

# Conceptual Design and Prospective Validation Framework for a Low-Cost Smart Device for Real-Time Monitoring of Dental Unit Waterline Quality in Resource-Limited Settings

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## ABSTRACT

Dental unit waterlines (DUWLs) can support biofilm development because their narrow-bore tubing, intermittent flow and periods of stagnation provide favorable conditions for microbial attachment and persistence. Current guidance for routine nonsurgical dental treatment uses drinking-water quality as a benchmark, including a heterotrophic bacterial count of no more than 500 CFU/mL, while sterile water or sterile saline is required for surgical procedures. Importantly, this microbiological criterion cannot be inferred directly from a low-cost turbidity, conductivity, temperature or hydraulic sensor without DUWL-specific experimental validation. This paper therefore presents a conceptual engineering design and prospective validation framework for a low-cost smart monitoring platform intended for resource-limited dental settings. The proposed system combines temperature, optical/turbidity, electrical conductivity and hydraulic measurements with local data logging, status indication, alarms and optional wireless communication. The revised methodology specifies the literature-search strategy, source-selection criteria, engineering requirements, proposed bill of materials, sensor specifications, power budget, calibration procedures, hydraulic verification, paired microbiological validation, field deployment and statistical analysis. A staged validation protocol is proposed to distinguish metrological performance from clinical or microbiological validity. The manuscript is deliberately positioned as a conceptual design and validation protocol rather than a report of completed clinical validation. The proposed platform is intended to provide continuous operational surveillance and to trigger inspection or confirmatory microbiological testing, not to declare water microbiologically safe. The framework provides a practical basis for subsequent prototype construction and controlled field validation in resource-constrained dental facilities.

**Keywords:** Dental unit waterlines; DUWL; biofilm; water quality; low-cost sensors; Internet of Things; ESP32; turbidity; electrical conductivity; real-time monitoring; resource-limited settings; anomaly detection; dental infection prevention; device validation

## INTRODUCTION

Dental water management is an important component of infection prevention, but it can receive less attention than instruments and environmental surfaces. Water delivered through handpieces, air–water syringes and ultrasonic devices travel through narrow-bore tubing in which low or intermittent flow and periods of stagnation can support microbial attachment and biofilm development [1–4]. The water emerging at the point of use may consequently differ from the incoming source water [8][9]. Current CDC guidance recommends that routine

dental treatment output water meet drinking-water quality, expressed as no more than 500 CFU/mL of heterotrophic bacteria, and recommends sterile water or sterile saline for surgical procedures [5].

Investigations from different clinical settings have reported environmental and opportunistic organisms in DUWLs, including *Pseudomonas*, *Legionella* and nontuberculous mycobacteria [3][10][11][27]. Biofilm contamination is sufficiently widespread to justify routine attention, although the presence of microorganisms should not automatically be interpreted as evidence that a clinical infection will occur. The risk is better understood as an infection-prevention and exposure-control issue requiring appropriate water treatment, maintenance and monitoring [3][6][30].

Conventional microbiological testing remains the appropriate reference approach when the objective is to determine microbial quality. However, discrete microbiological tests provide only intermittent snapshots. A continuous engineering monitor could provide a complementary time history showing changes associated with stagnation, flushing, maintenance, source-water variation or unusual hydraulic behavior. The value of such a monitor is therefore not that it replaces microbiology, but that it can identify operational changes between confirmatory tests.

The present manuscript has been revised in response to reviewer recommendations and is explicitly positioned as a conceptual design and prospective validation framework. It does not claim completed clinical validation. Where experimental measurements are discussed, they are presented as planned verification activities rather than as results. This distinction is important because the proposed physical and chemical measurements are surrogate or contextual signals and cannot legitimately be displayed as CFU/mL without a validated DUWL-specific prediction model [14][15].

## REVIEW METHODOLOGY

The evidence synthesis was undertaken as a narrative and engineering review designed to translate established DUWL water-quality requirements into an experimentally testable monitoring architecture. Clinical and microbiological evidence was considered alongside authoritative infection-prevention guidance, water-safety literature, engineering studies on low-cost sensors and IoT monitoring, and relevant technical standards. Manufacturer information is reserved for component specifications and is not treated as evidence of clinical effectiveness.

To make the review reproducible, the revised protocol specifies a structured search and screening approach. Searches should be conducted in PubMed/MEDLINE, Scopus, Web of Science, IEEE Xplore and Google Scholar. The planned search period is January 2000 through June 2026, with a final search update immediately before manuscript submission. Earlier seminal studies are retained where they provide foundational evidence on DUWL biofilm, contamination or waterline engineering.

Core search terms include: ("dental unit waterline" OR DUWL OR "dental waterline") AND (biofilm OR contamination OR microbiological OR bacterial OR *Legionella* OR *Pseudomonas*) AND (water quality OR monitoring OR sensor OR turbidity OR conductivity OR temperature OR flow OR pressure OR IoT OR "real-time monitoring"). Additional searches combine "dental unit waterline" with "heterotrophic plate count", "waterline treatment", "disinfection", "sensor validation" and "machine learning".

