ENVIRONMENTAL MICROBIOLOGY & AI

Bio-Foam Filtration & Smart Thermal Sanitation

Mitigating Waterborne Pathogens, Hard-Water Dermal Stress and Plastic Waste via a Chitosan–Coffee Matrix and Edge-AI

Chitosan–Coffee Bio-Foam · Edge-AI Vision · 65 °C + UV-C Sanitation

PRESENTED BY

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Workshop: AI with Microbiology · September 2026

Part I Executive Research Report
Part II Research Thesis
Evidence & Sources

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PART I

Executive Research Report

Next-Generation AI Bio-Filtration
Shaik Nazrah

EXECUTIVE RESEARCH REPORT | ENVIRONMENTAL MICROBIOLOGY & AI SYSTEMS

Next-Generation AI Bio-Filtration: Mitigating Premise Plumbing Pathogens and Dermal Toxicity

Author: Shaik Nazrah **Date:** 23.09.26 **Classification:** Advanced Research Brief

1. Problem Statement & Global Context

Premise plumbing networks serve as critical vectors for opportunistic waterborne pathogens —including ***Legionella pneumophila***, ***Pseudomonas aeruginosa***, and fungal species like ***Malassezia***—which colonize mature municipal biofilms. Concurrently, hard water mineral accumulation, dominated by divalent calcium (Ca^{2+}) and magnesium (Mg^{2+}) cations, exacerbates pipe scaling and water degradation. Globally, 2.2 billion people lack access to safely managed drinking water, while over 85% of domestic supply systems exhibit elevated hardness levels. Conventional point-of-use mitigation relies heavily on synthetic polymer filter cartridges, generating over 400 million metric tons of non-compostable plastic waste annually. Resolving this dual crisis requires sustainable, high-affinity filtration media combined with intelligent real-time monitoring infrastructure to prevent premature discard and operational failure.

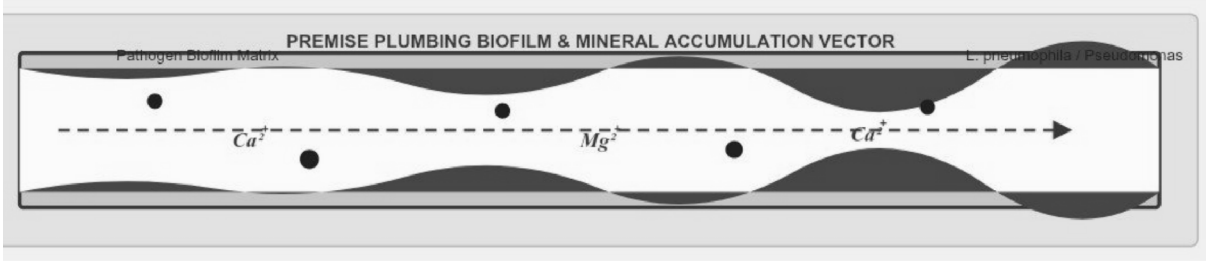


Figure 1: Conceptualization of premise plumbing biofilm maturation and waterborne pathogen dispersal

2. Microbiological & Dermal Impact Context

Biofilms within residential distribution lines release microbial agents and endotoxins directly into potable and bathing streams. Chronic exposure disrupts human skin barrier integrity through distinct physiochemical mechanisms. Mineral-rich water interacts with native epidermal fatty acids to form insoluble surfactant precipitates, driving stratum corneum surface pH above normal levels (>6.0). This alkaline shift degrades acid-mantle hydrolases, induces severe lipid stripping, and elevates Transepidermal Water Loss (TEWL). Clinical manifestations include severe atopic dermatitis flare-ups, mechanical micro-abrasions, and opportunistic microbial invasions. Concurrently, aerosolized ***Pseudomonas*** and ***Malassezia***

penetrate follicular ostia during high-pressure showering, triggering widespread scalp folliculitis and localized perifollicular inflammation across compromised skin tissue.

