y.D., J.V. and T.A.; writing—original draft preparation, R.R., Y.D., S.V.R., T.A., and S.V.; writing—review and editing, S.V.R., R.R., Y.D. and T.A.; visualization, S.V.R.; supervision, R.R., Y.D., J.V. and T.A.; project administration, R.R., Y.D., J.V., S.V.R. and T.A.; funding acquisition, R.R., Y.D., J.V. and T.A. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the UKRI Newton fund (grant n° 332387020) in the UK and FAPESC in Brazil. This project was a collaboration between the University of Bedfordshire and the Instituto Federal Catarinense. We would like to thank the farmers, cooperatives, students at the IFC, and EPAGRI for their input in the project. The paper also benefited from the REAMIT project funded by the Interreg North-West Europe (ref NWE831) in terms of the renewed focus on food waste.

Institutional Review Board Statement: Ethical approval for the project has been obtained from the University of Bedfordshire (Ethics approval number: BMRI/Ethics/Staff/2017-18/006).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Singh, R.; Gehlot, A.; Akram, S.; Gupta, L.; Jena, M.; Prakash, C.; Singh, S.; Kumar, R. Cloud Manufacturing, Internet of Things-Assisted Manufacturing and 3D Printing Technology: Reliable Tools for Sustainable Construction. *Sustainability* **2021**, *13*, 7327. [CrossRef]
2. Heidari, A.; Navimipour, N.J.; Unal, M.; Zhang, G. Machine Learning Applications in Internet-of-Drones: Systematic Review, Recent Deployments, and Open Issues. *ACM Comput. Surv.* **2022**. [CrossRef]
3. Heidari, A.; Navimipour, N.J.; Unal, M. Applications of ML/DL in the management of smart cities and societies based on new trends in information technologies: A systematic literature review. *Sustain. Cities Soc.* **2022**, *85*, 104089. [CrossRef]
4. Andronie, M.; Lăzăroiu, G.; Ștefănescu, R.; Uță, C.; Dijmărescu, I. Sustainable, Smart, and Sensing Technologies for Cyber-Physical Manufacturing Systems: A Systematic Literature Review. *Sustainability* **2021**, *13*, 5495. [CrossRef]
5. Yan, S.R.; Pirooznia, S.; Heidari, A.; Navimipour, N.J.; Unal, M. Implementation of a Product-Recommender System in an IoT-Based Smart Shopping Using Fuzzy Logic and Apriori Algorithm. *IEEE Trans. Eng. Manag.* **2022**. [CrossRef]
6. Valenti, W.C.; Kimpara, J.M.; de L Preto, B. Measuring aquaculture sustainability. *World Aquac.* **2011**, *42*, 26–30.

7. FAO. *The State of World Fisheries and Aquaculture 2020*; FAO: Rome, Italy, 2020. [CrossRef]
8. Medeiros, F. (Ed.) *ANUÁRIO 2020 Peixe BR da Piscicultura*; Annual Report; Associação Brasileira da Piscicultura: Pinheiros, Brazil, 2020; p. 10. Available online: www.peixebr.com.br (accessed on 20 June 2022).
9. Valenti, W.C.; Barros, H.P.; Moraes-Valenti, P.; Bueno, G.W.; Cavalli, R.O. Aquaculture in Brazil: Past, present and future. *Aquac. Rep.* **2021**, *19*, 100611. [CrossRef]
10. Engeplus, P. Santa Catarina aumenta em 10,6% a produção de peixes de água doce. *Portal Engeplus*, 27 August 2019.
11. Ramanathan, R.; Duan, Y.; Ajmal, T.; Dong, F.; Ransbeeck, S.V.; Valverde, J.M.; Valverde, S.B. IoT sensors in Aquaculture—Barriers and Facilitators for sustainability in Brazilian Context. In Proceedings of the International Conference on Industrial Engineering and Operations Management, Toronto, ON, Canada, 23–25 October 2019.