Records should be screened in four stages: identification, duplicate removal, title/abstract screening and full-text assessment. Sources are eligible when they address DUWL contamination, biofilm, treatment, microbiological assessment, water-quality monitoring, sensor engineering, IoT water monitoring, risk management or relevant standards. Sources are excluded when they are unrelated to dental water systems or sensor engineering, provide insufficient methodological information, duplicate another report, or cannot support a claim made in the manuscript. The final evidence set should be recorded in a screening log so that the number of records identified, screened, excluded and retained can be reported transparently.

The evidence hierarchy is deliberately separated into clinical evidence, authoritative guidance, technical standards, engineering literature and component documentation. Systematic reviews and primary microbiological studies provide evidence on DUWL contamination; CDC and ADA materials establish practice requirements; WHO and ISO/IEC documents provide water-safety, sampling and engineering context; engineering studies inform sensor and data-system design; and manufacturer datasheets provide component-level specifications. This separation reduces the risk of treating a component's advertised performance as evidence that the complete monitoring system is clinically effective.

### DUWL Contamination, Biofilm and Exposure Pathways

DUWL contamination is closely linked to biofilm formation. Microorganisms introduced through source water may attach to internal tubing surfaces, become embedded in extracellular material and later detach into the flowing water [1][2][7]. Tubing material, internal diameter, surface characteristics, water chemistry, flow conditions and maintenance procedures can influence the resulting microbial ecology [8][13][24].

Intermittent use adds a temporal dimension. During non-use, relatively static water remains in contact with tubing surfaces. When flow resumes, accumulated material and detached biomass may be transported toward the outlet. Optical changes following an idle period may therefore provide an operational signal, but they should not be interpreted automatically as microbiological failure [7][12][25]. Retrograde contamination is another consideration, particularly where retraction mechanisms are inadequate [9][26]. For monitoring purposes, the preferred measurement point is therefore as close as practicable to the point of use.

Water from dental instruments can generate droplets and aerosols, creating an exposure pathway for patients and dental personnel [17][29][39]. The proposed monitor is consequently framed as an early-warning and quality-assurance device. It is not designed to predict whether an individual patient will develop an infection, and the manuscript does not claim that continuous monitoring alone reduces dental infections.

### Water-Quality Targets and Sensor Limitations

The CDC benchmark of  $\leq 500$  CFU/mL applies to heterotrophic bacterial counts in water used for routine nonsurgical dental treatment [5]. It is a microbiological criterion, not a sensor threshold. Turbidity, conductivity, temperature, flow and pressure describe physical or chemical conditions. None is equivalent to a viable bacterial count unless a DUWL-specific relationship has been established experimentally and independently validated.

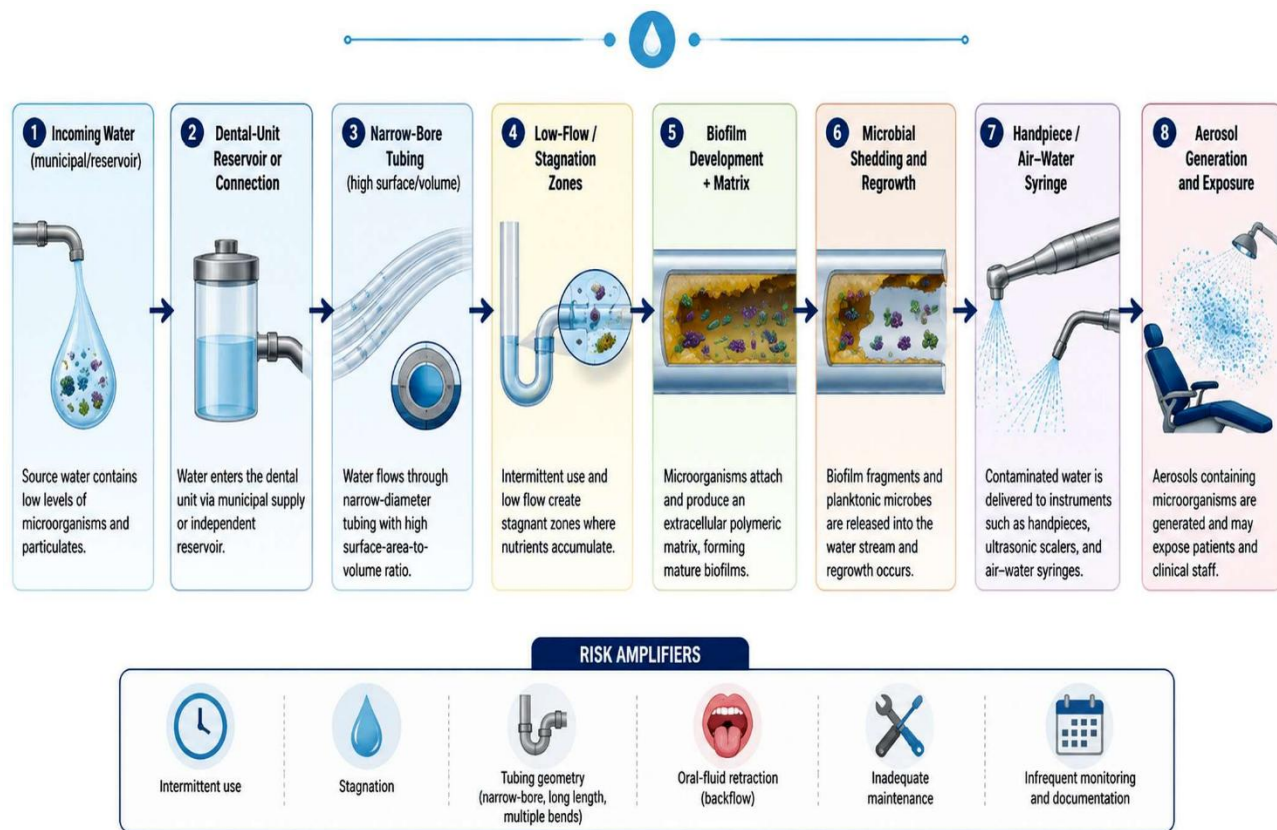
The user interface should therefore report operating states rather than unsupported microbiological conclusions. A Normal state can indicate that measured variables remain within a validated unit-specific baseline. A Watch state can identify a persistent deviation. A Test/Inspect state can request inspection or confirmatory microbiological sampling. A Sensor Fault state should suppress water-quality inference whenever measurements are missing, implausible or drifting. This approach prevents false reassurance and preserves the role of microbiological testing.