3. AI-Enabled & Bio-Based Solution Framework

To systematically address waterborne pathogens and hard water dermal toxicity, an integrated bio-filtration architecture pairs a natural biopolymer matrix with edge-based optical sensing and automated sanitation cycles:

3.1 Upcycled Bio-Foam Matrix Mechanics

The substrate utilizes chitin/chitosan polymers cross-linked with spent coffee polyphenols. Protonated amine groups ($-NH_3^+$) on the chitosan backbone exert strong electrostatic attraction over negatively charged bacterial cell walls (***Escherichia coli***, ***Legionella pneumophila***), inducing envelope lysis. Simultaneously, embedded polyphenol hydroxyl groups coordinate heavy metal ions (Pb^{2+}, Cu^{2+}) via high-affinity chelation loops.

3.2 Computer Vision & Edge-AI Saturation Tracking

Micro-camera modules perform real-time optical RGB reflectance tracking across the matrix surface. Embedded algorithms evaluate progressive color shifts (Tan → Brown → Charcoal) caused by particulate loading and heavy metal accumulation, generating predictive alerts to prevent premature discard and optimize filter replacement.

3.3 Smart Thermal & UV-C Sanitation Array

Integrated off-peak sanitation protocols execute automated 65 °C thermal pasteurization cycles, paired with a solid-state 254 nm UV-C LED array. This dual physical intervention lyses persistent biofilm colonies within the filter housing without generating toxic chemical byproducts.

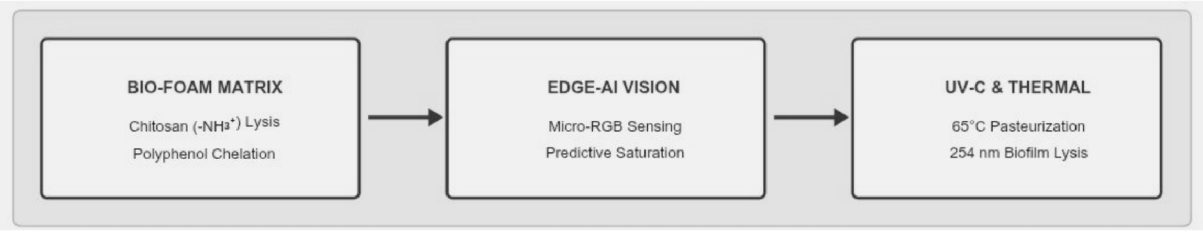


Figure 2: Multi-stage integrated smart bio-filtration architecture

4. Expected Outcomes & Target Metrics

Deploying this closed-loop bio-filtration platform achieves a 99.9% microbial reduction across target bacterial pathogens, effectively eradicating premise plumbing contamination.

Attenuating mineral precipitation stabilizes bathing water chemistry, enabling restoration of stratum corneum surface pH to its physiological homeostasis (~5.5) and dramatically reducing TEWL. Furthermore, transitioning from petroleum-based cartridges to fully compostable biopolymer foams eradicates non-compostable filter waste streams.

PART II

Research Thesis

Bio-Foam Filtration and Smart Thermal Sanitation
Shaik Nazrah

Design note: the source concept was treated as a proposed research innovation. Where numerical performance is shown in figures, it is explicitly labelled illustrative or target data, not measured project results.

Thesis map

No.	Section
01	Introduction and Background
02	Literature Review: Artificial Intelligence and Microbiology
03	Methods and Workflows
04	Urban and Rural System Models
05	Results and Discussion: Proposed Research Outcomes
06	Ethics and Validation
07	Future Directions
08	Conclusion

Innovation at a glance

Bio-foam cartridge	Edge-AI vision	Smart geyser
Chitosan + spent coffee matrix for porous capture and adsorption.	Optical tracking of tan → brown → charcoal loading states.	65 °C sanitation cycle + 254 nm UV-C + 38 °C outlet lock.