12. Jacquet, J.; Pauly, D. Funding Priorities: Big Barriers to Small-Scale Fisheries. *Conserv. Biol.* **2008**, *22*, 832–835. [CrossRef]
13. Rowan, N.J. The role of digital technologies in supporting and improving fishery and aquaculture across the supply chain—Quo Vadis? *Aquac. Fish.* 2022; *in press*. [CrossRef]
14. Yadav, A.; Noori, M.T.; Biswas, A.; Min, B. A Concise Review on the Recent Developments in the Internet of Things (IoT)-Based Smart Aquaculture Practices. *Rev. Fish. Sci. Aquac.* **2022**, 1–16. [CrossRef]
15. Yue, K.; Shen, Y. An overview of disruptive technologies for aquaculture. *Aquac. Fish.* **2021**, *7*, 111–120. [CrossRef]
16. Espinosa-Faller, F.J.; Rendón-Rodríguez, G.E. A ZigBee Wireless Sensor Network for Monitoring an Aquaculture Recirculating System. *J. Appl. Res. Technol.* **2012**, *10*, 380–387. [CrossRef]
17. Sung, W.-T.; Chen, J.-H.; Wang, H.-C. Remote fish aquaculture monitoring system based on wireless transmission technology. In Proceedings of the 2014 International Conference on Information Science, Electronics and Electrical Engineering, Sapporo, Japan, 26–28 April 2014; pp. 540–544. [CrossRef]
18. Lafont, M.; Dupont, S.; Cousin, P.; Vallauri, A.; Dupont, C. Back to the future: IoT to improve aquaculture: Real-time monitoring and algorithmic prediction of water parameters for aquaculture needs. In Proceedings of the 2019 Global IoT Summit (GIoTS), Aarhus, Denmark, 17–21 June 2019; pp. 1–6. [CrossRef]
19. Ding, Q.; Ma, D.; Li, D.; Wei, Y.; Wen, N. A Wireless Control Node for Dissolved Oxygen in Aquaculture. *Sens. Lett.* **2013**, *11*, 1069–1073. [CrossRef]
20. Huan, J.; Liu, X.; Li, H.; Wang, H.; Zhu, X. A monitoring and control system for aquaculture via wireless network and android platform. *Sens. Transducers* **2014**, *169*, 250.
21. Prapti, D.R.; Shariff, A.R.M.; Man, H.C.; Ramli, N.M.; Perumal, T.; Shariff, M. Internet of Things (IoT)-based aquaculture: An overview of IoT application on water quality monitoring. *Rev. Aquac.* **2021**, *14*, 979–992. [CrossRef]
22. Zhang, Y.; Hua, J.; Bin Wang, Y. Application Effect of Aquaculture IOT System. *Appl. Mech. Mater.* **2013**, *303–306*, 1395–1401. [CrossRef]
23. de Sousa, D.N.; de Almeida Kato, H.C.; Milagres, C.S.F.; de Freitas, A.A. Organização Social e Produtiva de Pescadores Para Agregação de Valor ao Pescado Em Mercados Institucionais. *Rev. Bras. Eng. Pesca* **2018**, *11*, 85–96. [CrossRef]
24. de Lima, G.F.; Lopes, R.L. Impactos ambientais dos resíduos gerados na pesca artesanal de moluscos bivalve no distrito de patané/arez-rn. *Holos* **2016**, *4*, 206. [CrossRef]
25. Silva AR, G.; Costa-Neto, E.M. Narrativas De Pescadores Artesanais Sobre As Transformações Ocorridas Na Pesca De Peixes Estuarinos Da Baía De Todos Os Santos, Bahia. *Rev. Ouricuri* **2018**, *8*, 58–79. [CrossRef]
26. Júnior, C.H.F.; Batista, V.D.S. Repartição da renda derivada da primeira comercialização do pescado na pesca comercial artesanal que abastece Manaus (Estado do Amazonas, Brasil). *Acta Sci. Hum. Soc. Sci.* **2006**, *28*, 131–136. [CrossRef]
27. Trimble, M.; Johnson, D. Artisanal fishing as an undesirable way of life? The implications for governance of fishers' wellbeing aspirations in coastal Uruguay and southeastern Brazil. *Mar. Policy* **2013**, *37*, 37–44. [CrossRef]
28. Oliveira, P.D.C.; Di Beneditto, A.P.M.; Bulhões, E.M.R.; Zappes, C.A. Artisanal fishery versus port activity in southern Brazil. *Ocean Coast. Manag.* **2016**, *129*, 49–57. [CrossRef]
29. Tsakanika, A.; Clauzet, M. Envolvendo os pescadores artesanais no desenvolvimento sustentável urbano e periurbano no Brasil. *Revibec-Rev. Iberoam. Econ. Ecol.* **2018**, *28*, 20.
30. Coelho, V.F.; Branco, J.O.; Dias, M.A.H. Indicadores de produtividade aplicados à pesca artesanal do camarão sete-barbas, Penha, SC, Brasil. *Ambient. Agua-Interdiscip. J. Appl. Sci.* **2016**, *11*, 98–109. [CrossRef]
31. Eayrs, S.; Cadrin, S.X.; Glass, C.W. Managing change in fisheries: A missing key to fishery-dependent data collection? *ICES J. Mar. Sci.* **2014**, *72*, 1152–1158. [CrossRef]
32. Kassem, T.; Shahrour, I.; El Khattabi, J.; Raslan, A. Smart and Sustainable Aquaculture Farms. *Sustainability* **2021**, *13*, 10685. [CrossRef]
33. Dupont, C.; Cousin, P.; Dupont, S. IoT for Aquaculture 4.0 Smart and easy-to-deploy real-time water monitoring with IoT. In Proceedings of the 2018 Global Internet of Things Summit, Bilbao, Spain, 4–7 June 2018; pp. 1–5. [CrossRef]
34. Shi, B.; Sreeram, V.; Zhao, D.; Duan, S.; Jiang, J. A wireless sensor network-based monitoring system for freshwater fishpond aquaculture. *Biosyst. Eng.* **2018**, *172*, 57–66. [CrossRef]