The proposed system also distinguishes sensor condition from waterline condition. Sensor condition includes calibration status, drift, missing observations and hardware faults. Waterline condition concerns sustained changes in measured operating behavior. A microbiological result such as  $>500$  CFU/mL must continue to come from a validated microbiological procedure unless a predictive model demonstrates adequate performance across the intended range of dental units [5][14][15][18].

**Table 1. Proposed waterline operating states and actions**

| Status | Meaning                                                                   | Automatic action  | device | Clinical interpretation        |
|--------|---------------------------------------------------------------------------|-------------------|--------|--------------------------------|
| Normal | Signals within the validated baseline envelope and no persistent anomaly. | Continue logging. |        | No microbiological conclusion. |

|                 |                                                                                         |                                              |                                                            |
|-----------------|-----------------------------------------------------------------------------------------|----------------------------------------------|------------------------------------------------------------|
| Watch           | Persistent deviation, increased variability, stagnation or treatment-related excursion. | Local notification; increase observation.    | Inspect according to SOP; consider targeted testing.       |
| Test/Inspect    | Multisensor anomaly or repeated Watch state.                                            | Generate service event and sample request.   | Follow approved maintenance and confirmatory microbiology. |
| Sensor fault    | Implausible, missing or drifting measurements.                                          | Suppress quality inference; request service. | Do not infer water status from faulty sensors.             |
| Maintenance due | Scheduled calibration or waterline maintenance interval reached.                        | Display reminder and log event.              | Follow manufacturer/facility protocol.                     |



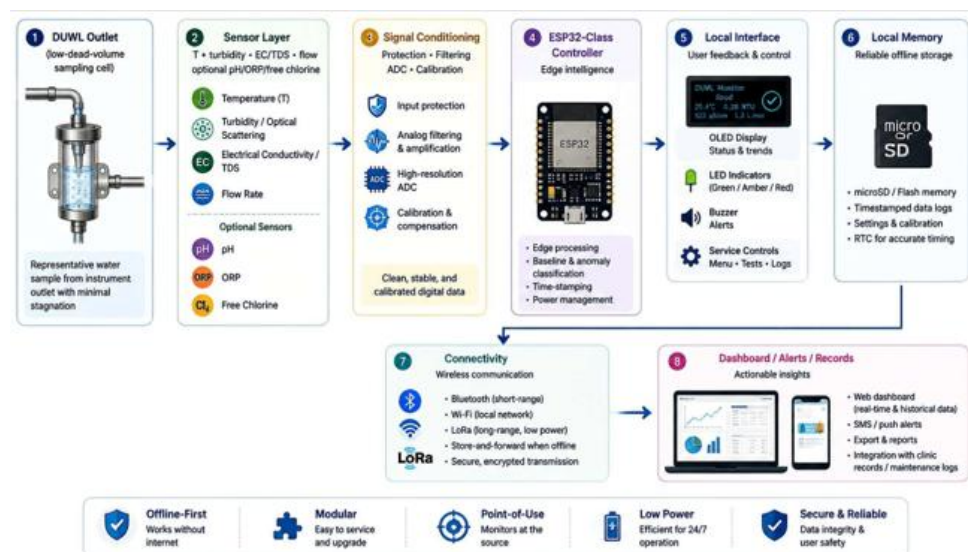
**Figure 1. Conceptual pathway linking DUWL configuration, stagnation, biofilm development, microbial release and patient/staff exposure. Original schematic retained from the submitted manuscript and visually enhanced for publication.**

## Engineering Requirements and Sensor Selection

The proposed monitor is designed around four principles: it should observe the waterline without materially disturbing hydraulic operation; it should remain useful during Internet or power interruptions; individual sensor modules should be replaceable; and every alarm should lead to a defined response. Temperature is primarily contextual and can support compensation. Turbidity or optical scattering can indicate particulate or shedding events. Conductivity can reveal changes in ionic conditions or treatment/source-water chemistry. Flow and/or pressure can indicate stagnation, flushing, blockage or leakage. Each measurement is confounded by nonmicrobial factors, so multisensor interpretation and unit-specific baselines are preferred [19][31][34].

