Grenze International Journal of Engineering and Technology, June Issue

A Comprehensive Review of IoT-based Water Quality Monitoring Techniques for Shrimp Aquaculture

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***Abstract*— Shrimp aquaculture is a major contributor to the world aquaculture sector and plays a significant role in food security, jobs and export, Maintaining the water quality parameters as they should be is a daunting task, because the parameters controlling the health of the shrimp like temperature, pH, DO. affect the health of the shrimp directly. The conventional monitoring tools available to the entrepreneurs based on water sampling and laboratory tests are time consuming, laborious and no real time results are available. This paper presents a review of the water quality monitoring system in shrimp farms based on IOT platform. The system architecture and the various sensors used and the data acquisition, the data analytical platforms based on cloud computing for analysis, real time monitoring, IPO support are discussed. The case studies of shrimp farms in Thailand, Ecuador, Vietnam showing the usefulness of these systems in practical life with the increase in productivity obtained from the resources used from that. It concur with and helps to increase the stability and efficiency of the resources to inform social responsibility. Research is given to future prospects of development in artificial intelligence, machine learning and bigdata. Edge computing and wireless mode of communication are discussed in this paper. The limitations and problems in the implementation of the systems in practice like cost, energy management, cyber security etc are dealt in this paper. So this review aims to give a view of the entire field and gives a base for future work in intelligent and sustainable shrimp aquaculture. The importance of IOT in increasing the efficiency of the industry and scalability and environmentally sustainability is established.**

***Index Terms*— AI, pH, IoT, DO, MQTT, WSNs.**

I. Introduction

A. Background and Importance of Shrimp Farming

Shrimp farming is a rapidly growing sector of global aquaculture, which greatly contributes to the seafood industry. Shrimp as among the most widely traded seafood commodities, have high economic value and are the source of income for millions of coastal and rural peoples in Asia, Latin America and Africa. With the increasing demand by consumers for sources of food which are high in proteins shrimp farming has been expanded in order to supply the needs of both local and export markets. Litopenaeus vannamei and Penaeus monodon are species cultivated in farmed systems using such methods as pond culture systems and recirculating aquaculture systems.

Grenze ID: 01.GIJET.12.2.103_21

The success of shrimp farming, however, depends primarily on the ability to maintain a healthy aquatic environment particularly the quality of water which is a fundamental determinant of shrimp health, growth rates and overall farm productivity.

B. Challenges in Water Quality Management

The maintenance of top water quality is one of the problems in shrimp aquaculture. Problems of temperature, pH, dissolved oxygen, turbulent, salinity and ammonia are faced by shrimp farms, which can have severe consequences. The traditional method of water quality management, which is done by water sample checking with off farm analysis, consumes much time, labor and is not useful for any immediate knowledge of water condition. This subsequently may take management longer to know of the severe water condition. With stressed fish, this will result in diseased fish. There are practices of monitoring water quality continually, or automated monitoring now in need, for effective management of disease on large farms or isolated areas.

C. Role of IoT in Aquaculture

The IoT in aquaculture has evolved into revolutionary technology and presents new solutions to old problems related to the monitoring of water quality. The IoT contains sensors, data collecting methods, communication systems and clouds by which aquaculture production systems can be observed and controlled in real time. Through participation in the IoT, growers can continuously monitor important water quality parameters in shrimp aquaculture and quickly make changes to enhance growth parameters. The IoT provides data analysis integrated into remote use systems so well informed and rational decisions can be made, greater operational efficiencies obtained, and dependence on manual methods reduced. These advantages are becoming increasingly important in order to augment agricultural production, promote sustainability, and comply with environmental laws.

D. Objectives of the Survey

The objective of this review is to present a thorough inspection of the relevant literature on IoT based water quality monitoring systems with a special regard in shrimp (Penaeus esp) cultivation. The purpose of this review is to analyze the current state of both research and technological developments in the applications. Accordingly, this research will investigate (1) the necessary preconditions of water quality for shrimp cultivation, (2) the devices and systems employed in traditional and IoT based methodologies of monitoring, (3) the concept and behavior of the systems of IoT solutions, (4) study of the application case of the real application level

II. Literature Review

A. Traditional Water Quality Monitoring Techniques

Traditionally, monitoring water quality in shrimp aquaculture has relied on manual sampling and laboratory analysis. Techniques such as grab sampling, titration, spectrophotometry and, if the farmer is lucky, alphabet field kits, are methods used to measure required parameters such as pH, dissolved oxygen, ammonia, nitrite and turbidity [45], [46], [49]. These methods may be reliable, have generally been widely accepted and used due to effectiveness and compatibility with standardized water quality indices. For example, grab sampling involves either specified intervals of time for intervals of water sampling specified distance apart and colleting discrete water samples at specified distance locations or sampling the discharge from the pump(s) of the system, after which the samples will be tested in a laboratory for chemical characteristics and physical characteristics. These methods, while they yield most valuable information, are time consuming, laborious and yield information from water samples, generally, allowing the consumers to view the quality of the water only at certain points, as a result, they are unable to detect short-term variation which affect shrimp considerably and very intensely their health.

What goes wrong is that all the details and troubles involving the logistics respecting traditional surveillance are involved, such as getting samples shipped and dependence upon efficient laboratory technicians, thus it becomes very disabling and costly especially in the instance of large operations of shrimp forms. Biological indicators, such as the presence of macroinvertebrates or particular species of fish (for the punters, around here) may give a fairly comprehensive idea of the health of the environment but are limited by their spatio-temporal limitations and require taxonomic knowledge [47]. Aquaculture ponds have also employed remote sensing techniques, via satellite photographs or drone surveillance to determine surface direction of changes in ponds [48]. However, such surveilance is restricted to detection of the directional fluctuations of the quality of water and is often dependent upon satisfactory weather conditions. Since, therefore, it is easily apparent that while traditional techniques are well substantiated in their use in aquaculture, in being no doubt satisfactory in many cases, that solutions are wanted, more continuous and automated, traditional methods become lacking as individual observation in space and in time does not give to farmers very satisfactory results in time nor in space for dynamic and real-time farm management.

