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Fish pond salinity sensors: measurement principles, sensor architectures, calibration, and real-time monitoring technologies

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ABSTRACT

Salinity is a critical water-quality variable in fish ponds because it influences osmoregulation, growth, feeding, and the survival of cultured species. Yet many small and medium-scale farms still depend on manual sampling or handheld meters, which provide intermittent measurements and may fail to reveal rapid changes caused by rainfall, evaporation, water exchange, or tidal intrusion. This review examines sensor technologies and monitoring architectures relevant to continuous pond-salinity measurement, using literature published no later than 2018. The discussion focuses on electrical-conductivity sensing, electrode configurations, temperature compensation, calibration, corrosion and biofouling, embedded signal conditioning, and wireless data transmission. Conductivity-based sensors offer practical advantages in cost, response time, and suitability for continuous measurement, but conductivity is not identical to salinity and must be interpreted through an appropriate calibration or conversion model. Two-, four-electrode, capacitive, microfabricated, and graphene-based designs address different trade-offs in sensitivity, polarization, fouling, and manufacturability. The review identifies field calibration, long-term stability, species-specific thresholds, and affordable maintenance as major unresolved issues. It concludes that a reliable pond instrument should combine temperature-compensated conductivity measurement, robust packaging, periodic reference checks, and actionable alerts rather than treating a low-cost sensor as a stand-alone solution.

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1. INTRODUCTION

Water quality is one of the main factors determining the success of fish farming, and salinity is particularly important in freshwater, brackish-water, and marine aquaculture. Changes in dissolved salt concentration can influence the osmotic balance of fish, affecting physiological processes, feeding behavior, growth, and survival. Pond salinity may fluctuate because of rainfall, evaporation, groundwater input, tidal exchange, water replacement, and seasonal changes. Consequently, farmers need reliable measurements that can identify unfavorable changes before they cause significant stress or production losses.

Traditional salinity monitoring commonly relies on handheld refractometers, portable conductivity meters, or laboratory analysis of collected water samples. These methods can provide useful measurements, but they generally require manual operation and do not continuously represent changing pond conditions. Manual sampling also makes it difficult to identify short-duration fluctuations or differences between locations within a pond. These limitations motivate the development of electronic sensors capable of continuous measurement, automatic data recording, and remote notification.

Electrical conductivity is a practical measurement principle for electronic salinity sensors because dissolved ions increase the ability of water to conduct electrical current. Conductivity sensors can therefore provide an indirect estimate of salinity when their outputs are calibrated against suitable reference solutions

and interpreted with appropriate compensation. Research on conductivity cells, microfabricated sensors, and wireless aquaculture monitoring provides a foundation for designing such systems [1]–[6]. This review connects these developments to the specific requirements of fish pond monitoring and identifies the technical issues that must be addressed before reliable field deployment.

2. RESEARCH SCOPE AND FUNDAMENTAL MEASUREMENT PRINCIPLES

This review examines publications available up to 31 December 2018 concerning salinity measurement, conductivity sensor design, water-quality instrumentation, and electronic monitoring in aquaculture. The selected literature includes research on electrode configurations, microfabrication, sensor materials, calibration, and wireless monitoring architectures. Some studies investigate marine or industrial water rather than fish ponds, but their measurement principles remain relevant to pond-salinity instrumentation. The review distinguishes direct salinity measurement from conductivity-based estimation because these quantities are related but are not interchangeable.

Salinity describes the concentration of dissolved salts in water, whereas electrical conductivity describes the ability of water to conduct electrical current. Conductivity is affected by the types and concentrations of dissolved ions, as well as temperature and, in some applications, pressure. The Practical Salinity Scale 1978 established a standardized relationship between seawater conductivity and practical salinity, providing an important foundation for conductivity-based measurement [7]-[9]. However, pond water may contain mixtures of dissolved substances that differ from standard seawater, so a marine conversion model should not automatically be applied to every freshwater or brackish-water pond.

Total dissolved solids (TDS) are also frequently used in low-cost water-monitoring devices, but TDS should not be treated as a direct equivalent of salinity. TDS estimates the mass concentration of dissolved substances, while conductivity measures their collective electrical response. Commercial instruments often estimate TDS from conductivity using an empirical conversion factor, which may vary with water composition. Therefore, a pond instrument intended to report salinity should be calibrated using water samples representative of the actual pond environment.

3. ELECTRICAL CONDUCTIVITY SENSOR TECHNOLOGIES

3.1. Two-electrode conductivity sensors

Two-electrode conductivity sensors are attractive for low-cost instruments because their construction and electronic interfaces are relatively simple. The basic design applies an alternating electrical signal across two electrodes immersed in water and measures the resulting electrical response. The measured response changes with the conductivity of the surrounding solution, allowing the instrument to estimate salt concentration after calibration. Flexible salinity-sensing research by Kaidarova *et al.* [10] demonstrated that two-electrode impedance measurement can be implemented using flexible conductive structures and can reduce some effects associated with conventional low-frequency measurements.

