IoT-Enabled Real-Time Water Quality Monitoring for Shrimp Farming: Trends, Challenges, and Future Directions in Sri Lanka: A Systematic Review

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***Abstract*— Shrimp farming plays a significant role in Sri Lanka's aquaculture industry, contributing substantially to the national economy. However, many shrimp farms still rely on manual monitoring methods to assess critical water quality parameters such as pH, temperature, dissolved oxygen, and salinity. These outdated approaches often result in delayed responses to unfavorable water conditions, leading to reduced productivity, increased shrimp mortality, and environmental degradation. This research proposes the development of an intelligent, real-time water quality monitoring system specifically designed for small- and medium-scale shrimp farms in Sri Lanka. The system integrates low-cost, semiconductor-based IoT sensors to continuously monitor key parameters and transmit the data to a cloud-based platform for real-time analysis and visualization. By automating the monitoring process, the system enables farmers to respond quickly to changes in water quality, improving shrimp survival rates and overall farm efficiency. The proposed solution is designed to be user-friendly and cost-effective, making it accessible to local farmers with limited technical expertise. This innovative approach not only enhances productivity but also promotes sustainable aquaculture practices by optimizing resource usage and minimizing environmental risks.**

Keywords *– Shrimp Farming, IoT, Real-Time Water Quality Monitoring, Predictive Analytics, Smart Aquaculture.*

I. INTRODUCTION

Shrimp farming plays a vital role in Sri Lanka's aquaculture sector, contributing significantly to national income and employment, especially in coastal areas [1], [2]. However, the industry faces numerous challenges, such as environmental pollution, water quality degradation, disease outbreaks, and inefficient farm management [3]. One of the most pressing issues is the lack of continuous monitoring and control of water quality parameters, which often results in reduced productivity and negative environmental impacts [3], [4], [5]. Traditional monitoring methods depend on manual sampling and laboratory testing, which are not only time-consuming and labor-intensive but also result in delayed responses to water quality changes [2], [4], [6], [7], [8]. Since shrimp are highly sensitive to variations in parameters like pH, temperature, dissolved oxygen (DO), and salinity, timely and accurate monitoring is essential for maintaining a healthy aquaculture environment and achieving better yields [1], [6], [9].

This IoT-based approach is expected to improve farm-level decision-making, enhance sustainability, reduce operational costs, and support small- and medium-scale shrimp farmers in Sri Lanka. It aligns with national efforts to modernize aquaculture practices and promote environmentally responsible shrimp farming amidst rising global demand [7], [10].

II. OVERVIEW OF SHRIMP FARMING IN SRI LANKA

Shrimp farming was first introduced in Sri Lanka during the 1980s, initially concentrated in the Northern and Eastern coastal regions[1], [2]. Over the years, the industry has developed significantly and has become one of the country's most economically essential aquaculture sectors. In recent years, shrimp has emerged as the second-highest export commodity in terms of value among Sri Lanka's fish and fishery product exports. The Northwestern Province, particularly areas such as Puttalam and Chilaw, has become a key hub for shrimp aquaculture, contributing substantially to the sector's growth and national income[11]. Initially, Sri Lankan shrimp farmers primarily cultured *Penaeus monodon* in brackish-water monoculture systems[1]. This remained the dominant practice until 2018, when the introduction of exotic and genetically improved Specific Pathogen Free (SPF) Pacific white shrimp (*Penaeus vannamei*) marked a significant shift in farming practices[12].
Sri Lanka's shrimp farming industry, primarily based on *Penaeus vannamei*, has faced numerous challenges, including water pollution, high mortality due to poor farm management, and unregulated effluent discharge[13]. It identified self-pollution as one of the major risks for long-term sustainability in Puttalam[3].

Over-intensification has led to the accumulation of toxic compounds such as ammonia, which severely affect dissolved oxygen (DO) levels and shrimp health. Improper soil management, the use of antibiotics, and inconsistent monitoring of critical parameters, such as pH, DO, and salinity, are significant threats to productivity[14]. Thus, a real-time solution is essential to avoid reactive responses and support proactive decision-making[8], [9].

III. Critical Water Quality Parameters in Shrimp Aquaculture

Dissolved oxygen (DO), pH, salinity, and temperature are critical water quality parameters that significantly influence the survival, growth, and productivity of shrimp[3], [15], [16]. In shrimp farming, water quality issues are becoming increasingly common due to high stocking densities, elevated feeding rates, and the intake of polluted water. A comprehensive understanding of ecological processes within shrimp aquaculture systems is essential for addressing disease prevalence among shrimp populations. Poor water quality management elevates stress levels in shrimp, thereby weakening their immune response and significantly increasing their susceptibility to pathogenic infections. This not only compromises overall health but also adversely affects production efficiency and yield[3], [8], [9].