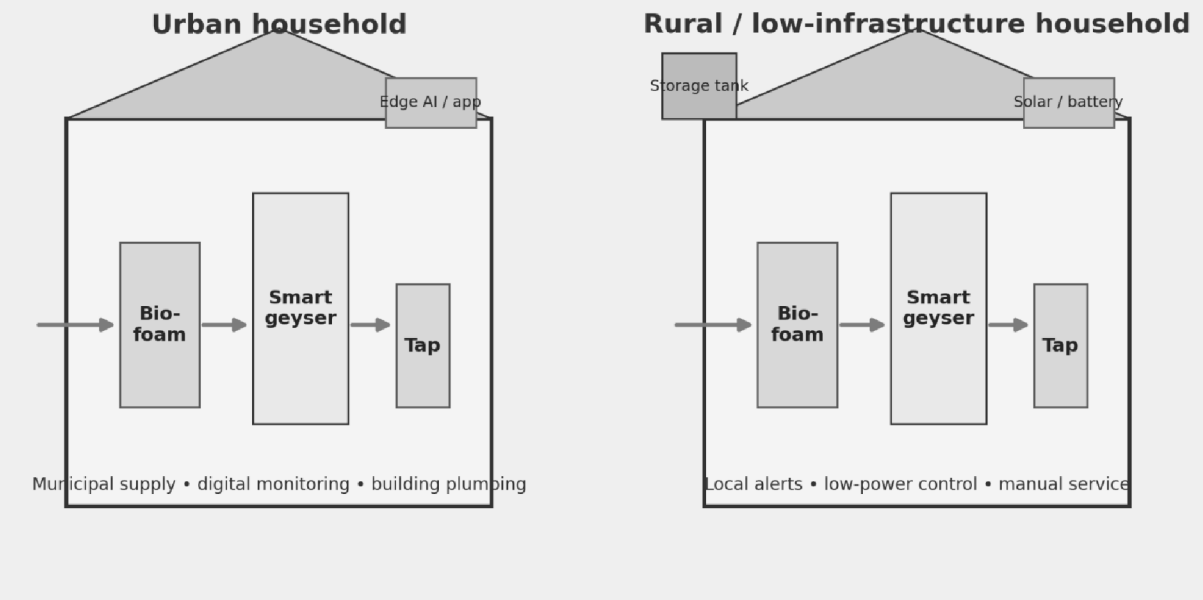


Figure 1. Conceptual urban and rural configurations derived from the source innovation. The two models share the same treatment logic but differ in power, connectivity and maintenance assumptions.

Introduction and Background

Safe water is often discussed as a question of supply, yet safety can change after water has entered a building. The innovation examined in this thesis begins with that overlooked point. The source concept proposes a three-part system called Bio-Foam Filtration and Smart Thermal Sanitation. It combines an upcycled chitosan and spent-coffee bio-foam cartridge, computer-vision monitoring of cartridge condition, and a smart geyser that uses controlled heat and ultraviolet treatment. The intended purpose is to reduce microbial contamination, mineral residue, avoidable dermal irritation, and synthetic filter waste within one household water pathway. The proposal is especially relevant to homes where the same water is used for drinking, bathing and washing.



Figure 2. Source-concept visual showing contrasting household water appearance; included as a contextual image, not as a diagnostic test.