**Table 2. Sensor selection requirements and limitations**

| Parameter                    | Physical principle                       | Primary engineering value                             | Main confounders                                        | Evidence role             |
|------------------------------|------------------------------------------|-------------------------------------------------------|---------------------------------------------------------|---------------------------|
| Temperature                  | Digital sensor/thermistor/RTD            | Context and compensation                              | Ambient temperature; low specificity                    | Core contextual sensor    |
| Turbidity/optical scattering | LED + photodetector                      | Detect suspended material and shedding events         | Bubbles, fouling, ambient light, nonmicrobial particles | Core surrogate            |
| Electrical conductivity      | Electrodes with controlled AC excitation | Detect ionic changes and treatment/source differences | Temperature, water chemistry, electrode polarization    | Core contextual sensor    |
| Flow                         | Low-flow meter or hydraulic inference    | Detect stagnation, flushing, blockage and leakage     | Very low flow, pulsation, added resistance              | Core hydraulic sensor     |
| Pressure                     | MEMS pressure transducer                 | Detect restriction/blockage and hydraulic state       | Installation pressure, drift                            | Optional hydraulic sensor |
| pH                           | Electrode/solid-state sensor             | Chemical-condition and treatment monitoring           | Drift, fouling, calibration burden                      | Optional                  |
| ORP/free chlorine            | Electrochemical/optical                  | Treatment residual monitoring                         | Calibration, electrode/reagent maintenance              | Advanced option           |
| ATP                          | Bioluminescence assay                    | Rapid biological activity indicator                   | Consumables; not continuous at low cost                 | Periodic validation       |

**Figure 2. Proposed smart-device block diagram showing the point-of-use sampling cell, multisensor layer, embedded processing, local storage/display and optional communication. The architecture is conceptual and is not presented as clinically validated.**

## Proposed Device Architecture

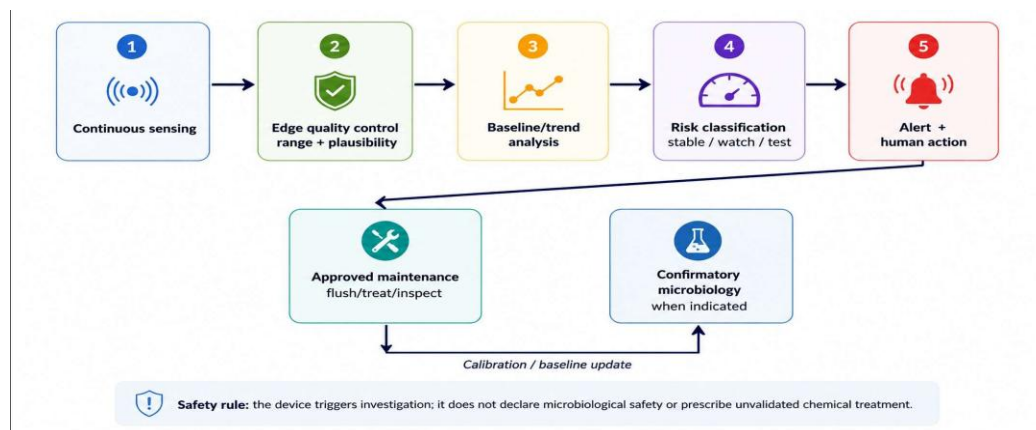
The proposed platform consists of a small point-of-use sampling interface, a low-volume flow-through cell, sensors, signal-conditioning electronics, an embedded controller, local display and storage, and optional wireless communication. Essential monitoring and alarms should continue without an Internet connection. Network access can be used for configuration, data transfer and synchronization rather than being a prerequisite for safe operation [19][20][35].

The sampling cell should have low internal volume, smooth wetted surfaces, minimal dead legs and materials compatible with approved waterline treatment chemicals. A bypass or flow-through arrangement is preferable to a large retained chamber because unnecessary retained water could create a new stagnation site. The complete assembly should be evaluated for pressure drop, residence time, minimum detectable flow, leakage and flushing disturbance before clinical deployment.

## Electronics, Embedded Software and Data Management

An ESP32-class controller is proposed because it can support sensor acquisition, local processing, non-volatile storage and optional Wi-Fi/Bluetooth communication. The controller itself is not the principal scientific contribution; measurement stability, protection, calibration, fault handling and safe integration with the dental unit are more important. Analogue channels require suitable protection and filtering, while optical and conductivity channels require controlled excitation and stable signal conditioning [19][35].