B. IoT Applications in Aquaculture

IoT has emerged as a disruptive alternative to conventional methods for determining quality of water in aquaculture through its restraints. IoT refers to a network of inlet/outlet sensors, microcontrollers, communication devices, cloud based servers, and data displays. These IoT systems can monitor key parameters such as turbidity, dissolved oxygen, ammonia, pH, salinity and low water temperature. This data can be transmitted as a wireless protocol onto a central communication platform such as Wi-Fi, to Loravan or Zigby [2],[3] and [6]. Real time data can be utilized by the farmer in shrimp cultures, to observe changes, send alerts, make decisions, which can supply the means for disease prevention and conserving equilibrium through diet alteration. The integration with web dashboards and mobile apps, gives the fish farmer the ability to access data and sensors remotely for fish farms which are situated in areas of inaccessible close representation to rural places [5,15,20]. Many studies have published and demonstrated the benefits of IoT based management of shrimp farming for increased accuracy and accountability. Chowdury et al. [4] and Rahman et al. [20], have shown large increases in the shrimp production and decreased mortality in ponds with IoT based monitoring. Some systems also control actuators which are able to automate such processes as water exchange and aeration which can respond to sensor input [6,39]. IoT which have a built in scalable property are generally suited to larger or smaller concerns. The cloud based storage of historical data allows for the predictive technology to be utilized, where use of possible long tern trends in products or character changes of shrimp allow for optimal farming technique and conduct to be implemented. In spite of favorable results from their use, present day systems of IoT suffer from a number of disadvantages that will require further investigation and development, such as sensor maintenance, data security and interfacing with currently suitable infrastructure.

C. Comparative Analysis of Existing Systems

Substantial differences in operating efficiency, response characteristics, and ability to wait exist between conventional monitoring systems and those based on IoT. The farmer finds it difficult to respond quickly to the degrading water situation because conventional systems give accurate but static data [45], [50]. An IoT-based system, however, offers dynamic and continuous monitoring which is responsive in real time and can effect emergency actions when the parameter parameters exceed optimum levels. For example, an IoT-based system can effect emergency actions such as water exchange or Agon in several minutes, while a conventional system may not discover high ammonia levels until hours or even days after sample collection. In addition, the IoT system can monitor several points simultaneously, thus giving a much more descriptive picture of the health of the pond, while a traditional one is usually limited by the few samples which can be taken.

Another important difference is the differences in analysis capabilities gained by both views. AIOT' systems frequently include machine learning algorithms for projection as well as for discovering existing patterns, which improve the decision -making process [24], [26], [31]. This is almost absent in future capacity, which futures are mostly reactionary. Nevertheless, the AIoT systems have their share of problems too. The sensor can cause the loss of performances due to data loss, drift, calibration errors and connectivity problems [52], [53]. Maintenance of networks of sensors and technical knowledge can also impede in value -based adoption among farmers on a small scale. The advantages of real -time monitorring, remote accessibility and automation make AIOT a better alternative for modern aquaculture. Comparative studies constantly show that fish farms, which implement AIOT technologies, have better yields, lower operational costs and better efficiency of resources [2], [14], [39].

D. Gaps in the Literature and Scope for Innovation

However, while IoT strategies for monitoring aquaculture have progressed in a positive way, there are still some main weaknesses in the present literature. The great majority of systems developed use single parameters of water quality and do not consider the intricacies of these different parameters and the effects of these interactions. For example, the effect of one form of ammonia being toxic is not considered together with the pH ranges at high temperatures, both of which have a bearing on shrimp mortality [7], [33]. Very few studies have been undertaken considering the long term capabilities of the sensors used under commercial conditions regarding reliability and accuracy etc. In particular, the product of biofouling on performance of sensed materials, possible drifts in calibration from year to year and the energy efficiency of batteries has not been efficiently studied in this area [18], [36]. This need for long term studies leads to the requirement for

understanding in this field of the operability cost/efficiency of the system, in many cases essential before the system can be commercially perceived.
While much promise is expected to result from the adoption of AI & ML techniques in predictive systems and modeling, many of these studies still adopt the old threshold system of echelons. Studies regarding deep learning models (ie LSTM, convolutional neural nets) for anomaly detection and forecasting, etc are in their cradle. Considerable validation studies will be necessary to establish their pertinence in aquaculture systems. Associated with these deficiencies is the need for connectivity and uniformity of devices. Diverse hardware, proprietary means of communication, and diverse data formats negate any interconnectivity of IoT devices between devices and platforms. Also, attention to cyber security problems and privacy deficiencies that develop from the traffic of a farm information status via public domains is lacking. Social science/economic aspects (ie farmers proclivity toward acceptance of technologies, cost/value comparisons, regional policy influences relative to technological adaptation) receive little attention in these highly technical papers. Bridging these deficiencies in aqua-feed technology will depend much on multi-disciplinary groups of aqua-engineers, aquaculturists, and data analysts and researchers, and policy makers to arrive at solidly grounded solutions of scale, security and those which are agreeable to farmers in the implementation of IoT technology in shrimp culture systems.
The review comparisons as shown in Table I.

TABLE I. COMPARISON BETWEEN TRADITIONAL AND IOT-BASED WATER QUALITY MONITORING APPROACHES

Criteria	Traditional Techniques	IoT-Based Techniques
Monitoring Frequency	Periodic / Manual Sampling	Continuous / Automated
Data Type	Snapshot Data (Offline)	Real-time Streaming Data
Accuracy	High in lab tests but limited in field	Consistent with real-time calibration
Scalability	Limited to few ponds	Highly scalable through wireless networks
Labor Requirement	High (manual sampling & analysis)	Low (automated sensing & cloud upload)
Response Time	Delayed (hours to days)	Immediate (seconds to minutes)
Operational Cost	Moderate (recurring)	High initial, low maintenance
Decision Support	Manual decision based on test	Data-driven, AI-enabled decisions

Traditional techniques offer accurate but static measurements, failing to capture temporal variations that critically affect shrimp health. IoT systems, in contrast, provide continuous and multi-parameter monitoring, supporting dynamic decision-making and rapid intervention.