Temperature plays a critical role in regulating the biological and physiological activities of aquatic organisms within shrimp farming ecosystems. Seasonal fluctuations in water temperature are largely influenced by variations in air temperature, solar intensity, and day length[8], [17]. As water temperature increases, it accelerates chemical reactions, decreases the solubility of dissolved gases, and enhances both the taste and odor of water, along with intensifying biological activity among aquatic flora and fauna. During the study period, water temperature varied between 18 °C and 32 °C, which may be attributed to diurnal solar positioning and seasonal transitions. While aquatic organisms in unpolluted environments typically exhibit a broad tolerance to temperature variation, polluted water bodies may experience abrupt temperature shifts that disrupt metabolic functions, reduce dissolved oxygen (DO) levels, and negatively impact aquatic health. Therefore, continuous temperature monitoring is essential, especially as it correlates with increased levels of free carbon dioxide and influences DO concentration—both of which are vital to maintaining aquatic equilibrium[8], [16], [17].

pH, a critical indicator of water quality, represents the hydrogen ion activity in a solution and is expressed as the negative logarithm of hydrogen ion concentration at a given temperature[18]. In aquaculture, maintaining an optimal pH range is essential for the physiological well-being and productivity of aquatic organisms. Water with pH values between 6.0 and 9.0 is generally considered conducive for the healthy growth and metabolic functions of cultured species. However, growth may be significantly inhibited when pH levels fall below 5.0 due to the increased physiological stress it places on aquatic organisms[17], [19]. Seasonal variations often influence pH levels, with lower values typically observed during late winter. This decline is primarily attributed to reduced phytoplankton activity resulting from limited sunlight and photosynthetic activity, which affects carbon dioxide absorption and subsequently alters the water's buffering capacity. In the shrimp farm under study, the water was found to be consistently alkaline, with pH values generally ranging between 6.5 and 8.5, conditions considered optimal for sustaining water productivity and supporting the normal physiological processes of aquatic life[1], [14], [17], [18], [20]. These findings underscore the importance of continuous pH monitoring to ensure the sustainability and health of aquaculture environments.

Fluctuations in dissolved oxygen (DO) levels, including episodes of hypoxia (low oxygen) and anoxia (near or complete oxygen depletion), are common and potentially harmful events in aquaculture environments[3], [8], [17], [19]. These variations can occur daily or seasonally and have a profound impact on shrimp health, growth, and overall pond ecosystem stability. Among the various water quality parameters, DO is widely recognized as the most critical, particularly in shrimp farming systems where oxygen demand is high due to stocking density, feed decomposition, and organic load[15], [21], [22]. Shrimp, being aerobic organisms, require a minimum concentration of dissolved oxygen to maintain normal physiological functions and immune responses. Numerous studies recommend that DO levels in shrimp ponds should be maintained above 4–5 mg/L (ppm) to avoid stress and disease susceptibility[15], [23], [24]. When DO levels fall below this threshold, shrimp experience reduced metabolism, feeding inhibition, and increased vulnerability to opportunistic pathogens, ultimately leading to higher mortality rates and production losses. Dissolved oxygen in aquaculture ponds is primarily sourced from two mechanisms: diffusion from atmospheric air and photosynthetic activity by aquatic plants and phytoplankton. During the daytime, especially under sunny conditions, photosynthesis significantly contributes to oxygen production, while at night, respiration dominates, and oxygen levels decline sharply. This diurnal fluctuation can create dangerous early morning lows, particularly in systems with high biological oxygen demand (BOD)[17], [21], [25]. Temperature is a key factor influencing DO concentration, as the solubility of oxygen decreases with rising water temperatures. Warmer water not only holds less oxygen but also increases the metabolic rate of aquatic organisms, further accelerating oxygen depletion. In heavily stocked shrimp ponds, this can quickly lead to hypoxic conditions if not properly managed[6], [26], [27]. To mitigate these risks, mechanical aeration using devices such as paddle wheel aerators or diffused air systems is commonly employed to supplement DO levels, especially during critical periods such as nighttime or cloudy weather[17], [19]. The strategic use of aerators not only supports shrimp oxygen requirements but also enhances water circulation, prevents thermal stratification, and promotes waste degradation by aerobic microorganisms[7].