The embedded software should perform sensor initialization, self-test, acquisition, plausibility checking, filtering, calibration compensation, baseline comparison, state classification, local logging and alarm management. Every record should include a timestamp, dental-unit identifier, sensor measurements, operating state, alarm status, calibration events, maintenance events and firmware version. Local storage should continue during communication outages, and patient identifiers should not be collected unless they are specifically required by an approved study [35][40].



**Figure 3. Closed-loop DUWL quality-assurance model. Baseline updating is restricted to periods following documented intervention and verification. Original figure retained and visually enhanced.**

## Calibration and Metrological Verification

Calibration must be performed on the completed monitoring assembly under conditions representative of actual operation. Low-cost sensors can vary between individual units and may drift with temperature, water chemistry, fouling, disinfectant exposure and repeated cleaning cycles [19][21][31]. A reference thermometer should be used for temperature calibration; turbidity should be evaluated against suitable reference materials; conductivity should be checked using traceable standards; and flow should be evaluated across the low-flow range expected at the dental outlet.

The minimum reported metrological outcomes should include bias, mean absolute error (MAE), root mean square error (RMSE), repeatability, response time, useful operating range and drift. Calibration should also include challenge conditions such as bubbles, particulate disturbances, disinfectant exposure and repeated cleaning. Metrological calibration should be clearly distinguished from clinical validation: the former establishes whether the instrument measures a physical variable consistently, whereas the latter asks whether the resulting measurements are useful for identifying microbiologically relevant events.

### Bill of Materials, Technical Specifications and Cost Model

The bill of materials has been expanded in response to the reviewer request. Because the manuscript does not report procurement records for a completed prototype, the values below are presented as proposed engineering targets and indicative cost fields to be populated from quotations or manufacturer documentation before experimental procurement. No unsupported claim of a final purchase price is made.

**Table 3. Proposed bill of materials, specifications and lifecycle-cost requirements**

| Subsystem              | Representative component                  | Required specification to report                                           | Power requirement                | Cost information to report                   |
|------------------------|-------------------------------------------|----------------------------------------------------------------------------|----------------------------------|----------------------------------------------|
| Controller             | ESP32-class MCU                           | 3.3 V logic; ADC/digital interfaces; local processing; Wi-Fi/BLE optional  | Measure active and sleep current | Local/region/import price; replacement cost  |
| Temperature            | Replaceable digital temperature probe     | Expected operating range; accuracy; resolution; response time              | Voltage/current or mW            | Unit price; expected replacement interval    |
| Optical turbidity      | LED–photodetector flow-through cell       | Calibrated range; repeatability; optical path; fouling resistance          | LED/detector power               | Sensor + optical cell cost; replacement cost |
| Conductivity           | AC-excitation EC interface                | Expected $\mu\text{S}/\text{cm}$ range; accuracy; temperature compensation | Excitation + electronics power   | Electrode cost; calibration-standard cost    |
| Flow/hydraulic sensing | Low-flow meter or pressure sensor         | Low-flow range; accuracy; pressure drop; response time                     | Sensor supply/current            | Unit price; replacement interval             |
| Display/alarm          | OLED/LED + buzzer                         | Readability; alarm audibility; local status indication                     | Display + alarm current          | Replacement cost                             |
| Storage/RTC            | microSD/flash + RTC                       | Storage capacity; timestamp accuracy; write endurance                      | Storage/write current            | Media and RTC replacement cost               |
| Power supply           | Regulated low-voltage supply + protection | Input range; regulated output; surge/overcurrent protection                | System total power budget        | Supply and protection cost                   |
| Enclosure/sampling     | Locally                                   | Ingress                                                                    | None                             | Fabrication and                              |

|                    |                                            |                                                  |                                |                                         |
|--------------------|--------------------------------------------|--------------------------------------------------|--------------------------------|-----------------------------------------|
| cell               | manufacturable polymer/compatible material | protection; chemical compatibility; cleanability |                                | replacement cost                        |
| Optional chemistry | pH/ORP/free chlorine                       | Range; accuracy; calibration burden              | Sensor-specific                | Sensor + consumables + replacement cost |
| Connectivity       | Existing Wi-Fi/BLE or cellular add-on      | Offline-first operation; synchronization         | Communication current/data use | Module, SIM/data and replacement costs  |