III. WATER QUALITY PARAMETERS IN SHRIMP CULTIVATION

Effective shrimp farming depends on the careful monitoring and control of a number of different water quality parameters. Each parameter is critical to the survival, growth and health of shrimp. Fluctuations in water quality can result in stress, disease outbreaks and reduced productivity. Therefore, it is critical to understand the optimal ranges and interactions of the parameters. This section will examine the different water quality variables important for shrimp aquaculture and their affect on shrimp physiology and farm performance.

A. Temperature

Temperature is a critical factor that affects metabolic rates, feeding behavior, immune responses, and molting cycles in shrimp. Most shrimp species thrive within a certain temperature range, usually between 26 ° C and 32 ° C. It is very important to maintain this range for optimum enzymatic activity and energy utilization. Where increased temperature usually causes an increase in growth rate, it also causes an increase in oxygen consumption which may put great stress on the aquatic systems unless balanced by adequate aeration. Conversely, temperature below optimum limits has the effect of slowing down metabolic processes, reducing feed intake and increasing susceptibility to diseases. In extreme cases, thermal stress can result in large - scale death incidence, especially during seasonal infection, or in poorly regulated pond systems.
Shrimp farming systems often involve the aerators and temperature regulators, especially to maintain frequent thermal conditions, more significantly in the re-establishment of the Aquaculture System (RAS). But the open pond state is insecure against external climatic conditions. The temperature sensor on the basis of IoT, when deployed along with cloud analysis would assist farmers to correlate trends and automated alerts for anomalous deviations.

B. pH

The degree of acidity and alkalinity of water is measured in terms of its pH. The pH of the water is a very important factor which influences the health of shrimps and also the chemical stability of other factors such as

ammonia. Shrimp farming has been advised, ideally, a pH of 7 5 to 8 5., A fluctuation in this range will interfere with some of the physiological processes, disturb osmotic regulation and cause great stress to the immune system of the shrimps. Low pH values (acid) cause harmful metals to be released from sediments of the pond, while high values increase the toxicity of the ammonia. It is, therefore, essential that constant checks should be made, so that the animal does not suffer from a form of toxicity induced by variations in pH in the water.
Inadequate pH alterations can indicate bacterial upsets, algae blooms, or lower buffering qualities of the water body. Conventional methods use handheld meters or test kits, but pH sensors due to the application of the IoT give real data and signals of warning. Systems such as these allow farmers to take timely rectifying measures such as lime applications or controlled water exchanges. The incorporation of pH data into AI based decision systems would serve to maintain the atmosphere of the aquatic environment at a level constant and in the preventions of cascading failures throughout the Essess.

C. Dissolved Oxygen (DO)

The DO is essential for respiration in shrimp and is often the most limiting factor in systems of intensive aquaculture. Levels below 3 mg/L are considered stressful and levels from 5 to 10 mg/L are most favourable for growth and immune response. Lack of oxygen or hypoxia, lethargy, and lack of feeding result in increased susceptibility to diseases and in serious cases mass mortalities. The problem is aggravated in systems of high-density stoking, particularly at night when production of oxygen by photosynthesis is inhibited.
To avoid these disadvantages, the application of aeration systems and continuous water circulation systems must be done regularly to obtain satisfactory amounts of oxygen. However, it is possible that occasional manual determinations of DO may not be feasible in either extensive ponds, or where peace of mind is required, as to the extent to which DO is being checked in isolated areas. The IoT based DO sensors are of great advantage, since they provide for the continuous measurement of DO with the corresponding traditional allied factors, and the automatic control of aeration systems. The great advantage of the data for the control on the DO ineffably adds to the enjoyment of shrimps and at the same time diminishes the costs of running them, as the more traditional systems using less data is avoided. Advanced aeration systems use equations which may easily be written in the future to provide for reliable predictions as to the biomass or temperatures to be found. In this manner the exact amelioration of the O2 environment can be obtained with reference to known data on the predictions possible with of the progress of weather, temperature etc.

D. Ammonia and Nitrite

Ammonia and nitrite are nitrogen compounds resulting from excretions from the shrimp and decay of the feed. The ammonia is present in ionized form (NH4 +) and free form (NH3), the latter of which is very toxic to the shrimp. This toxicity increases with increasing temperature and pH. High amounts of ammonia will produce the effects of gill burn, depressed immunocompetency and death. Nitrite as an intermediate product of ammonia oxidation unites with hemacyanin in the shrimp which affects the whole blood and produces disturbance of oxygen transportation producing the "brown blood disease". It is very necessary to control these parameters, we say, in particular when the systems have little water renewal or small biofilter capacity. The methods of control have traditionally been experiments of a chemical nature which can never keep pace with the rapid accumulation of these waste materials. On the other hand, through the use of IoT based sensors, the control of bio flock management or, in real time tracking and incorporation with rear orders systems is made possible. This takes place through the automatic alerts and adibiotic responses allowing of corrective abilities of biofilter adjustment, feed rate optimization or water renewal. The controlling of the nitrogenous wastes is necessary to allow the operative survivability of the balanced microbial ecosystem and also the promulgation of long term shrimp health.

E. Salinity

Salinity is defined as the quantity of dissolved salts in the waters and is an essential factor in the study of osmo regulation, molting and acid-base equilibrium of shrimps. Some species of animals such as Litopenaeus Vannamei can be subjected to extreme fluctuations of salinity, but thrive best in salinities of 15 to 25 pp. Extreme variations in salinity due to tongues of water and rains cause the stress effects known as sky-sticking which is brought about by the reduced eating as well as the increased proclivity to the slate of disease. The consideration of salinities in the semi-intensive and interior shrimp culture becomes more acute in the use of the underwaters as well as the mixed waters as a supply given in the present case. The IoT based salinity sensors provide instant determinations of salinities and give to the producers the opportunity of adapting both the raw waters and the increase of the minerals to the supply of the environment. Furthermore, since the readings of salinities affect other factors such as ammonia toxicity and PH, it is an important unit of the total water quality management system. The salinity record also provides the an available positive status of the salinity inputs in the adaptive stocking as well as in the refinement of the site selections at the farms.

