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MICROSTRIP ANTENNA FOR SENSING WATER PURITY AND IMPURITIES: A SYSTEMATIC REVIEW

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Abstract

Microstrip and planar microwave sensors offer a compact solution for water quality monitoring, changing the electromagnetic characteristics of a liquid into measurable changes in resonance frequency, reflection or transmission coefficients, phase and quality factor. In this critical review, the representative peer-reviewed studies on salinity, chlorine, ammonia, iron, lead, trace-metal pollution and chloride detection are discussed with focus on sensor topology, operating frequency, liquid-sensor interaction, calibration strategy and evidence quality. The literature demonstrates that patch, split-ring resonator (SRR), complementary SRR (CSRR) and related planar structures can sense controlled changes in aqueous composition with small sample volumes and, in some cases, without direct electrical contact. The electromagnetic response is however generally non-specific as several dissolved species can alter the complex permittivity and conductivity simultaneously. Therefore, a large resonance shift or a low fitted error should not be interpreted in itself as a validated limit of detection or selective chemical identification. A trend away from laboratory salinity measurement toward in-situ monitoring, portable instrumentation and chemically assisted selective detection is seen in recent work. The main remaining issues to be resolved are matrix effects in real water, temperature dependence, packaging and substrate variability, calibration drift, independent validation, uncertainty reporting and multi-analyte discrimination. The review therefore recommends differential or multi-frequency architectures, controlled microfluidic interfaces, selective chemical reactions or recognition layers where appropriate, and portable VNA/LiteVNA readout and statistically rigorous calibration and validation protocols.

Keywords: microstrip antenna; microwave sensor; water quality; salinity; SRR; CSRR; dielectric permittivity; chlorine; trace metals; calibration; environmental monitoring

1. Introduction

Reliable water-quality monitoring requires not only a measurable response, but also reproducibility, traceable calibration, environmental stability and a defensible relationship between the electromagnetic observable and the chemical quantity of interest. An alternative measurement path is provided by microwave sensing, where dissolved species alter the complex dielectric properties and conductivity of aqueous media, thus perturbing the resonance of a planar structure [1-5]. Thus, the appeal of microstrip, SRR and CSRR sensors is not only the small size, but also the possibility of combining a localized high field zone, a controllable sample interface and inexpensive RF electronics in one platform. The reviews of planar resonant sensors mention that frequency variation, coupling modulation, frequency splitting and differential operation are different sensing mechanisms and should be compared on their own physical basis [3], [5].

The basic sensing quantity is complex relative permittivity, which is denoted as $\varepsilon^*r = \varepsilon'r - j\varepsilon''r$, where $\varepsilon'r$ is electric-energy storage and $\varepsilon''r$ is dielectric loss. Conductivity contributes to the effective electromagnetic loss and can affect the resonance depth and bandwidth, as well as the resonance position. In terms of concepts, the first-order perturbation can be expressed as $\Delta f/f0 \approx -K\varepsilon\Delta\varepsilon'$, where $K\varepsilon$ is an effective interaction factor that is dependent on the resonator field distribution and the geometry of the sample. This is not a universal concentration equation, $K\varepsilon$ varies with the resonator, liquid volume, the container, substrate, frequency and loading configuration. The studies published support resonance perturbation as a sensing observable however concentration must be determined by experimentally validated calibration and not simply by resonance shift [1], [3], [6], [5].

Recent studies show the evolution from small laboratory sensors to wide water quality monitoring, selective portable measurements. Lee et al. demonstrated a microstrip patch sensor for salinity determination [1]. Zhang et al. presented a broadband microwave sensor array for water-quality sensing [2]. Yee et al. employed a complementary double split-ring resonator for ammonia and iron concentration measurements [7]. Frau et al. showed microwave sensing in polluted fresh water related to mining activity [4], and Mekki et al. studied chlorine dosage using a contactless patch configuration [8]. Recent studies include NaCl density [9], high-range salinity using SC-SRR structures [10], [11], and selective chloride detection with a portable LiteVNA and a precipitation-assisted dielectric strategy [6]. Together, these studies show a progression of technology, but do not establish a universal calibration or detection limit between different water matrices.