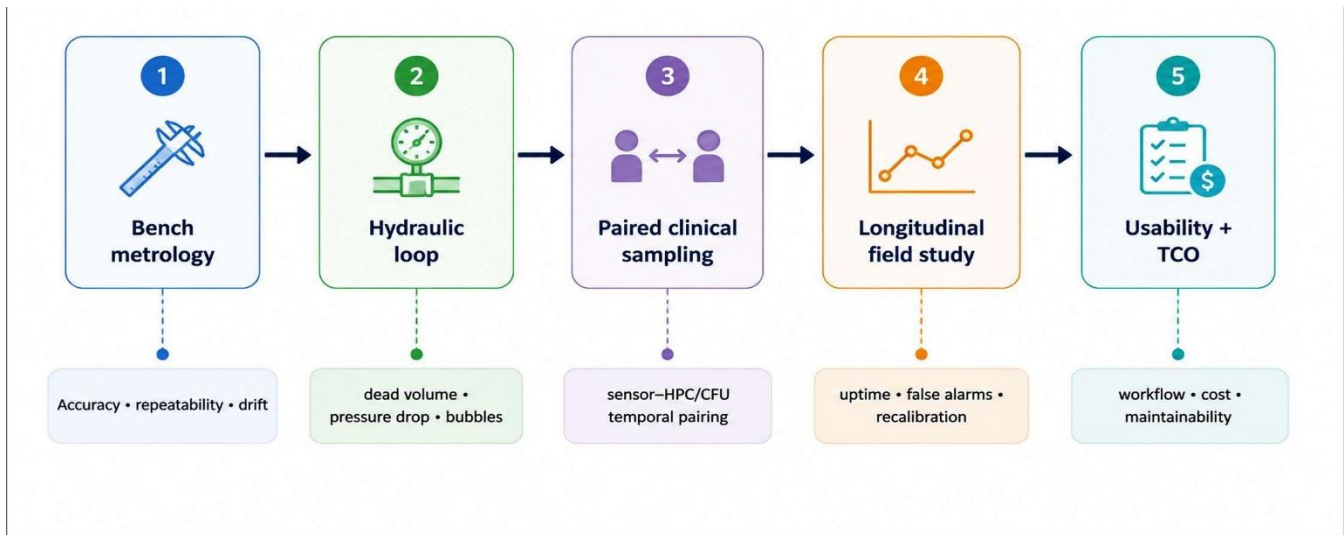
For the final prototype, procurement should distinguish locally sourced, regionally sourced and imported components. Calibration equipment, recurring standards or reagents, sensor replacement and maintenance labor should be included in the total cost of ownership (TCO). The economic analysis should report acquisition cost, annual operating cost, expected replacement intervals and a three-year TCO per monitored dental unit.

Table 4. Requirements for deployment in resource-limited settings

| Design criterion          | Minimum requirement                                          | Verification metric                                         |
|---------------------------|--------------------------------------------------------------|-------------------------------------------------------------|
| Affordability             | Low-cost core device with modular advanced sensors           | Acquisition cost + three-year TCO                           |
| Repairability             | Replaceable sensor modules and documented connectors         | Mean repair time; local repair success rate                 |
| Connectivity independence | Local logging and alarms without Internet                    | Data completeness during simulated network outage           |
| Power resilience          | Safe low-voltage supply with data protection                 | No data corruption after defined interruptions              |
| Chemical compatibility    | Wetted materials compatible with approved maintenance agents | Leakage, swelling, cracking and sensor drift after exposure |
| Hydraulic safety          | Minimal dead volume and pressure drop                        | Measured pressure drop and residence time                   |
| Usability                 | Simple status states and maintenance prompts                 | Task completion time and user error rate                    |

### Proposed Validation Methodology

Validation is divided into sequential stages so that engineering performance is established before microbiological or field claims are made. The sequence is: (1) sensor metrology; (2) integrated electronics and software verification; (3) hydraulic verification; (4) paired sensor–microbiological sampling; (5) longitudinal field deployment; and (6) implementation and usability assessment. This staged approach reduces the risk of attributing poor clinical performance to a sensor when the underlying problem is calibration, hydraulic disturbance or software failure.



**Figure 4. Proposed six-stage validation pathway, progressing from sensor metrology and integrated-device verification to hydraulic testing, paired microbiological sampling, longitudinal field deployment and implementation assessment. Original figure retained and visually enhanced.**

**Table 5. Proposed validation protocol and acceptance criteria**

| Stage                              | Sample/setting                                  | Measurements                                             | Frequency                                                      | Primary endpoint                            | Proposed acceptance criterion                                            |
|------------------------------------|-------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------------|---------------------------------------------|--------------------------------------------------------------------------|
| I. Sensor metrology                | Laboratory reference setup                      | Temperature, turbidity, EC, flow/pressure                | Multiple levels with repeated measurements                     | Bias, MAE, RMSE, repeatability              | Predefined limits based on intended use and reference uncertainty        |
| II. Integrated-device verification | Completed prototype                             | Acquisition, timestamps, storage, alarms, communication  | Continuous bench operation                                     | Data completeness and fault handling        | ≥95% valid records under normal operation                                |
| III. Hydraulic verification        | Dental-unit simulator / representative unit     | Pressure drop, residence time, flow disturbance, leakage | Normal and stressed operating conditions                       | $\Delta P$ , dead volume, leakage, recovery | No unacceptable restriction; no leakage; predefined residence-time limit |
| IV. Paired microbiology            | Multiple dental outlets                         | Sensor time series + microbiological sample              | Baseline and repeated matched sampling                         | Association/classification performance      | Pre-specified sensitivity/specificity/AUC targets                        |
| V. Longitudinal field study        | Multiple dental units across facilities         | All sensors, maintenance and microbiology                | Continuous sensing with scheduled/event-triggered microbiology | False alarms, missed events, lead time      | Predefined event-detection and data-completeness targets                 |
| VI. Usability / economics          | Expected operators and participating facilities | Task time, errors, calibration effort, TCO               | Repeated representative tasks                                  | Usability and lifecycle burden              | Predefined task-success and TCO targets                                  |