Salinity is a fundamental water quality parameter that significantly affects the physiological and metabolic functions of cultured aquatic organisms, particularly shrimp[8], [19], [23]. It plays a critical role in osmoregulation, the process by which aquatic animals maintain the balance of salts and minerals within their body fluids relative to the surrounding water. Optimal salinity conditions are essential for maintaining cellular homeostasis, enzymatic activities, molting, growth rates, and survival of shrimp[28], [29]. In tropical aquaculture systems, salinity levels tend to fluctuate seasonally due to variations in evaporation and precipitation. During the dry summer months, increased evaporation rates typically lead to a rise in pond salinity. Conversely, in the rainy season, salinity levels tend to decrease due to freshwater influx from rainfall or surface runoff, potentially leading to osmotic stress in cultured shrimp populations if not properly managed[8]. The early larval and post-larval stages of both *Penaeus monodon* (black tiger shrimp) and *Penaeus vannamei* (Pacific white shrimp) generally require seawater salinity levels close to that of natural marine environments, typically around 30–35 parts per thousand (ppt)[19], [28], [29]. However, as shrimp mature, they exhibit a remarkable adaptability to a wide range of salinity levels. Numerous studies have indicated that *P. vannamei*, in particular, can tolerate salinity ranges from 5 ppt to 38 ppt[8]. Despite this tolerance, the optimal salinity range for maximum growth performance, feed conversion efficiency, and survival lies between 15 and 23 ppt[28]. Salinity outside the optimal range can adversely impact shrimp health. Low salinity may affect osmoregulatory capacity and increase susceptibility to stress and disease, while excessively high salinity can reduce feeding rates and slow metabolic processes. Additionally, abrupt changes in salinity due to sudden weather changes can cause physiological shock, leading to increased mortality or reduced growth rates[19], [26], [30]. To ensure stable salinity levels, shrimp farmers must implement effective water management practices such as controlled water exchange, use of salinity buffers (e.g., seawater/freshwater mixing), and real-time monitoring using salinity sensors[4], [7]. Monitoring salinity in conjunction with other water quality parameters like temperature, pH, and dissolved oxygen allows for proactive management of the shrimp pond environment, ultimately improving productivity and sustainability[1], [7], [31].

IV. Traditional Water Quality Monitoring Methods

In Sri Lanka, shrimp aquaculture remains heavily dependent on conventional manual methods for monitoring water quality[1], [3], [14], [32]. Most shrimp farmers conduct basic water testing manually once or twice a day, typically using handheld instruments or visual inspection techniques. While these methods are low-cost and relatively straightforward, they present significant limitations in terms of precision, frequency, and responsiveness to sudden environmental fluctuations. One of the most critical drawbacks is the inability to continuously monitor dynamic parameters such as dissolved oxygen (DO), which is known to vary significantly over short time intervals, particularly during nighttime when photosynthesis ceases and phytoplankton respiration causes rapid DO depletion[2], [14], [32]. This issue is exacerbated by the tropical climatic conditions in Sri Lanka, where extreme daytime temperatures and sudden weather changes can further stress aquaculture systems. High ambient temperatures increase water evaporation and reduce gas solubility, thereby affecting DO concentrations. Without real-time monitoring and timely intervention, such changes can quickly lead to hypoxic conditions, increasing shrimp mortality and lowering overall productivity[3], [32]. Commercial shrimp farms also face practical challenges in implementing comprehensive water quality assessments across large farming areas. Monitoring a wide range of ponds or tanks spread over extensive lands becomes labor-intensive and costly[32]. In addition, the high cost of advanced water quality monitoring technologies, such as multi-parameter probes or automated data loggers, limits their accessibility, especially for small- and medium-scale farmers. Consequently, water quality analysis is often limited to a small subset of parameters typically temperature, pH, and salinity that are relatively easy to measure and deemed most immediately relevant to shrimp health[1], [2], [20]. However, this selective monitoring approach overlooks critical variables like ammonia, nitrites, nitrates, and DO variability, which are equally important in maintaining optimal aquaculture conditions. The absence of continuous and comprehensive monitoring can delay detection of deteriorating water quality, resulting in stress, disease outbreaks, and economic losses[5]. These limitations highlight the urgent need for an affordable and automated real-time water quality monitoring system tailored to the Sri Lankan context. Integrating cost-effective semiconductor-based IoT sensors can enable continuous monitoring of key parameters such as temperature, DO, pH, and salinity[7], [10], [33]. Such a system would allow farmers to respond proactively to unfavorable conditions and maintain water quality within the ideal range, thereby improving shrimp survival, reducing labor dependence, and enhancing overall farm efficiency and sustainability.