F. Turbidity

Turbidity is an appraisal of the solids suspended in the water such as silt, organic matter and plankton. Excessive turbidity is detrimental to photosynthesis, light penetration and the number of beneficial phytoplankton. It is a carrier of pathogenic organisms, and reduces the value of ultra violet sterilizers. Moderate turbidities are tolerated in shrimp culture, and even place an advantage, but too great a turbidity from clogging of gills gives rise to mechanical stress of the shrimp population, and deterioration of the quality of the water. Measurements of turbidity in the laboratory by means of nephelometers and Secchi discs are inconvenient, and indefinite in their results. A method of application of turbidity measurers on an IoT basis is worth while for preventive management of the lode of sediments, aeration, feeding regime, and also gives opportunity to appraise real time clarity of the water. Reducing the water turbidity would not only make the the shrimp visible in their habits of feeding and numbers, but through this encourage salubriously of the micro-biological and algal communities. Integrated monitoring will also give opportunity of correlation of other data, such as TSS (total suspended solids) and B.O.D. (biochemical oxygen demand), which will then allow exploration of the total health of the system.

G. Phosphates and Other Indicators

Phosphates are nutrients resulting from feed inputs and biological wastes that are a source of algae growth. While small amounts are beneficial, increased phosphates result in depletion of oxygen and eutrophication and algae blooms. This will also increase the potential for water quality crashes, especially during phytoplankton die-offs. In addition, phosphates may affect sediment composition and promote the growth of harmful microbial communities or biofilms.

Thus, the determination of phosphates in pond ecosystems is extremely important in order to maintain the ecological equilibrium. Testing can be done by spot tests by means of colorimetric tests or sophisticated sensors, by way of IoT sensors, continuous testing for a useful monitoring and detection of the build-up of nutrients may be envisaged. If these are combined with feeding algorithms and biofloc models it may be possible to control nutrient input strategies and enhance the protection of the environment (G. W. Ronja, 2019). TSS, COD (chemical oxygen demand) and microbe load are further particulars that are essential to obtain a complete bird's eye view of the dynamics of pond water quality in shrimp farming. A table of important sensors and their parameters is given in Table II.

TABLE II. SUMMARY OF KEY SENSORS AND PARAMETERS IN SHRIMP AQUACULTURE

Parameter	Sensor Type	Typical Range	Measurement Unit	Ideal Range for Shrimp	Sensor Example
Temperature	Thermistor / DS18B20	0–50 °C	°C	26–32 °C	Waterproof DS18B20
pH	Glass electrode / ISFET	0–14	pH units	7.5–8.5	Atlas EZO-pH
Dissolved Oxygen	Optical DO Probe	0–20 mg/L	mg/L	> 5 mg/L	YSI ProDSS
Ammonia	Ion-Selective Sensor	0–10 mg/L	mg/L	< 0.1 mg/L	Vernier NH3-ISE
Nitrite	Colorimetric Sensor	0–5 mg/L	mg/L	< 0.5 mg/L	SmartColor 300
Salinity	Conductivity Probe	0–50 ppt	ppt	15–25 ppt	Atlas EZO-EC
Turbidity	Nephelometric / IR Sensor	0–1000 NTU	NTU	< 50 NTU	DFRobot Turbidity

IV. TRADITIONAL MONITORING APPROACHES

The traditional methods of monitoring water quality in shrimp aquaculture depend mainly on laboratory tests in the form of manual operations. Such methods have for several years represented the mainstay of the process, giving reliable information to shrimp culturists on a few water parameters. Because of their lack of responsiveness and adaptability, their efficiency and speed however, they are becoming a matter of criticism. The different conventional methods are examined in this section, and their weaknesses and applicability to modern day shrimp farming discussed.

A. Manual Sampling Techniques

In manual collection of water samples, samples are periodically collected, from tanks or ponds, with bottles or with syringes. The samples are used for tests on the spot, or they are sent to the laboratory for further examination. For manual examination, such instruments as Secchi disks, pH meters, and DO probes are employed. Farmers and technicians usually sample according to a schedule that has been predetermined, which may be either daily or weekly, for it is more convenient to sample the upper levels of the bodies of water. Manual sampling is easy and inexpensive, but it is heavily dependent upon the skill and availability of trained persons. It gives only a snapshot view of the conditions in the body of water at the time and place of sampling, and it may not be at all representative of the variations with time or place. Important variations may escape notice in these methods (especially variations at night, or variations between samples). Human error in sampling, handling and interpretation of results, may cause danger to the quality of the data acquired.

B. Laboratory Analysis

Following collection, samples are nearly always sent to labs for biological and chemical analyses. Whenever laboratory analyses are performed, accurate measurements can be made of a number of variables such as ammonia, nitrite, nitrate, phosphate, COD, BOD, heavy metals and microbial loads, etc Once the methods of analysis which are commonly spectrophotometry, chromatography and titrations, are exact, very accurate results will be obtained. In spite of the analytical capabilities of laboratory methods these methods do have some important disadvantages. The time lag between sampling and obtaining results gives too little assistance in decision-making, for real time management. The cost of frequent laboratory analysis is often exorbitant, especially so with industries in remote farm areas due to the transport of samples. There are also likely to be changes in the samples during transit to the laboratory which may alter results, particularly for such factors as the oxygen sensitive and temperature sensitive factors.