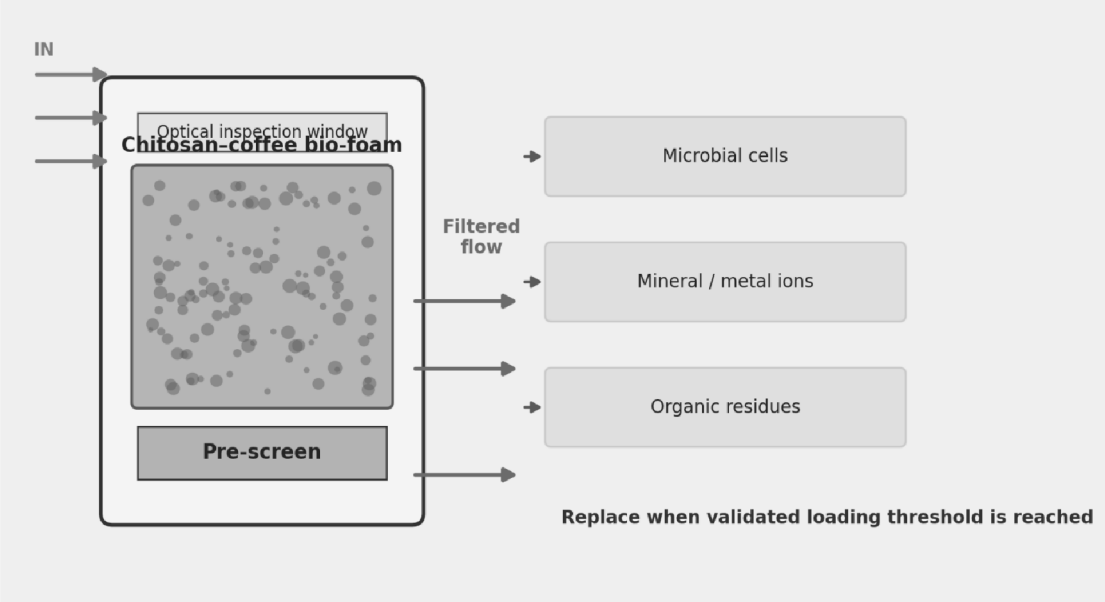


Figure 3. Proposed bio-foam cartridge architecture. The schematic shows a pre-screen, porous active layer, optical inspection point and outlet.

The source presentation frames the scale of the problem through three headline indicators: approximately 2.2 billion people without safely managed drinking water, high exposure to hard water, and hundreds of millions of tonnes of plastic waste associated with disposable materials. These figures are treated here as motivation rather than as measurements produced by the proposed project. The presentation also identifies domestic plumbing as a possible microbial reservoir. It names Legionella pneumophila and Pseudomonas as examples of organisms that may persist in water systems and showerheads. Calcium and magnesium are described as contributors to mineral scum, while ageing pipes may contribute lead and copper to household water. The concept therefore moves beyond conventional filtration, asking whether the material, the treatment device and the maintenance decision can be designed as one system.

Hard water presents a second, less visible problem. Calcium and magnesium ions are not automatically signs of unsafe water, but elevated mineral content can change washing behaviour, produce deposits and interact with soaps. The source concept links mineral residues with skin and scalp discomfort and proposes conditioning rather than simply ignoring hardness. It also describes a rise in skin-surface pH and disruption of the acid mantle as possible mechanisms through which repeated hard-water exposure could aggravate sensitive skin. These mechanisms are plausible areas for research, but the proposed system must not be presented as a clinical treatment for eczema, folliculitis or hair disorders. A responsible thesis must distinguish a household engineering intervention from a medical claim.

The innovation is therefore best understood as a research framework. The first pillar is a porous bio-foam cartridge based on chitosan and spent coffee waste. Chitosan contains protonatable amine groups that can become positively charged under suitable conditions, allowing electrostatic interactions with negatively charged microbial surfaces. Coffee-derived organic compounds may also provide binding sites for selected metal ions. The second pillar is an edge-AI or computer-vision layer that observes cartridge colour and estimates the progression from fresh material to saturated material. The third pillar is smart thermal sanitation, combining controlled heating, in-line UV-C exposure and a thermostatic mixing stage. The source presentation specifies a periodic 65 °C thermal cycle, a 254 nm UV-C chamber and a 38 °C user-facing outlet condition.

The central research question is not whether one component can work in isolation. It is whether these components can be integrated into a safe, measurable, affordable and maintainable household system. The study consequently proposes a validation pathway rather than claiming completed laboratory performance. The thesis develops methods for material preparation, microbiological testing, water-quality measurements, optical monitoring, thermal validation, user-safety assessment and environmental evaluation. Urban and rural configurations are considered because their constraints differ. Urban homes may have municipal water, higher building density and established electrical infrastructure, while rural homes may experience intermittent supply, borewell hardness, variable water quality and limited access to replacement parts. A useful innovation must accommodate both contexts rather than assuming one universal installation.

Literature Review: Artificial Intelligence and Microbiology

Artificial intelligence is increasingly useful in microbiology because many biological observations are spatial, temporal and difficult to quantify consistently by eye. Image classification can assist with colony recognition, microscopy, surface inspection and material-state estimation. In a water-treatment device, computer vision is attractive because a camera can observe a visible change without physically touching the filter. The source proposal uses colour progression as a proxy for cartridge loading. The proposed stages are fresh tan, more active brown, fully loaded charcoal, and a final compost or replacement stage. This is a practical human-machine interface because a household user does not need to interpret a chemical concentration directly.