Despite their simplicity, two-electrode sensors can experience electrode polarization, corrosion, and surface contamination [11]. Direct current excitation is generally unsuitable for stable long-term conductivity measurement because electrochemical reactions may alter the electrode surfaces and distort the signal. Alternating excitation helps reduce these effects, but the selected frequency and electrode material still influence measurement performance. For pond applications, two-electrode designs are most appropriate when cost and simplicity are important and when regular cleaning and calibration can be maintained.

3.2. Four-electrode conductivity sensors

Four-electrode configurations were developed to improve measurement stability and reduce errors associated with electrode polarization and contact resistance. In this arrangement, two electrodes introduce the excitation current while the remaining electrodes measure the voltage difference within the water. This separation reduces the influence of electrode-interface effects on the measured conductivity. Ramos *et al.* [3] presented a four-terminal conductivity sensor that also incorporated temperature measurement to compensate for conductivity changes caused by water temperature.

Four-electrode systems are particularly relevant when conductivity varies over a broad range or when long-term measurement stability is required. Broadbent *et al.* [2] developed a miniature conductivity, temperature, and depth instrument using a planar four-electrode cell for coastal salinity measurements. Their work demonstrated the feasibility of compact sensor construction using printed-circuit-board microfabrication techniques. Although the original application involved coastal water, the same principles can support more reliable salinity instruments for brackish-water aquaculture.

3.3. Microfabricated and capacitive sensors

Microfabrication provides opportunities to reduce sensor dimensions, integrate multiple sensing elements, and simplify the production of compact instruments. Huang *et al.* [6] developed a miniature conductivity and temperature sensor system for ocean monitoring using a multi-electrode conductivity cell and an integrated temperature element. Birkelund *et al.* [5] also investigated a miniaturized multisensor platform for aquatic studies, demonstrating the potential of integrating different measurement functions into a compact device. These developments are relevant to fish pond systems because smaller sensor packages can be installed in protective housings or distributed across several measurement locations.

Capacitive and contactless conductivity sensing offers an alternative to conventional exposed-electrode arrangements. Huck *et al.* [8] investigated a capacitively coupled electrolyte-conductivity sensor based on barium strontium titanate, demonstrating an approach in which the sensing structure can be separated from direct electrolyte contact. This arrangement is attractive where corrosion and electrode contamination are important concerns. Nevertheless, the practical suitability of such sensors depends on their sensitivity, fabrication complexity, electronic interface, and calibration requirements.

3.4. Graphene-based and flexible sensors

New electrode materials have been investigated to improve sensitivity, flexibility, and manufacturing cost. Nag *et al.* [9] developed a salinity sensing system using laser-induced graphene on flexible polymer substrates and demonstrated conductivity-related responses to different sodium chloride concentrations. The study is particularly relevant because it connected a material-level sensing element with signal conditioning and microcontroller-based measurement. Kaidarova *et al.* [10] subsequently demonstrated a flexible salinity sensor designed to reduce the effects of biofouling under specific measurement conditions. Flexible and printed sensors may be useful for compact instruments installed in floating monitoring platforms or protective housings. Their potential advantages include reduced material consumption, low fabrication complexity, and the possibility of producing sensor elements in different geometries. However, long-term performance in fish ponds requires further investigation because water chemistry, suspended solids, microbial growth, and mechanical handling can affect exposed sensing materials. Material selection should therefore be evaluated through extended immersion tests rather than short laboratory measurements alone.

4. TEMPERATURE COMPENSATION AND SENSOR CALIBRATION

Temperature compensation is essential because electrical conductivity generally changes as water temperature changes, even when the dissolved salt concentration remains constant. An instrument that measures conductivity without accounting for temperature may incorrectly interpret thermal variation as a change in salinity. Integrated conductivity and temperature systems provide a practical solution by collecting both measurements and applying an appropriate correction during signal processing. Studies by Broadbent *et al.*, Ramos *et al.*, and Huang *et al.* demonstrate the importance of combining conductivity measurement with temperature sensing [2], [3], [6].

Calibration determines the relationship between the sensor output and known salinity or conductivity values. A reliable calibration procedure should use reference solutions that cover the expected operating range of the target pond. For freshwater and brackish-water applications, calibration should reflect the actual ionic composition as closely as possible rather than relying exclusively on seawater standards. Periodic comparison with a calibrated commercial instrument or laboratory reference is also necessary to detect sensor drift.

Calibration should be treated as an ongoing maintenance activity rather than a one-time manufacturing step. Electrode deposits, changes in surface condition, cable degradation, and electronic component aging may gradually alter the sensor response. A practical instrument should therefore support recalibration, retain calibration records, and identify measurements that fall outside its validated operating range. These measures are particularly important when salinity data are used to guide water exchange or other pond-management decisions.

5. SENSOR INTEGRATION AND REAL-TIME POND MONITORING

A complete pond-salinity monitoring instrument requires more than a sensing element because the measured signal must be conditioned, processed, stored, and communicated. A typical architecture includes a conductivity probe, a temperature sensor, an analog signal-conditioning circuit, a microcontroller, a power supply, and a communication module. The microcontroller converts sensor signals into calibrated measurements and can compare the results with configured warning levels. This architecture can also be

extended to include pH, dissolved oxygen, temperature, and water-level sensors when broader water-quality assessment is required.