C. Limitations of Conventional Methods

One of the most significant downsides of traditional techniques is the lack of continuous, real-time data. Since shrimp farming is dynamic, the biomass in culture, the feed inputs and various other environmental conditions can vary enormously and lead to rapid changes in water parameters. Due to the fact that the traditional methods of early diagnosis cannot record these rapid changes, there is greater loss of stock and the corrective measures in management are realized at a slower rate. The laboratory and manual methods of measuring the water quality are slow and impractical for use over an extensive area, or where multi site operations are being carried on. The traditional methods again are not compatible for integration with such automated systems as automatic feeders or aerators. This makes it necessary that management decisions be based more on the reaction to past environmental occurrences, than on proactive solutions to situations which could produce direct losses. The dependence on manually operated systems renders the industry less amenable to scaling and presents a greater degree of variability.

D. Comparative Studies and Benchmarks

Studies have consistently supported the superiority of IoT-based monitoring over conventional approaches in aquaculture. There is numerous evidence that IoT systems increase accuracy, accountability and environmental stability, while reducing labor and operating costs. Immediate responses such as changing feeding programs or aeration may be possible since the sensor network provides continuous data rather than relying on laboratory reports. Benchmark data suggest the effectiveness, alarm capability and the scalability of systems between conventional systems and IoT oriented systems yield mixed success. The smart monitoring systems will continue to supplement or replace the old systems. These older systems are still extremely necessary when it comes to cross verification as well are useful for in depth chemical testing. The introduction of IOT has greatly enhanced acceptable and efficiently managed water quality under intensive and commercial shrimp farming conditions in Mammana.

V. IoT-based Water Quality Monitoring Systems

A. System Architecture Overview

Figure 1 illustrates the system architecture and data flow of an IoT-based water quality monitoring system that has been developed specifically for shrimp aquaculture purposes. The network of "smart" sensors which form the basis of the entire system collects and transmits data continuously on important environmental parameters like temperature, pH, DO, salinity and ammonia in the shrimp ponds. These sensors are connected to a local processing and control mechanism, typically using a Node MCU or an Arduino microcontroller.

This device converts the sensor signals to a digital format, applies preliminary filtering or averaging methods, and packages the readings for transmission. The filtered data are transmitted using a wireless communication module which can be Wi-Fi or long range modes of transmission such as LoRaWAN. This allows the necessary data to be relayed from remote locations where the ponds could be located. The data are received and stored in a cloud platform providing for large scale data management and analytics and historical tracking of data trends. The user can observe the data compiled from the various sources through a cloud based interface which displays the information on a dashboard providing real time graphs, threshold alarms and system diagnostics which are accessible via web or mobile devices.

The suggested architecture includes an alert system whereby farm operators can be notified immediately using SMS, e-mail, or something like a mobile application whenever a parameter strays outside of the prescribed safe limit. This feedback loop of sensor acquisition to cloud-based data analytics and alert generation is a closing loop of process whereby water quality is subject to proactive feedback and management. This will enable optimized feeding, a reduction in mortality and improved shrimp production while minimizing overhead by requiring reduced human involvement in the processes.

Figure 1. Illustrative IoT Architecture for Water Quality Monitoring in Shrimp Aquaculture

B. Sensor Technologies in Aquaculture

Key water quality parameters can be continuously measured thanks to sensors, which generate the basis of IoT-based systems. Precision on high levels, low consumption of energy of electricity, and high resistance against to which contemporaneous success are the standard of assessment of sensor technologies. There are some classical sensors, which may be utilizable, such as temperature sensor, pH electrodes, oxygen determined optodes, ammonia selective ion sensors, turridity meters and conductive salinity sensors. These sensors have been calibrated to permit salts saline environments, etc., and are utilized with waterproofing means. A more advanced attack on sensor systems is the multiplexer possibilities by which diverse measurements are able to be accomplished at one measurement. More frequently is the utilization of the optical sensor and biosensor for measurement of contaminants or microbal load. It is suitable for it to embed the sensor within a microcontroller, whereby the technique of edgecomputing can be employed and the prephase of data onboarded. Sensor technologies are becoming more reliable, cheap and adaptable to a variety of aquaculture conditions.

C. Data Acquisition and Transmission

Protocols and Methods. Data acquisition in the IoT systems is the regular sampling of measurements from sensors that are transmitted to a larger platform for analysis. These are usually communication protocols such as MQTT, HTTP/HTTPS, CoAP, etc. These protocols are especially well suited for use in remote shrimp farms where a low-power low-bandwidth technology is needed for good pond coverage. Therefore, Wireless Sensor Networks (WSNs) provide total pond coverage by allowing communication in real time between the various sensor nodes. The frequent use of data buffering, compression and encryption techniques is necessary in order to achieve an efficient and secure transmission of the measured quantities. The IoT gateways act as intermediaries because they process the data from the sensor nodes, adding data from neighboring sensors as well as sending such data to the cloud servers. In some implementations the connection between farms located remotely is done through satellite or mobile networks. These protocols and network systems determine the reliability and continuity of the data flow which is implicitly required for correct operation of responsive water quality management systems.

Edge Computing and Cloud Computing: Edge computing is the practice of processing the data as close to the point of production as possible, for instance on micro-controllers/ gateways for later uploading to the cloud, thereby reducing the need for continual connectivity to the internet, reaction time and bandwidth requirements.

Cloud computing, on the other hand, has the long term capacity for data storage, extensive analytical capabilities, and huge amounts of storage capability. It will allow for longer processes to be rely on, such as trend analysis over the years, predictive modelling as well as interface with outside sources of data such as weather forecasting. Increasingly shrimp aquaculture monitoring for its processes is adopting a hybrid of edge and cloud computing processes in order to give the complexities needed for verification, but likewise to allow for responsive and effective operational procedure.