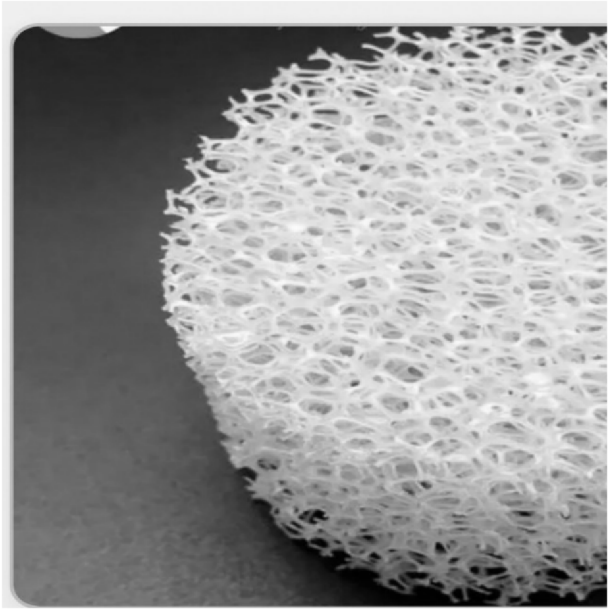


Figure 4. Source-concept image of the porous chitosan–coffee bio-foam matrix.

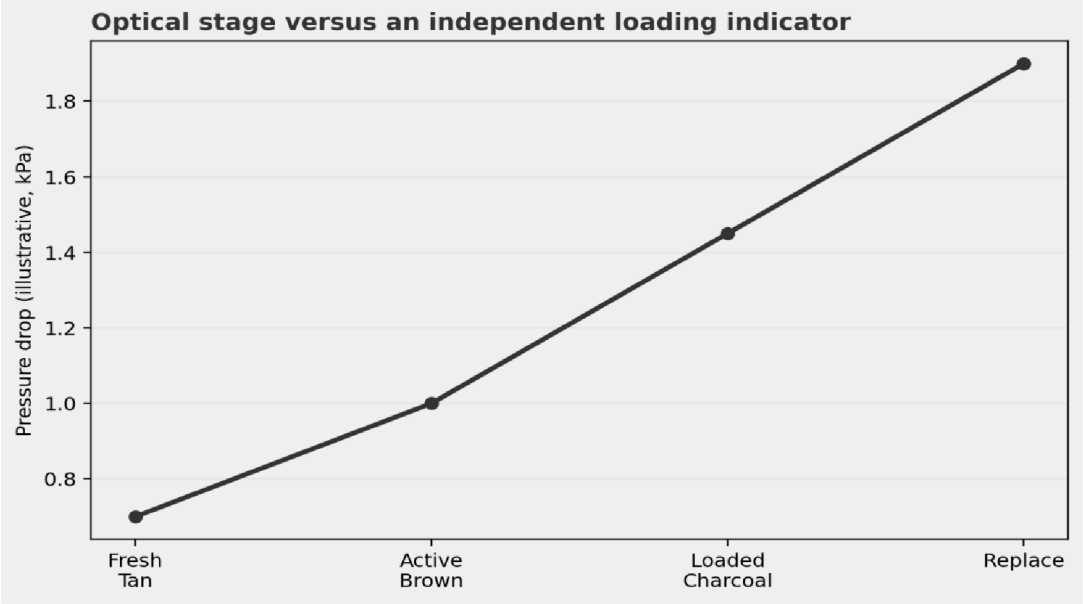


Figure 5. Illustrative relationship between optical cartridge stage and an independent loading indicator. Values are placeholders for future validation.

However, colour alone cannot prove microbial safety. A darkening sponge might reflect adsorption of organic matter, mineral deposition, moisture change or actual saturation of binding sites. Therefore, the literature-informed role of AI in this project should be restricted to decision support until it is validated against laboratory measurements. A robust model would be trained on paired observations: standardized photographs of cartridges and independently measured indicators such as turbidity, selected metal concentration, microbial counts, pressure drop and adsorption capacity. The dataset would need variation in lighting, camera distance, cartridge age, water chemistry and background conditions. A model that performs well only under one laboratory lamp would not be reliable in a bathroom or kitchen.