2. Review Scope and Evidence Appraisal

This manuscript is submitted as a critical review and not specifically as a PRISMA systematic review. Identification and verification of literature are based on peer-reviewed work on planar or microstrip microwave sensing of aqueous composition and water quality including patch, SRR/CSRR, differential and related resonant structures. The evidence was qualitatively assessed according to: (i) experimental versus simulation only validation; (ii) analytic and concentration range; (iii) measurement observable; (iv) sample matrix and use of real water; (v) reported calibration procedure; (vi) selectivity or interference testing; (vii) repeatability and uncertainty; and (viii) whether an actual limit of detection was experimentally established. Values given by an original paper are clearly distinguished from values

that can only be calculated from a reported slope or plotted response. [1], [13] The review uses a rigorous terminology rule throughout: "reported LOD" is used only when the original source explicitly establishes a detection limit using a stated analytical or statistical criterion; "estimated LOD" is used only for a value derived by review authors from source data; and "not reported" is used when no LOD is established. Thus, sensitivity, resolution, regression error and LOD are not interchangeable quantities [3], [5], [12].LOD stands for Limit of Detection for a sensor.

3. Electromagnetic Sensing Principles

Microstrip water sensors operate through perturbation of a localized electromagnetic field by the liquid under test. In a patch or resonator, the sample may be placed directly over a high-field region or separated from the conductor by a thin dielectric container. The latter configuration can reduce corrosion and contamination of the antenna but introduces additional dielectric loading from the container. The measured response therefore represents the combined electromagnetic interaction of the liquid, container, substrate, conductor, and surrounding environment. This interface dependence is a recognized issue in planar microwave resonant sensing and dielectric characterization [3], [11], [5], [14].

For a simple resonant equivalent circuit, the resonance frequency is approximated by $f0 = 1/(2\pi\sqrt{(LC)})$. A contaminant-induced change in effective capacitance or inductance therefore shifts f0. In practice, dissolved salts can simultaneously change conductivity and complex permittivity, so the response may appear as a frequency shift, a change in |S11| or |S21|, a change in bandwidth/Q, or a phase variation. Consequently, retaining the full spectral response or several independent resonance features can provide more information than a single scalar resonance frequency [1], [3], [7], [5].

The quality factor can be expressed as $Q = f0/\Delta f_{-3dB}$ for a conventional resonance definition. Q is useful for describing resonance sharpness and loss, but it should not be interpreted as a direct measure of analytical sensitivity. A narrow resonance may improve frequency-resolution potential, while practical performance also depends on field confinement, instrument noise, fabrication tolerance, sample placement, temperature stability, and calibration uncertainty. Recent reviews specifically emphasize differential sensing and environmental immunity as important directions for practical microwave sensors [3], [5], [14].

Table 1. Classification of planar microwave architectures reported for aqueous sensing.

Architecture	Typical implementation	Primary RF observable	Main advantage	Principal limitation	Evidence
Conventional patch	Inset/edge-fed patch with liquid above or near high-field region	f_r, |S11|	Simple, low-cost fabrication	Packaging, temperature and matrix loading	[1], [8], [10]
SRR/CSRR	Split-ring or complementary split-ring resonator coupled to a planar feed	f_r, Q, |S11|	Strong localized field confinement	Position and fabrication sensitivity; cross-sensitivity	[3], [11]

Multi-frequency / array	Multiple resonances or sensing elements	Feature vector across resonances	Potential multivariable inference	Calibration and coupling complexity	[2], [5]
Reference/differential	Sensing element paired with a reference element	Differential Δf or Δ|S|	Can suppress common-mode environmental effects	Requires matched reference conditions	[3], [5]
Chemically assisted	Microwave resonator coupled with selective reaction/passivation	Peak shift or spectral change	Can improve chemical specificity	Added chemistry and reagent/lifetime constraints	[6]

4. Sensor Architectures and Sample Interfaces

Patch antennas are a simple and widely available platform. Their resonant fields penetrate into the volume occupied by the liquid and changes in dielectric loading can be sensed by resonance perturbation. Silicon substrates allow for compact structures while FR-4 is an attractive option for low-cost fabrication. However, it introduces higher dielectric loss and more variability in the material than low-loss microwave substrates. Therefore the choice of the substrate has to be considered together with Q-factor, frequency, mechanical stability, fabrication tolerance and calibration requirements and not just on cost [1], [3], [10], [11].