D. Data Management and Analytics

Storage and Processing: The sensor data must be stored in a structured database when it is of sufficient scope and complexity. Such a database is usually a time based database like InfluxDB or based on SQL. These databases offer fast times for query execution, and quick access, and allow computer programs to be interfaced. The

aquaculture information needs to be redundantly stored with redundancy features of cloud storage companies as AWS or Google Cloud, or Azure. The processing includes the cleansing, filtering, and analysis of the data for patterns, aberrations, or correlations. The predictive analysis with machine learning techniques has become popular for predicting phenomena such as algal blooms or oxygen depletion. The data fusion techniques which produce data from different sensors allow for a more robust picture of pond integrity, allowing for a more scientific basis for sound management decisions in farm management.
Visualization Tools and Dashboards: It is therefore necessary to have visualization tools that take this unprocessed sensor data and present it in a way that gives the end user useful insights. Dashboards are a convenient graphic interface that represents data on a continuous time basis, gives historical trends and alerts users to healthy or unhealthy status of the systems. The visualizations can be predictive alerts, bar graphs, heat maps, time series graphs, etc. Usually this is done through custom applications, but common open source tools exist such as Grafana that implement this well.
Farmers can create reports, set alert thresholds, and even remotely control IoT devices with these dashboards. Managers are able to monitor operations in any location owing to mobile responsiveness which has greatly heightened flexibility and responsiveness. Visualization tools facilitate data driven conversations to take place between all participating stakeholders such as technicians, veterinarians and regulatory agencies.

E. Advantages and Limitations

The usage of IoT-based systems in shrimp aquaculture can have remarkable benefits. Some of the benefits would be the real-time controllability, early recognition of anomalies, less labour, enhanced decision making and better efficiency of resources. would exemplify a better quality and health for shrimp production, as well as have improved yield and lower impact to the environment due to better controllability of feeding and serviceability of water treatments systems.
However, there seem to be limitations still. There is a very much higher installation cost of most of the new systems that are proposed, particularly so for small-scale farmers. There are also problems with the systems incorporated to bio-fouling, sensor calibration and maintenance. There needs to be great caution shown towards secrecy of information and privacy dealing with connectivity levels in rural areas. Not the less, the new developments to low-cost sensors area, solar powered devices and artificial intelligence-based integration is strengthening the value of these IoT systems in aquaculture.
To quantify the improvements to production, many of the studies that are carried out give extensive data which compare the traditional methods of production with the IoT supported systems, which are illustrated in tabular format in Table III.

TABLE III: QUANTITATIVE COMPARISON OF SYSTEM PERFORMANCE

Metric	Traditional Systems	IoT Systems	% Improvement
Sampling Frequency	1–2 samples/day	60–120 samples/hour	~3000×
Measurement Delay	3–6 hours	< 1 minute	~99% faster
Labor Requirement	3–4 persons	1 technician	70% reduction
Shrimp Survival Rate	65–75%	85–92%	+20%
Operating Cost (monthly)	₹ 18 000	₹ 12 000	−33%

Quantitative evidence underscores that IoT deployments significantly improve response time and operational efficiency while reducing recurring costs.

VI. CASE STUDIES

The real-world applications of IoT-based water quality monitoring systems in shrimp farming give powerful information on the usefulness, advantages and difficulties of these systems. In this chapter practical case studies from shrimp farms in Thailand, Ecuador and Vietnam are presented, with a number of best practices and lessons learned in practice.

A. Thailand Shrimp Farm

Practical applications of IoT-based water quality monitoring system in shrimp culture. To address the problem of irregularity of shrimp growing and recurring diseases, a commercial shrimp farm in eastern Thailand was fitted with an IoT based water quality monitoring system. This had a sensor for the frequent measurement of pH, ammonia, dissolved oxygen and temperature of the water. The data gathered were passed wireless to a cloud platform where the farm operators were able to view in real time the dashboard. The farm after implementation showed a great improvement in the feed conversion ratio along with the survivability of the shrimp. Automatic alerts provided rapid response to drops in oxygen values overnight, and the use of historical data trends provides for a feed schedule that was tailored. By implementation of forecast based preventive water management practices the farm also lowered its chemical usage. Besides the mere productivity results, this infection also increased market share and competition among the various farms. useful to provide background information as to the viability, benefits and problems for these technologies.

B. Ecuador Shrimp Farm

Faced with erratic weather phenomena and recurrent blooms of algae, a large shrimp farm in the coast of Ecuador used IoT surveillance controls were made for deploying a network of multi-parameter sensors in different ponds which were controlled by a central control unit. The data were automatically analyzed, the risk status predicted and reactions such as turning on an aerator and changing the water flow were possible through using an AI-enhanced platform. A proactive approach decreased mortality rates considerably and harvested crop yields increased by 20% in the first season. This change in methods also made the farm a feather cheaper by decreasing the need for manual labour costs. Events on the part of management brought this system into play and gave them faith in their ability to surveillance and control water to create readily available, stable quality in the dispersed farming areas. The success of the implementation of smart farming techniques initiated the regional spread of such operations.

C. Vietnam Shrimp Farm

To be more environmentally friendly and meet international export requirements a middle-sized shrimp farm in the Mekong Delta in Vietnam applied an Internet of Things system. The farm used a monitoring platform based on a mobile application and modular sensors on such parameters as ammonia, turbidity, and salinity. Regular reports on compliance to the regional authorities were provided and remote supervision for employees was possible. The farm changed techniques in the management of the sediments when they appreciated a relationship between stresses on shrimp and increases in turbidity. With this understanding the total yield improved and the incidence of disease decreased. The automated data logging system increased the traceability and transparency essential to access to international markets of the farm and simplified export certification documentation. Figures 2 and 3 quantitatively and visually reinforce the discussion that IoT-enabled aquaculture provides superior insight into ecosystem dynamics compared with conventional observation methods.

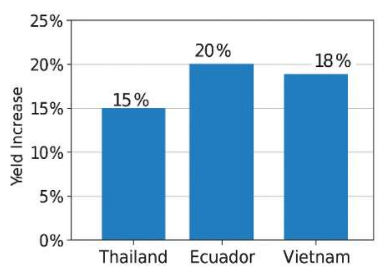

Figure 2. Comparative Shrimp Yield Improvements in IoT-Enabled Farms

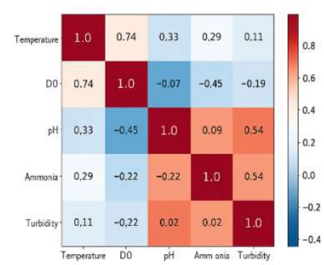

Figure 3. Correlation Heatmap of Key Environmental Parameters

D. Lessons Learned and Best Practices

The findings from the case studies indicate that as beneficial as IoT can be, a realistic approach is vital to a successful installation. Firstly, reliable connectivity must be reached by remote farms by investment in solid satellite or wireless infrastructure. Secondly, abiding results can only be achieved by ensuring proper calibration and maintenance of the sensors. The forms attempted to assure efficiency of the system by training staff and establishing organized maintenance programs.