Wireless sensor networks provide a way to monitor multiple locations without installing extensive signal cables throughout a pond facility. Simbeye and Yang presented a wireless monitoring and control architecture for aquaculture using sensor nodes and ZigBee communication [12]. Simbeye, Zhao, and Yang also demonstrated wireless sensor network deployment for aquaculture monitoring and control, including real-time water-quality data collection [13]. These studies indicate that communication and energy management are important parts of a practical monitoring system, particularly where sensors are deployed in outdoor environments.

Several studies have extended water-quality monitoring toward remote access and integrated pond management. Odey and Li [14] developed AquaMesh, a wireless mesh sensor network for aquaculture that supports data transmission through different communication technologies and remote access to measurements. Luo *et al.* [15] presented a remote monitoring system that combined water-quality sensors, wireless communication, and automated aeration control. Encinas *et al.* [16] investigated a distributed Internet of Things architecture for aquaculture water-quality monitoring. Together, these studies show that sensor measurements can support more timely management when they are integrated with reliable communication and data presentation.

Field-oriented platforms have also been developed to support continuous monitoring in aquatic environments. Schmidt *et al.* [17] designed a low-cost autonomous buoy for coastal aquaculture and water-quality monitoring, including the measurement of salinity, temperature, and dissolved oxygen. Parra *et al*. [18] developed low-cost sensors and a wireless monitoring architecture for aquaculture tanks, demonstrating the importance of sensor calibration, data transmission, and abnormal-condition detection. Shi *et al*. [19] presented a wireless sensor network for freshwater fishpond aquaculture and highlighted the importance of network reliability and energy-saving strategies. These studies provide useful design guidance for pond instruments, although their measured parameters and deployment conditions differ.

6. TECHNICAL CHALLENGES AND DESIGN CONSIDERATIONS

The first major challenge is maintaining measurement accuracy under changing pond conditions. Temperature variation, mixed dissolved ions, suspended particles, and biological growth can influence sensor response or complicate the conversion from conductivity to salinity. Sensor fouling is especially important because deposits and biological films may change the effective electrode surface and introduce measurement errors. Research on four-electrode sensors and flexible salinity sensors offers possible ways to reduce some of these effects, but regular field validation remains necessary [3], [10].

The second challenge is achieving long-term reliability without making the instrument too expensive for small-scale farmers. A sensor may perform well during laboratory testing but become unreliable after prolonged exposure to pond water, sunlight, humidity, and mechanical disturbance. Wireless communication also introduces practical issues such as packet loss, limited network coverage, power consumption, and intermittent connectivity. Research on wireless water-quality monitoring has identified sensor maintenance, power management, network architecture, and data reliability as important considerations for sustained deployment [12], [20].

The third challenge concerns the interpretation of salinity measurements for different fish species and farming systems. A single universal threshold cannot represent the acceptable salinity range for all cultured species and life stages. Freshwater species, brackish-water species, and marine species may respond differently to the same environmental change. Therefore, monitoring software should allow farmers to configure species-specific warning levels and should distinguish between a sensor reading, an estimated salinity value, and a management recommendation [21].

7. RECOMMENDED ARCHITECTURE AND FUTURE RESEARCH

A practical fish pond salinity instrument should use a temperature-compensated conductivity sensor as its primary measurement element. A four-electrode probe is a strong candidate where stability and resistance to polarization are priorities, while a two-electrode or flexible sensor may be suitable for lower-cost applications with appropriate calibration and maintenance. The electronic unit should include stable alternating excitation, signal conditioning, temperature acquisition, microcontroller processing, and a protected power supply. A waterproof enclosure and replaceable probe design can further improve serviceability in outdoor pond environments.

Future research should prioritize long-term field validation in different pond types and water compositions. Tests should compare the sensor output with reference conductivity and salinity instruments across the expected temperature and salinity ranges. Researchers should also investigate electrode materials,

biofouling-resistant surfaces, low-power communication, and automatic identification of sensor drift. Finally, monitoring platforms should present clear trends and warnings that help farmers make informed decisions without implying that conductivity measurements alone provide a complete assessment of water quality.

8. CONCLUSION

Electronic salinity monitoring can improve the ability of fish farmers to observe water-quality changes and respond to potentially harmful conditions. Conductivity-based sensing provides a practical foundation because it can be implemented using two-electrode, four-electrode, capacitive, microfabricated, and graphene-based designs. However, reliable salinity estimation requires appropriate calibration, temperature compensation, and consideration of the chemical composition of pond water. Wireless sensor networks and embedded monitoring architectures can extend these measurements into continuous and remote pond-management systems. The most suitable design will depend on the target fish species, pond environment, required measurement range, maintenance capacity, and available budget. Ultimately, a useful fish pond salinity sensor must deliver stable and interpretable measurements under real operating conditions rather than merely demonstrate acceptable performance in a laboratory.

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