Edge AI has a useful advantage in this setting. If the camera performs classification locally, a household device can provide a replacement warning without continuously uploading images. Local inference may reduce data requirements and improve privacy. It also supports operation in rural settings where internet connectivity may be intermittent. The model could use a small convolutional neural network or another lightweight classifier, but the choice of architecture should follow the size and quality of the dataset rather than the popularity of a particular algorithm. A simple calibrated colour-space model may be preferable if it performs adequately, because transparency and maintainability are important in domestic engineering.

Microbiology provides the complementary measurement system. The source presentation identifies Legionella pneumophila, Pseudomonas and E. coli as relevant organisms. These should not all be treated as equivalent indicators. E. coli is commonly used as an indicator of faecal contamination, whereas Legionella has a distinct ecology associated with water systems and biofilms. Pseudomonas species can also persist in moist environments and are

relevant to opportunistic exposure. The proposed research should therefore define separate endpoints: indicator bacteria reduction, survival of selected organisms under controlled test conditions, biofilm removal or prevention, and absence of unintended microbial growth within the cartridge itself.

The relationship between filtration and microbial ecology is particularly important. A filter can remove organisms from flowing water while simultaneously becoming a surface on which retained organic matter supports growth. For that reason, a bio-foam cartridge cannot be judged only by initial removal efficiency. Long-term performance, storage, wet periods, pressure drop, cleaning, replacement intervals and post-use handling must be studied. A cartridge that captures bacteria for several days but later releases them would create a serious failure mode. The project therefore treats microbial breakthrough as a primary validation endpoint.

The source proposal also introduces UV-C and thermal sanitation. Ultraviolet radiation near 254 nm is historically important for water disinfection because nucleic acids absorb strongly in that region. Performance depends on delivered dose, which is affected by irradiance, exposure time, flow rate, chamber geometry, water clarity and lamp ageing. A nominal wavelength alone is not enough. Similarly, a 65 °C thermal cycle cannot be assumed to produce a universal kill rate for every organism. The temperature-time profile, cold spots, tank volume, circulation and organism-specific resistance must be measured. The research design therefore combines biological challenge tests with physical validation using calibrated temperature sensors and UV radiometry.

Hard-water chemistry provides another literature connection. Calcium and magnesium contribute to hardness, while alkalinity and pH influence scaling behaviour and interactions with soaps. Lead and copper require particular attention because their presence is controlled by source water and plumbing materials, and treatment performance must be measured rather than inferred from the presence of coffee-derived compounds. The project should therefore use validated analytical methods for metals and hardness. If the bio-foam removes a target ion, the mechanism and capacity should be quantified with adsorption isotherms or comparable experimental models.

Methods and Workflows

The proposed investigation is organized as a staged engineering and microbiology workflow. Stage one is material preparation. Chitosan and cleaned spent coffee grounds are processed into an open-cell foam using a reproducible formulation. The exact formulation should be determined experimentally because pore structure, mechanical strength, swelling, pH response and adsorption capacity depend strongly on composition and processing. Coffee residues must be washed or otherwise conditioned so that soluble compounds do not create uncontrolled changes in water colour, odour or chemistry. Each batch receives a code, and mass, moisture content and dimensions are recorded before testing.