### Proposed Sample Size and Field-Sampling Plan

The final sample size should be determined from the primary validation endpoint rather than selected solely for convenience. A pragmatic first field study may include approximately 10–20 dental units distributed across at

least two facilities, provided that the final number is justified by an a priori power or precision calculation. Repeated paired observations should be collected from each unit so that within-unit variation, between-unit variation and facility effects can be separated. If preliminary pilot data are available, their variance estimates should be used to calculate the definitive sample size.

Each participating dental unit should be characterized by water source, unit model, tubing configuration, reservoir use, maintenance history, disinfection practice and typical operating schedule. Sampling should occur at the point of use. Continuous sensor acquisition may be configured at a short interval such as 1–10 seconds for transient events, with summarized records stored at approximately one-minute resolution to balance temporal resolution, memory and power consumption. The exact interval should be fixed before the field study and justified by sensor response time and hydraulic behavior.

### **Microbiological Reference Method**

Microbiological testing should provide the reference outcome against which sensor behavior is evaluated. The primary reference method should be a validated heterotrophic plate count procedure, with sampling and preservation performed according to the approved laboratory protocol and applicable water-sampling guidance. Each microbiological sample should be collected from the same outlet and as close as practicable to the corresponding sensor observation. Sample volume, pre-flush or post-flush condition, transport time, storage conditions, culture medium, incubation conditions and counting rules must be specified in the final study protocol.

Where resources permit, additional methods such as ATP measurement, flow cytometry, molecular testing or organism-specific culture may be included as secondary endpoints. These methods should not be mixed indiscriminately: each answers a different biological question. The primary analysis should retain a clearly defined reference outcome, preferably log-transformed heterotrophic bacterial counts, and the study should distinguish microbiological detection from clinical infection outcomes.

### **Hydraulic Verification Protocol**

Before installation on clinical units, the completed sampling assembly should be tested for pressure drop, residence time, minimum detectable flow, leakage, flushing disturbance and recovery after maintenance. Representative tubing dimensions and connectors should be used. The device should not cause clinically meaningful restriction, alter normal flushing behavior or create a large retained water volume. Measurements should be recorded before and after installation so that any hydraulic effect attributable to the monitoring assembly can be quantified.

### **Statistical Analysis Plan**

The primary analysis should use repeated paired observations rather than treating all readings as independent. Sensor time series are serially correlated, while microbial counts are commonly right-skewed. Heterotrophic counts may therefore be analyzed on a log<sub>10</sub> scale after confirming the suitability of the transformation. A linear mixed-effects model can be used for continuous microbial outcomes, with sensor variables and operational state as fixed effects and dental unit, and where appropriate facility, as random effects.

For classification of a predefined elevated-risk microbiological state, sensitivity, specificity, positive predictive value, negative predictive value, ROC curves and area under the curve should be reported with confidence intervals. Alarm performance should include false alarms per device-day and missed-event rate. For early-warning analysis, lagged associations and time-to-event methods may be used to estimate whether a persistent sensor change occurs before a microbiological increase. Bland–Altman analysis is appropriate for agreement between a sensor and a reference instrument when the measurement scale and assumptions support it.

If machine learning is introduced, the split between training and testing data should be performed by dental unit or by time period rather than by randomly distributing individual sensor readings. This prevents observations from the same chair from appearing in both training and testing sets and producing overly optimistic performance

estimates [20,39]. Model outputs should remain framed as screening recommendations unless independent validation demonstrates clinically acceptable performance.

**Table 6. Validation endpoints and statistical analyses**

| Validation domain         | Primary endpoint                            | Suggested analysis                                    |
|---------------------------|---------------------------------------------|-------------------------------------------------------|
| Sensor accuracy           | Bias and agreement versus reference         | MAE, RMSE, bias plots, Bland–Altman where appropriate |
| Repeatability             | Within-device variability                   | Coefficient of variation; repeatability SD            |
| Drift                     | Change over deployment time                 | Slope versus time; recalibration interval             |
| Microbiological screening | Detection of predefined elevated-risk state | Sensitivity, specificity, PPV, NPV, ROC/AUC           |
| Temporal prediction       | Lead time before microbiological increase   | Lagged association; time-to-event analysis            |
| Alarm performance         | False alarms and missed events              | False alarms/device-day; missed-event rate            |
| Hydraulic safety          | Pressure drops and dead volume              | Measured $\Delta P$ and residence time                |

|           |                                       |                                                    |
|-----------|---------------------------------------|----------------------------------------------------|
| Usability | Task completion and error             | Time-on-task; error rate; structured questionnaire |
| Economics | TCO and cost per monitored chair-year | Cost model and sensitivity analysis                |

## Closed-Loop Quality Assurance and Clinical Workflow

### Research Gaps and Future Experimental Work

The most important unresolved evidence gap is the lack of large, longitudinal DUWL datasets in which continuous sensor measurements are paired with microbiological outcomes. General IoT water-quality studies demonstrate technical feasibility of multiparameter sensing but do not establish that a particular sensor signature predicts bacterial contamination in dental units [19][35][36].