The electric field is concentrated in the narrow gaps (or slots) of the SRR and CSRR structures, thus enhancing the interaction with a small volume of liquid. This can lead to dramatic changes in resonance, but field enhancement can also enhance sensitivity to sample position errors, container thickness, and fabrication tolerances. The sensor surface can be protected and reusability improved by using non-contact Teflon or glass/Pyrex containers, but the container becomes part of the electromagnetic measurement chain and must be kept mechanically controlled during calibration and measurement [3], [10], [11], [5].

Differential and multi-frequency architectures have to deal with a different problem: the separation of analyte-related changes from common environmental disturbances. A reference resonator under the same thermal and packaging conditions can be used to get a differential observable, and multi-frequency arrays can generate a response vector instead of a single resonance. Differential-mode sensing is found as a very useful scheme for environmental immunity in the reviews of planar microwave sensors, while recent works are combining multiple sensing mechanisms with microfluidics and algorithms [3], [5], [14].

5. Representative Verified Evidence

Representative studies which can be verified bibliographically and technically are summarized in Table 1. The table does not include the unsupported inference from the original manuscript stating that the selected studies constitute a homogeneous quantitative dataset. Work that is simulation only is clearly marked. LOD status is independent of sensitivity or model-fit error. [1 - 11].

Table 2. Evidence chain required to convert an electromagnetic response into an analytically defensible concentration measurement.

Stage	Required evidence	Output	Purpose	Common weakness	Evidence
1. Reference measurement	Traceable concentration, temperature and matrix	C_ref	Defines ground truth	Reference-method uncertainty not reported	[4], [6]
2. Interface control	Fixed sample volume, container, spacing and orientation	Geometry metadata	Controls loading variability	Container dielectric effects ignored	[1], [8], [10], [11]
3. RF acquisition	Calibrated VNA/reader and repeated sweeps	S11/S21, phase, resonance	Provides raw EM evidence	Instrument drift and bandwidth limits	[1], [2], [7]
4. Feature extraction	f_r, Δf, |S11|, Q, bandwidth or multiband features	x	Creates quantitative predictor	Single-feature ambiguity	[3], [5], [14]
5. Calibration	Physical model, lookup table or regression	C_hat = g(x,T,matrix)	Maps RF response to concentration	Overfitting and poor transferability	[2], [7], [8]
6. Validation	Replicates, blanks, spikes, interferents and independent samples	Bias, precision, LOD if established	Supports analytical claims	Often incomplete in literature	[4], [6], [12]

6. Comparative Critical Discussion

6.1. Operating Frequency and Electromagnetic Interaction

The evidence from the representatives is concentrated in the low GHz range, particularly around 2-3 GHz for compact patch and SRR sensors. This is not to be taken as evidence that 2-3 GHz is optimal in all instances but a practical compromise between water loading, resonator size, instrumentation, and simplicity of fabrication. Zhang et al. [2] proved a multi-element array covering the range of 1-10 GHz where the wider spectral information could help to characterize water quality. The operation near 2.1-2.4 GHz is also presented in the 2025 SC-SRR studies [10], [11]. Thus frequency selection should not be treated as a fixed optimum but rather a design variable associated with field distribution, loss, sample volume and the desired measurand [3], [5].

6.2. Sensitivity Is Not Equivalent to Selectivity

An important point is that sensitivity and selectivity are independent properties. The electromagnetic response is generally sensitive to the combined complex permittivity and conductivity of the liquid and chemically different solutions can lead to similar changes in a single resonance. Selectivity requires independent physical signature, multiple resonances, differential/reference channels or a selective chemical interaction The 2021 ammonia/iron study established separate concentration-response models, not simultaneous multi-analyte discrimination [7]. The 2026 chloride study addressed specificity by adding AgNO3 such that chloride caused a controlled precipita-

tion-induced dielectric change, and showed how chemical specificity can be combined with microwave readout [6].