V. Applications for IoT in Aquaculture Monitoring

The Internet of Things (IoT) has revolutionized aquaculture practices across several Asian countries by enabling real-time monitoring and automation of water quality management[7], [10], [21], [34]. Through the integration of interconnected devices such as microcontrollers, low-cost water quality sensors (measuring parameters like pH, dissolved oxygen, and temperature), wireless communication modules, cloud-based data storage, and user-friendly visualization dashboards, IoT systems provide farmers with timely insights to optimize farm operations and ensure the well-being of aquatic species[4], [6], [7]. In countries such as Bangladesh and Indonesia, IoT-driven platforms like Smart Aqua and Aqua-IoT have already demonstrated measurable benefits, including improved feed conversion ratios, early detection of disease outbreaks, reduced shrimp mortality, and enhanced environmental sustainability. These systems allow for continuous monitoring and predictive alerts that support data-driven decision-making, thereby increasing both productivity and profitability in aquaculture enterprises[7], [10], [21]. Despite these advancements in neighboring regions, the adoption of IoT-based aquaculture systems in Sri Lanka remains minimal[1], [10], [11]. Most local shrimp farms continue to rely on manual or semi-automated water quality monitoring approaches, which are inadequate for responding to the dynamic and sensitive conditions required for optimal shrimp health[1], [2]. High initial costs, lack of technical know-how, and limited access to affordable digital infrastructure have been cited as major barriers to IoT adoption in the country[4]. The critical need for integrating such modern technologies into Sri Lanka's aquaculture sector, particularly to support small- and medium-scale shrimp farmers who often lack access to real-time monitoring tools[5], [9], [35], [36], [37]. Given the country's vulnerability to climate variability and disease outbreaks, IoT-based solutions present a viable path forward to improving aquaculture efficiency, biosecurity, and economic resilience[3], [35]. To address this gap, locally tailored, cost-effective IoT systems, preferably based on semiconductor sensor technology and open-source platforms, should be developed and promoted[38], [39]. These systems must prioritize ease of use, mobile accessibility, and support for low-bandwidth rural environments, enabling widespread adoption even among resource-constrained farmers. Such an approach not only aligns with Sri Lanka's strategic goals for sustainable aquaculture development but also sets the foundation for the eventual integration of AI-based predictive analytics and automation in future innovative farming initiatives[10].

A systematic literature review was conducted to identify, evaluate, and synthesize existing research on IoT-enabled real-time water quality monitoring for shrimp farming. The process followed structured guidelines for evidence-based reviews to ensure comprehensive coverage and transparency in study selection [4], [7], [10].

VI. Methodology

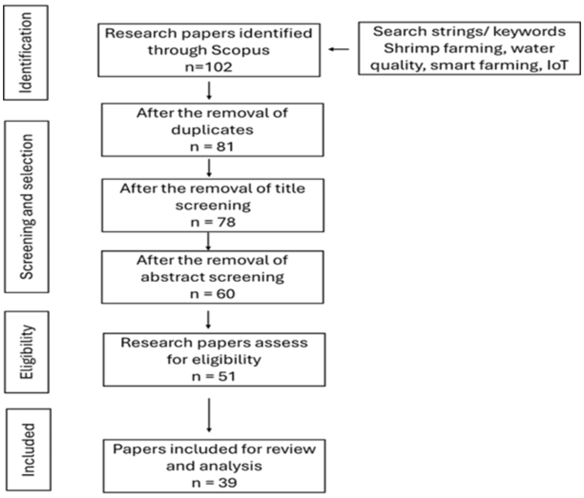

Figure. 1

The literature search was performed across multiple scholarly databases, including ScienceDirect, Scopus, Web of Science, and Google Scholar, to capture both peer-reviewed journal articles and relevant conference proceedings.

Scopus Search terms were developed based on key concepts in the research topic, combining IoT-related terms such as "Internet of Things", "real-time monitoring", and "wireless sensor networks" with aquaculture-specific terms such as "shrimp farming", "water quality", and "aquaculture management" [3], [5], [34], [38]. The initial search yielded 102 publications. After removing 24 duplicates, 78 unique studies remained for screening. Titles and abstracts were reviewed to exclude studies unrelated to IoT or water quality monitoring, as well as those focusing on non-aquaculture domains, which led to the exclusion of 39 papers. The remaining 39 full-text articles were assessed against the inclusion criteria: direct application of IoT or automated sensing in aquaculture, measurement of key water quality parameters such as pH, dissolved oxygen, temperature, and salinity, relevance to shrimp farming or transferable to shrimp aquaculture contexts, and publication in English. Studies without experimental validation, purely conceptual works without implementation, or those focusing on unrelated aquaculture systems were excluded [6], [15], [31]. This stage excluded 13 papers, resulting in 26 articles being selected for the final analysis.