Some of the measures which were thought to be best practice were that education of the stakeholders to ensure buy in to the system, integration possible with the deployed current agricultural management software, and a staged installation process to ensure ongoing attention to costs. The forms found that good efficiency and long-term upgraded results followed where staff became involved early in their training programmes and regular adjustments were made to the systems. Ultimately it was essential that the utilisation of the data was for the purpose of analytics in the future, rather than pure monitoring, if cost efficient aquaculture management was to be possible.

VII. Future Trends and Challenges

Several emerging trends will influence the next generation of Internet of Things-based water quality monitoring systems as the aquaculture sector adopts smart technologies more.
The main operational issues and technological developments that will probably affect shrimp aquaculture in the future are covered in this chapter.

A. AI and Machine Learning Integration

Aquaculture data management is being revolutionized by the incorporation of AI and ML into Internet of Things systems. Artificial intelligence (AI) models can forecast changes in water quality, identify subtle patterns, and offer practical recommendations by evaluating vast amounts of historical and real-time data. ML-powered predictive analytics can foresee occurrences like algal blooms or oxygen depletion, enabling preventative measures that lower risk and boost yields.
AI-powered automation can improve operational choices like feeding schedules and aeration schedules. Smart systems will become more self-sufficient as deep learning and edge AI continue to progress, enabling precision aquaculture and maximizing farm profitability through adaptive control algorithms.

B. Big Data and Cloud Infrastructure

The foundation for scalable and responsive IoT systems is provided by the growth of cloud computing and big data analytics. High-speed processing, centralized data storage, and smooth data source integration across several farm locations are made possible by cloud infrastructure. Large datasets that include environmental readings, shrimp growth metrics, and system alerts can now be stored on farms and mined for long-term trend analysis and strategic planning.
Predictive model development, cross-variable analysis, and sophisticated queries are made easier by big data tools. These solutions, combined with the ease of cloud accessibility, give decision makers the ability to work with external stakeholders, automate compliance and reporting tasks, and monitor operations remotely from any area. The improvements in the cloud infrastructure provide data security, redundancy, and reliability.

C. Wireless Communication Advances

Aquaculture data transmission is changing as a result of emerging communication technologies like 5G, LoRaWAN, and NB-IoT. The wide bandwidth, low latency, and long-range capabilities of the protocols are essential in order for shrimp farms that are extensive or remote to maintain reliable connections. Better connectivity means that there are uninterrupted data transfer and instantaneous responses in IoT devices. LPWAN (Low Power Wide Area Network) technologies should enhance the maintenance cycle of battery-powered sensors by supplying them with a longer usage life. Farms will be able to reduce capital expenses associated with infrastructure having to do with wiring, improve spatial monitoring accuracy, and extend sensor networks as wireless technologies are developed.

D. Cybersecurity and Privacy

Cybersecurity is now a major concern due to the increased reliance on cloud-based systems and remote monitoring. Cyberattacks could target IoT devices, and any compromise could jeopardize sensitive data or farm operations.
Strong encryption, multi-factor authentication, secure data transmission protocols, and frequent vulnerability assessments are necessary to guarantee data availability, confidentiality, and integrity.
Particularly for farms engaged in international trade, adherence to local policies and data protection laws like the GDPR is crucial. The vital importance of strong cybersecurity frameworks and openness in gathering, storing and sharing data are necessary ingredients for fostering public trust of IoT systems.

E. Security, Privacy, and Data Reliability

The integration of IoT in aquaculture introduces vulnerabilities at the device, network, and cloud levels. Threats include sensor spoofing, man-in-the-middle attacks, unauthorized dashboard access, and malicious data modification.
These risks can compromise decision-making and farm productivity. To address these challenges, the following mitigation strategies are recommended as shown in Table IV.
Enhancing data reliability involves deploying redundant sensor nodes, using fog-computing buffers for local decision-making, and maintaining immutable blockchain logs for transparency. Regular security audits and firmware updates are crucial for maintaining resilience.

TABLE IV: RECOMMENDATIONS FOR CYBER SECURITY

Threat Category	Potential Risk	Recommended Mitigation
Data Interception	Leakage of water-quality data in transit	Apply end-to-end TLS 1.3 encryption and VPN tunneling
Unauthorized Access	Control-panel hijacking	Implement two-factor authentication and OAuth 2.0 authorization
Sensor Spoofing	False readings triggering wrong actions	Use blockchain-based data immutability and periodic checksum validation
Cloud Breaches	Loss of stored data or metadata	Employ role-based access and AES-256 encrypted backups
Network Downtime / Reliability	Data gaps due to poor connectivity	Enable edge-buffering and redundant mesh networking
Data Drift / Calibration Errors	Inaccurate trends over time	Periodic auto-calibration and anomaly-detection algorithms

F. Standardization and Interoperability

The absence of recognized standards among the manufacturers of devices and sensors for the IoT is hampering the smooth integration of devices and systems. This fragmentation hampers system flexibility, and without it, there can be no integration. Universal standards must be used with respect to data formats, communication protocols, and device compatibility if we are to get general acceptance.
Interoperability enables farms to have a few diverse systems which can relate to each other as one system such as a disease detection, eating automation, environmental monitoring. Such integration enhances farm management in a total way thus improving efficiencies. Furthermore, standardisation gives rise to co-operation between researchers, regulators, and suppliers of data.