6.3. Sensitivity, Resolution, and Limit of Detection

Do not interchange sensitivity, resolution and limit of detection. Sensitivity is typically expressed as a slope such as $\Delta f/\Delta C$ or $\Delta|S11|/\Delta C$. Resolution is the smallest change that can be practically resolved under the given conditions. The LOD requires an analytical decision criterion based on blank variability and calibration uncertainty. Several microwave-sensor studies report strong monotonic responses or low regression error, but do not establish a LOD. For example, the RMSE reported by Yee et al. is a measure of the agreement between a concentration-response model and its data set, and is not an analytical detection limit per se [7]. Thus, the revised review reports LOD only when it is known from the source, and otherwise reports it as not reported.

6.4. Real Water versus Prepared Solutions

The evidence base is mostly concentrated in controlled laboratory solutions, but there is significant real-water work available. Frau et al. conducted microwave measurements in polluted fresh water from mining activities, demonstrating that resonant responses can be utilized for tracking water-quality alterations in a complicated matrix [4]. This is especially important because the ionic background, suspended matter, natural organic matter, pH and temperature variation of environmental waters cannot be simulated by prepared NaCl, ammonia, iron or chlorine solutions. Thus, the laboratory sensitivity should be regarded as a controlled-material result, rather than as a direct evidence of the field selectivity or universal accuracy [3], [4], [5].

Non-contact sample holders offer benefits in chemical compatibility and reusability but add an extra dielectric layer. The effective resonance is altered by the presence of a Teflon box, a Pyrex tube or similar container and has to be mechanically fixed between calibration and measurement [8], [10], [11]. Temperature is also important because the electromagnetic properties of water and aqueous solutions are temperature dependent. Thus, a practical system should either contain a temperature measurement or a reference resonator, and should report calibration uncertainty over the intended operating range. The long-term drift, aging of the substrate, repeatability of the connectors, and fabrication tolerances should be characterized by repeated measurements and not inferred from a single simulation-to-measurement comparison [1], [3], [5], [14].

Table 3. Verified evidence landscape for representative microstrip and planar microwave water-quality studies.

Study	Target	Test matrix	Validation context	Reported contribution	Interpretation limitation	Ref.
Lee et al., 2017	Salinity	NaCl/seawater solutions, 20–35 ppt	Simulation + experiment	0.01 ppt resolution reported; frequency separation quantified	Single-analyte controlled matrix; no selectivity study	[1]
Zhang et al., 2019	Water-quality parameters	Aqueous samples; multi-	Experimental	Multi-frequency microwave	Calibration complexity and matrix	[2]

		frequency sensing		water-quality sensing	dependence	
Yee et al., 2021	Ammonia and iron	Prepared aqueous samples	Experimental	Resonance-shift concentration models; high R^2 reported	Fit accuracy is not equivalent to analytical LOD	[7]
Frau et al., 2021	Trace metals	Polluted freshwater context	Experimental/in-situ oriented	Microwave monitoring of trace metals	Field matrix and calibration effects remain important	[4]
Mekki et al., 2023	Chlorine	Drinking-water samples	Experimental patch sensor	RF response related to chlorine dosage	Selectivity and independent field validation limited	[8]
Hui et al., 2023	Lead	Water-monitoring system	Experimental/IoT-oriented	Microstrip antenna-based lead detection	Analytical validation requires broader matrix testing	[15]
Yeap et al., 2024	NaCl density	Aqueous NaCl solutions	Experimental	Microwave density measurement	Prepared-solution validation	[9]
Jasim et al., 2025	Salinity	0–100 ppt saline solutions	Experimental	Large resonance shift reported	Independent matrix validation not established	[10]
Jasim et al., 2025	Saline solution	0–100 ppt; CSRR-enhanced patch	Experimental	f_r, S11 and Q characterization	Selectivity and real-water validation not established	[11]
Liu et al., 2026	Chloride ion	High-salinity water, 0–40 g/L	Portable experimental	Selective precipitation–dielectric microwave strategy	Added chemistry increases system complexity	[6]