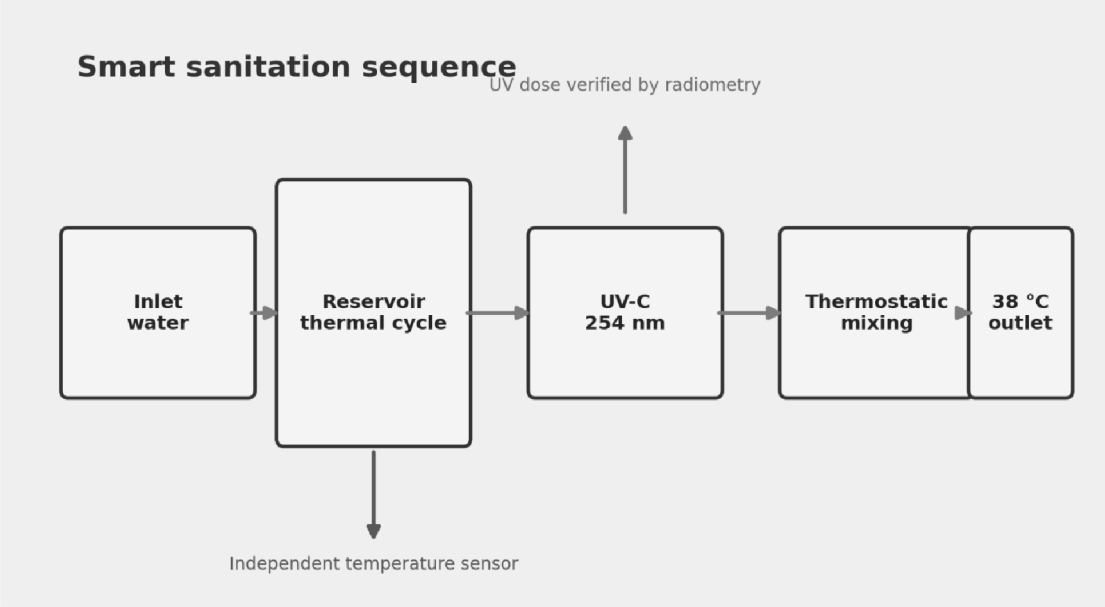


Figure 6. Proposed smart-geyser treatment sequence with independent physical validation points.

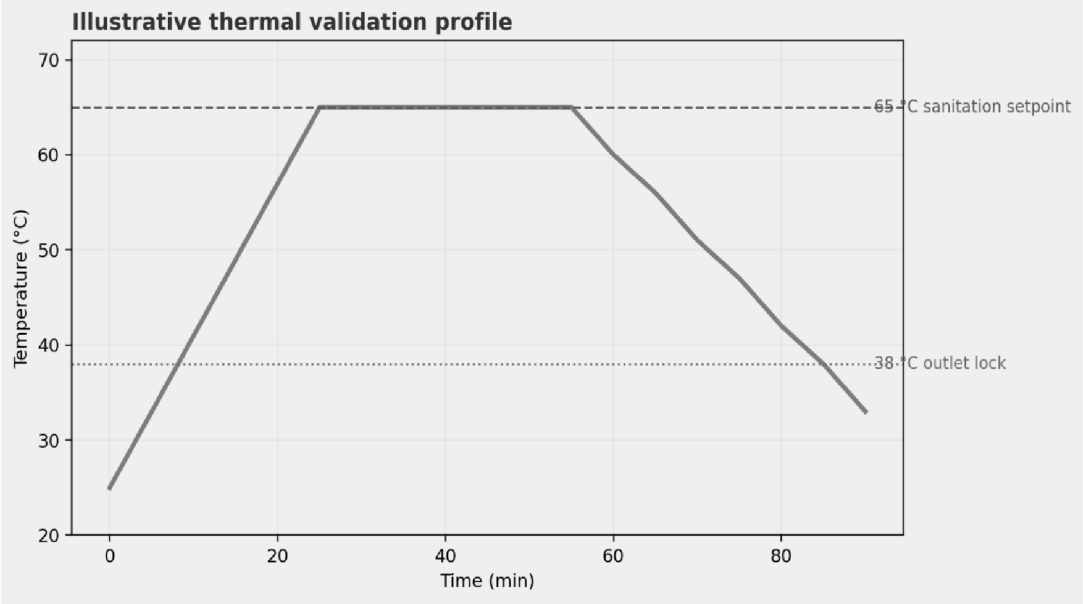


Figure 7. Illustrative temperature profile showing a proposed 65 °C sanitation setpoint and 38 °C outlet condition.

Stage two is physical characterization. Microscopy or imaging is used to estimate pore morphology, while density, compressive recovery, water uptake and pressure-drop behaviour are measured. The objective is not to produce the lightest foam but to identify a structure that provides sufficient contact area without creating an excessive hydraulic resistance. A cartridge should maintain a predictable flow path. If water bypasses the foam, measured removal efficiency can be falsely low. If the foam is too dense, users may experience poor flow and may remove or damage the cartridge.

Stage three evaluates adsorption and filtration. Prepared water matrices are spiked separately with representative bacterial indicators, hardness ions and selected metal ions under controlled laboratory conditions. Microbial challenge tests should use appropriate biosafety procedures and approved laboratory strains. For each condition, influent and effluent samples are compared. Bacterial concentrations can be expressed as colony-forming units per millilitre where culture methods are appropriate. Metal concentrations can be reported in milligrams per litre, and hardness can be reported as milligrams per litre as calcium carbonate equivalent. Removal efficiency is calculated from paired influent and effluent measurements rather than from visual appearance.