G. Data Reliability and Integrity in IoT Aquaculture

For a sustainable future, it is important to have data reliability. Sensor drift, biofouling or signal interference can affect the quality of the data. The use of redundant sensing nodes, the implementation of edge level caching and the application of data correction algorithms using a Kalman Filter creates robustness. To create efficiencies in terms of veracity, the use of blockchain technology can be adopted to create a platform where transactions of data exist in an immutable and transparent manner, such that it is known by farmers and appropriate regulatory agencies. Periodic synchronisation of the edge devices with the cloud will create consistency in use of Sensor Data whilst the systems are offline.

H. Energy and Cost Efficiency

In the case of small and medium shrimp farms, the operational costs and the energy consumption characteristics are important parameters. The functioning of the IoT devices depends on the energy supplied guaranteeing their continued operation. If they do not have energy efficient components nor use energy supplied from renewable sources, then their long-term operation may not be a practicable proposition. There will be a need to develop low power sensors and gateways supplied from solar energy for sustainability. Reducing the overall cost of access to the IOT eco-systems including hardware, connectivity and software remains a priority. Affordable modular systems, subscription-based platforms and local manufacture of sensors offer a productive means of reducing barriers to entry and promoting equitable access to smart farming technologies.

I. Training and Awareness

The ability of farm personnel to operate the technology and maintain it is a prerequisite for the successful application of IoT based systems. Many farms do not have the expert knowledge required for the calibration of sensor systems, the interpretation of data or the debugging of software systems, where applicable. The development of easy-to-use interfaces and systems to facilitate the training of staff is important. It is important that farmer education, training and information workshops, extension briefings and awareness programmes is created to disseminate knowledge of the technology and impart information on the advantages, limitations and procedures in the operation of IoT systems. Using learned organisations, universities and agri-tech start up companies to inform farmers will help in the effective implementation of smart aquaculture systems and sustainable long-term outcome.

VIII. CONCLUSION

A. Summary of Key Findings

This study presents a comprehensive review of the integration of Information and Communication Technology (ICT) and networked sensor systems for monitoring water quality in shrimp farming and aquaculture. The study opens with a statement of the importance of water quality to aquaculture and a brief discussion of the shortcomings of conventional monitoring techniques including laboratory analyses and sampling techniques. It shows how the IoT systems including wireless technologies, sensing systems, data management and big data technologies can provide an effective, scalable and real time solution to this problem. Findings presented in this study show considerable advantages of the use of IoT technologies and how they provide advantages in monitoring water quality parameters, responsiveness of operations and sustainability of shrimp farming operations through a detailed consideration of system architecture, sensor technology, protocols, data management platforms, analytics, big data platforms and international case studies. The successful implementation of ICT technologies for efficient farm production in case studies undertaken in Vietnam, Ecuador and Thailand are discussed and the positive benefits of monitoring are analyzed in terms of production and efficiency of resources utilized in farm management, environmental compliance and legal obligations met. The discussion now focuses on adding context to the discussion in terms of technology trends including AI application, big data analysis and wireless and networking implications.

B. Practical Implications

The benefits of IoT to shrimp farmers are not reflected in the results of this survey. Benefits from IoT to shrimp farmers will include possible real time monitoring for rapid intervention, which means lower disease potential and better health for the shrimp, while data driven management will improve production efficiency while lowering contamination of feed/ water targets and supplementation. The application of automated data collection and remote audit control offers more prompt responses to regulatory agencies suggestions. However, the need for good channels of communicating how to use this technology must be established to help the farmers. To this end, there are several ways of accomplishing this, including leaving open lines of communication, properly calibrating the sensors used and communicating and training those that must operate the sensors and actuators. The vendors supplying the IoT system must see that it is offered in a more user-friendly format and still have local customer service when it may be required. The aid of government and research organizations will be beneficial via grants and lower sales tax rates, and the advent of more open systems. Again, a co-ordinated effort in promoting the utility of smart aquaculture technologies and their commercial manner of usage will give the shrimp producers a more effective production means and potentially show them ways of lowering production costs.

C. Future Directions and Recommendations

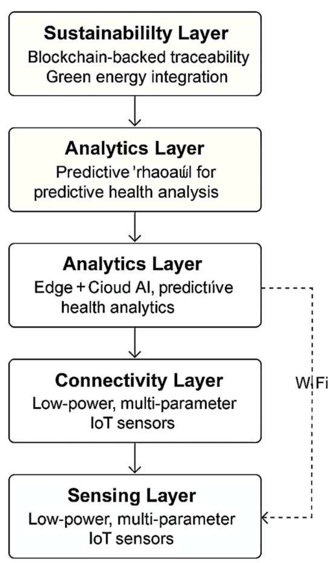

Figure 4. Future Roadmap for Smart Shrimp Aquaculture

The future promise of the IoT in aquaculture greatly depends on the continued development of technology directed towards edge computing, AI based support decision systems and sensors that require little energy. Future research should be dedicated to low cost developed modular systems that can help small and medium scale farmers particularly in resource starved parts of the world. To achieve this will require interoperable

frameworks that allow integration of the IoT technology with the automation tools already available in aquaculture such as smart feeders and climate sensors. It will be required to build also institutional capacity. Teaching and training for farmers and technicians that come as part of continued education initiatives will help close skills gaps and allow continued use of these systems. Policymakers will also have to realise that there is a need for the development of national policy guidelines for the integration of the IoT into aquaculture and develop policies that foster new technological innovations by means of pilot projects and public/private partnerships. As the industry develops, it will be essential that the policies, technology and education related to the IoT in fisheries, become totally interlinked and interdependent if the full potential is going to be realised.
The Future Roadmap for Smart Shrimp Aquaculture depicted in Figure 4 presents a multi-layered framework supported by AIoT framework that covers several aspects, such as sensing, IoT connectivity, analytical applications, decisions, and sustainable development. The Sensing layer acquires necessary water-quality data; this data will be transmitted via the connectivity layer using either Wi-Fi or LoRaWAN. The analytics layer uses AI and cloud processing to serve prediction needs, Decisions would be automated for aeration, feeding, and water management.

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