The overall selection process is illustrated in Figure 1, showing the number of records identified, screened, excluded, and included at each stage, providing transparency and reproducibility in the review methodology.

VII. RESULTS

The final review included 26 studies, covering a diverse range of IoT-enabled water quality monitoring applications relevant to shrimp farming. Most studies originated from Asia, particularly Bangladesh, Indonesia, Vietnam, India, and China, with limited representation from African and South American contexts. No studies were found that focused explicitly on Sri Lanka, highlighting a geographic research gap. Water Quality Parameters Across the reviewed studies, dissolved oxygen (DO), temperature, pH, and salinity emerged as the most frequently monitored parameters [5],[7],[15],[28]. Several systems also integrated sensors for ammonia, nitrite, nitrate, turbidity, and total dissolved solids (TDS), though these were less common due to higher costs and calibration requirements [6],[19],[27]. Sensor Technologies. Most implementations used low-cost electrochemical and semiconductor-based probes connected to microcontrollers such as Arduino, ESP32, or Raspberry Pi [7],[36]. Wireless transmission was typically enabled through Wi-Fi modules [31], [34], with cloud platforms such as ThingSpeak, Blynk, and custom dashboards used for data visualization. System Performance Many studies reported that IoT-based systems provided high-frequency data collection (every 1–10 minutes) with real-time alerts for parameter deviations. This enabled proactive intervention, reducing shrimp mortality and improving growth performance [5], [7], [21]. Field trials demonstrated that real-time systems could maintain DO above 4 mg/L and salinity within optimal ranges more consistently than manual monitoring approaches [19], [28]. Economic and Operational Benefits Several studies quantified operational benefits, including reduced labor requirements, early detection of harmful conditions, and improved feed conversion ratios [7], [21], [36]. However, initial installation costs and maintenance (sensor calibration, biofouling prevention) were identified as recurring challenges [4], [6], [31].

VIII. DISCUSSION

The reviewed literature demonstrates the clear potential of IoT-enabled water quality monitoring to improve aquaculture efficiency, biosecurity, and sustainability. The consistency of monitored parameters, DO, pH, temperature, and salinity reflects their critical importance to shrimp health and productivity [3], [8], [15]. Notably, most systems employed commercially available, low-cost sensors, making them financially feasible for small- to medium-scale operations, although maintenance remains a significant barrier. Technology Readiness. While many studies demonstrated working prototypes in controlled environments, fewer reported long-term deployment in operational farms. Durability under harsh aquaculture conditions (biofouling, corrosion, fluctuating salinity) is still underexplored, suggesting a need for robust sensor housings and automated calibration mechanisms [6], [31]. Data Utilization: Current systems primarily provide real-time monitoring and threshold-based alerts. Only a small subset integrated predictive analytics or machine learning for forecasting water quality trends [6], [7], [36], indicating an opportunity for AI-enhanced decision support. Relevance to Sri Lanka: The absence of Sri Lanka-specific research underscores an urgent need to develop and validate IoT systems tailored to local shrimp farming practices. Factors such as tropical climate variability, seasonal salinity shifts, and disease prevalence necessitate adaptive monitoring strategies. Furthermore, rural connectivity limitations suggest that LoRa or NB-IoT-based architecture may be more appropriate than Wi-Fi-dependent systems [4], [31].

Future Directions To maximize impact, future research should prioritize long-term field validation of IoT-based systems in commercial shrimp farms to assess reliability, scalability, and return on investment [6], [31]. The integration of multi-parameter sensing beyond the “core four” (DO, pH, temperature, salinity) to include nitrogen compounds, turbidity, and other critical indicators will enable more comprehensive water quality assessment [15], [19], [27]. Leveraging AI-powered intelligent agents can enhance these systems by enabling real-time anomaly detection, predictive modeling of water quality trends, and automated decision recommendations, thereby shifting aquaculture management from reactive responses to proactive, preventive interventions [6], [7], [36]. Furthermore, emphasis should be placed on user-centric design, ensuring that interfaces are intuitive, mobile-accessible, and optimized for farmers with limited technical training, which will facilitate adoption and long-term sustainability [4], [31], [35].

Overall, IoT-enabled real-time monitoring offers a scalable pathway to address the operational inefficiencies and environmental risks currently facing Sri Lanka’s shrimp aquaculture sector. By adapting proven solutions from other countries and addressing local constraints, such systems could significantly enhance productivity, sustainability, and economic resilience.

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