7. Research Gaps and Engineering Requirements

The evidence demonstrates that the key research gap is not showing now that a microwave resonance can be sensitive to dissolved material. That is a well established skill. The more difficult engineering problem is to secure a stable, selective and quantitatively validated measurement in a changing water matrix. Future papers should report the sample temperature, ionic background, pH if relevant, sample volume, container dimensions, sensor-to-container spacing, VNA calibration, number of repeated measurements, confidence intervals, and uncertainty of the concentration reference method. You need these details for any meaningful comparison between sensors. [3], [5], [14]

Another major gap is interference from multiple contaminants. It is improbable that one single resonance feature can uniquely identify several dissolved species since their electromagnetic effects may overlap. Multi-frequency arrays, differential reference resonators and spectrum level machine learning algorithms can improve discrimination but machine learning must be validated on independent samples and not random splits of highly correlated measurements. Otherwise the model can learn

features specific to sample or measurement session rather than general chemical relationships. [1], [2], [4], [8], [11], [6]

Miniature vector network analyzers and integrated electronics are becoming more portable. However, a portable reader will bring about changes in noise, dynamic range, calibration and frequency resolution compared to a laboratory VNA. This emphasizes the necessity of end-to-end validation of the system with the intended reader, rather than assuming that a laboratory VNA reading will just carry through unchanged. [3], [5], [14].

Table 4. Recommended reporting standards for sensitivity, resolution, LOD, selectivity and validation.

Metric	Operational definition	Minimum reporting requirement	Interpretation caution	Refs.
Sensitivity	Slope of response versus concentration, e.g., $\Delta f/\Delta C$ or $\Delta\|S11\|/\Delta C$	Units, fitted range, uncertainty and regression model	Slopes from different observables are not directly comparable	[1], [7], [9]
Resolution	Smallest experimentally distinguishable concentration change	Noise/uncertainty basis and replicate measurements	Not synonymous with LOD	[1]
LOD	Concentration meeting an explicitly defined analytical detection criterion	Method for blank variability/calibration uncertainty and validation	Never infer LOD from a frequency shift alone	[12]
Selectivity	Ability to discriminate target analyte from interferents	Interference/multi-analyte experiments	Single-analyte calibration does not establish selectivity	[7], [6]
Repeatability	Variation under repeated measurements	n, mean, SD/CV and conditions	One trace cannot establish repeatability	[4], [8]
Real-water validity	Performance in environmental/drinking-water matrices	Reference comparison, recovery/spike tests and matrix description	Prepared solutions alone do not establish field validity	[4], [6]

8. Recommended Experimental and Reporting Protocol

A more robust experimental protocol would consist of a traceable reference measurement of the water property of interest, followed by the controlled preparation of calibration standards. Where possible, at least three independent preparation/measurement replicates should be performed for each concentration, randomizing the order of measurement to reduce drift bias. First, the sensor should be characterized with a blank/reference solution and the temperature should be noted. Instead of storing only one scalar feature, the resonance frequency, the S11/S21 magnitude, the bandwidth and the phase should be kept. Calibration models should be tested on an independent test set and performance should be summarized by RMSE,

MAE, coefficient of determination, confidence intervals and when appropriate LOD calculated from an explicit analytical criterion.

Samples should be validated against an established reference method suitable for the target analyte for real-water validation. Recovery experiments, matrix spike, interference experiments and replicated measurements should be included. An useful field study should report mean response and variability due to temperature, flow, sensor location, sample conductivity, and packaging. Such practices would greatly improve the reproducibility of results and allow future studies to distinguish true sensor improvements from changes in experimental conditions.

8.1. Evidence-based interpretation of recent advances

The state of the art demonstrates a change of paradigm from passive dielectric response demonstration to engineering of the entire sensing chain. Early patch work on salinity established resonance-frequency measurement as a compact salinity observable [1]. Later studies extended this concept to broadband water-quality sensing [2] and to complementary split-ring structures concentrating the electric field and providing additional observables such as S11 and Q [7], [11]. The 2025 SC-SRR work explicitly modeled the complex permittivity, conductivity, and concentration over 0–100 ppt, demonstrating the value of using multiple RF features instead of a single resonance parameter [11].