Another challenge is distinguishing biological events from ordinary hydraulic or optical disturbances. Turbidity may increase because of bubbles, flushing or particles unrelated to microorganisms, while conductivity may change because of source-water chemistry or treatment. Combining sensor signals with operating state may improve discrimination, but that benefit must be demonstrated experimentally. Long-term exposure to disinfectants, biofilm material and cleaning cycles must also be evaluated because short laboratory tests can underestimate drift and replacement requirements [22][23][34].

## DISCUSSION

The revised framework supports the use of continuous DUWL monitoring as an additional layer of operational surveillance, while maintaining microbiological testing as the reference for determining microbial compliance. This distinction is consistent with current infection-prevention guidance, which requires dental treatment water to meet drinking-water quality and emphasizes routine maintenance and monitoring [5].

The engineering contribution is not the use of an ESP32 or an individual low-cost sensor in isolation. Rather, it lies in combining complementary measurements with unit-specific baselines, local data logging, fault detection, hydraulic verification and a closed-loop response process. The system is intended to help staff identify when a dental unit behaves differently from its verified baseline and to direct attention to units requiring inspection or microbiological confirmation.

The manuscript should not claim that the proposed architecture reduces dental infections until a prospective implementation study demonstrates such an effect. The immediate research priorities are analytical validity, hydraulic safety, reliable operation, screening performance, usability, maintenance burden and lifecycle cost. If these properties are demonstrated across multiple units and facilities, the platform could provide a practical quality-assurance layer where conventional monitoring is difficult to sustain.

### **Limitations**

This work is a narrative-technical review, conceptual engineering design and prospective validation protocol rather than a completed experimental validation study. No original clinical dataset is presented. Consequently, no claims of sensor accuracy, hydraulic performance, microbiological sensitivity or specificity, false-alarm rate, clinical effectiveness or infection reduction are made. The bill of materials and cost model describe the information that must be reported and the engineering targets that should be established before procurement; final prices should be based on documented quotations or supplier records.

The proposed sensor combination is also subject to water chemistry, tubing design, disinfectant exposure, temperature, operating schedule and maintenance history. A model trained on one group of dental units may not generalize to another institution. External validation across several facilities and equipment types will therefore be necessary. Finally, the proposed sampling frequency and field-study size should be confirmed through pilot measurements and an a priori statistical calculation before the prospective study begins.

### **CONCLUSIONS**

DUWL contamination remains an important water-quality and infection-prevention concern because narrow tubing, intermittent flow, stagnation and biofilm formation can alter water quality at the point of use [1–3][5]. A low-cost monitoring platform could provide useful continuous information between microbiological sampling events, particularly in resource-limited settings where repeated laboratory testing may be difficult to sustain. However, the proposed physical and chemical sensors should be treated as operational and surrogate measurements rather than direct microbiological analyzers.

This revised manuscript presents a transparent conceptual architecture together with a reproducible literature-search strategy, expanded engineering requirements, a proposed bill of materials and cost model, calibration and hydraulic verification procedures, paired microbiological validation, statistical analysis and explicit acceptance criteria. The next stage should be prototype construction followed by bench verification and a controlled longitudinal field study. Until those studies are completed, the system should be described as a research and early-warning platform rather than a validated clinical decision system.

### **Author Contributions**

Conceptualization: Dorothy Namuleme and Ukagwu Kelechi John. Literature synthesis: Bwogi Bashir and Ukagwu Faith. Device architecture and engineering framework: Dorothy Namuleme, Ukagwu Kelechi John, Mutamba Raymond and Katongole Geoffrey Brian. Manuscript preparation and critical revision: all authors.

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No external funding is claimed for this conceptual design and validation framework. Funding sources for prototype fabrication and prospective clinical validation should be declared when those activities are undertaken.

### **Institutional Review Board Statement**

Not applicable to the present literature and design paper. Any prospective validation involving dental units, clinical procedures, patient-linked information or biological sampling should receive the appropriate institutional and regulatory approvals before data collection.

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### Informed Consent Statement

Not applicable to the present conceptual paper. Prospective field studies should obtain consent where required by the relevant institutional and national framework.

### Data Availability Statement

No original clinical dataset was generated for this manuscript. A future validation study should, where ethically and legally permissible, make anonymized sensor time-series data, microbiological outcomes, calibration records and analysis code available to support reproducibility.

### Conflicts of Interest

The authors declare no conflict of interest.

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