The field is also moving toward practical environmental measurement. Frau et al. [4] showed microwave measurements in polluted freshwater. Mekki et al. studied the dosage of chlorine using a contactless patch configuration [8] and Yeap et al. correlated the microwave transmission response with the NaCl density [9]. The 2026 chloride study is especially relevant as it was incorporating an SRR, passivation, a portable LiteVNA, and a precipitation reaction to improve specificity [6]. This gives evidence for a more general design principle: chemical selectivity may have to be introduced through the sample interface or a selective reaction, rather than be expected from a passive dielectric resonator alone.

Recent reviews also suggest differential sensing, microfluidics, metamaterial-inspired resonators and algorithmic inversion as important paths to environmental immunity and practical deployment [3], [5]–[13]. However, any additional architectural or algorithmic complexity should be justified by a proven increase in uncertainty, selectivity, repeatability or robustness in the field. The appropriate unit of evaluation is the complete measurement system – sensor, sample interface, RF reader, calibration model, environmental compensation, and reference method – not just resonance shift.

Table 5. Representative frequency information from verified studies; frequency is contextual and is not a performance ranking.

Study	Reported/representative frequency	Target	Interpretation	Ref.
Lee et al., 2017	~2.98 GHz resonance	Salinity	Representative patch operating point	[1]
Yee et al., 2021	~2.38 GHz unloaded resonance	Ammonia/iron	Representative CSRR operating point	[7]

Mekki et al., 2023	~2.94 GHz class	Chlorine	Representative patch-sensor region	[8]
Yeap et al., 2024	~2 GHz class	NaCl density	Representative microwave-sensor region	[9]
Jasim et al., 2025	2.13–2.44 GHz class	Salinity	Representative patch/CSRR range	[10], [11]
Liu et al., 2026	~0.9–1.2 GHz characteristic peak	Chloride	Characteristic response region of reported portable system	[6]

9. Conclusion and Future Trends

Microwave sensors, such as microstrip and planar, provide a compact approach for water quality monitoring by translating the electromagnetic properties of a liquid into measurable changes in resonance frequency, reflection or transmission coefficients, phase and quality factor. In this critical review representative peer-reviewed research on salinity, chlorine, ammonia, iron, lead, trace-metal pollution and chloride detection are discussed with an emphasis on sensor topology, operation frequency, liquid-sensor interaction, calibration approach and evidence quality. Literature suggests that patch, split-ring resonator (SRR), complementary SRR (CSRR) and related planar structures can detect controlled changes in aqueous composition with small sample volumes and under certain conditions without direct electrical contact. However, the electromagnetic response is generally non-specific as many dissolved species can modify the complicated permittivity and conductivity simultaneously. Thus a large resonance shift or a low fitting error should not be considered as evidence for a limit of detection or a selective chemical identification. Recent work points to a move away from laboratory salinity measurement to in-situ monitoring, portable instrumentation and chemically assisted selective detection. The key challenges that remain to be addressed include matrix effects in real water, temperature dependence, packing and substrate variation, calibration drift, independent validation, reporting of uncertainty and discriminating between multi-analyte. The review therefore proposes differential or multi-frequency topologies, regulated microfluidic interfaces, selective chemical reactions or recognition layers where appropriate, portable VNA/LiteVNA readout and statistically rigorous calibration and validation processes. [1], [2], [3], [4] Future microstrip water sensors will likely integrate electromagnetic structures with controlled sample interfaces and complementary chemical information. Differential resonators can reject common mode disturbances, multi-resonance arrays can provide higher dimensional response, microfluidic channels can control the volume and flow of the sample, selective reactions or recognition layers can introduce chemical specificity. Distributed monitoring can then be supported by portable readers and wireless data acquisition. The most promising way forward is not to have a stand-alone 'high-sensitivity antenna', but rather an integrated measurement chain where sensor geometry, sample handling, calibration, reference measurement and data analysis are all designed together.

Artificial intelligence can help with spectral feature extraction and multi-parameter classification but it should be considered as calibration and inference layer, not a replacement for physical validation. To consider a model as transferable, independent test samples, cross-day validation, temperature variation and uncertainty analysis

should be carried out. Besides resonance shift, new substrates, graphene, metamaterial-inspired resonators and miniaturized structures would also have to be tested against practical metrics - repeatability, stability, fabrication tolerance and field robustness.

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