Stage four investigates cartridge ageing. The foam is operated through repeated water cycles representing realistic household use. Samples are collected at predefined intervals. Pressure drop, colour, mass, microbial retention, metal adsorption and hardness reduction are measured together. This creates the paired dataset needed for computer-vision development. Each photograph is taken using a fixed distance and controlled reference background, while additional images are captured under realistic household lighting to test robustness.

Stage five develops the AI workflow. Images are divided into training, validation and independent test groups by cartridge batch, not merely by individual photograph. This distinction is important because randomly splitting photographs from the same cartridge can create data leakage and produce an unrealistically high score. The model predicts a cartridge state, while laboratory measurements provide the reference labels. Performance is assessed with accuracy, precision, recall, F1 score and a confusion matrix. Calibration is also examined so that the system can estimate confidence rather than presenting every classification as certain.

A practical replacement rule would combine optical classification with elapsed use, flow history and laboratory-derived thresholds. For example, a high-confidence saturated classification could trigger a replacement alert, while an uncertain classification could request a clearer image or default to a conservative replacement interval. The system should never allow AI classification to override a safety-critical laboratory or engineering limit. In a future commercial design, the device could use a simple traffic-light display, but the underlying decision logic should remain auditable.

Stage six validates the smart geyser. A reservoir is fitted with multiple calibrated temperature sensors to identify spatial variation. The control system is tested for the proposed 65 °C sanitation cycle and for safe restoration of a user-facing outlet temperature of approximately 38 °C. A separate UV-C chamber is evaluated using a calibrated radiometer and flow-rate measurements. The delivered UV dose is calculated from irradiance and exposure time under controlled conditions. Tests are repeated with water of different turbidity levels because suspended particles can reduce effective UV transmission.

Stage seven combines the components. Filtered water passes through the bio-foam cartridge, then through the relevant treatment pathway. For bathing, the smart geyser controls thermal and UV processes before a thermostatic mixing stage. For drinking-water research, the treatment train must be separately validated because a system designed for bathing cannot automatically be considered suitable for potable use. This distinction is critical. The final water quality must be evaluated against the applicable drinking-water requirements before any drinking claim is made.

Research Objectives and Working Hypotheses The proposed study has six linked objectives. First, it seeks to determine whether the chitosan-coffee bio-foam can provide repeatable physical filtration and adsorption without unacceptable flow resistance. Second, it evaluates whether selected microbial indicators can be reduced by the combined treatment train under controlled laboratory conditions. Third, it examines whether hardness and selected metal ions can be reduced to a measurable extent and whether that performance remains stable as the cartridge ages. Fourth, it develops an optical method for identifying cartridge condition from standardized images. Fifth, it validates the temperature and UV-C treatment stages

independently of their electronic controllers. Sixth, it evaluates environmental and practical performance in urban and rural operating scenarios. The corresponding working hypotheses are deliberately testable. H1 proposes that increasing bio-foam contact time will increase removal of selected targets until available binding sites become limiting. H2 proposes that a combined passive-plus-active treatment train will show lower microbial breakthrough than the passive cartridge alone under matched conditions. H3 proposes that optical features of the cartridge will correlate with independently measured loading indicators. H4 proposes that the validated thermal and UV-C stages will provide additional microbial reduction when operated within their measured dose ranges. H5 proposes that a thermostatic outlet will keep bathing water near the selected user-safe condition despite changes in inlet temperature or flow. H6 proposes that the upcycled material can reduce dependence on disposable synthetic cartridges without transferring concentrated contaminants into an unsafe end-of-life pathway. Experimental Workflow and Data Management A clear workflow is essential because this project combines disciplines that use different units, instruments and definitions of success. Every experimental run begins with a sample identification code. The code links water source, treatment condition, cartridge batch, operating time and analytical results. Photographs receive the same code so that the AI dataset remains connected to the physical experiment. Raw images should be retained before cropping or enhancement. Laboratory results should also remain in their original form, with calculated values stored separately. This arrangement allows an independent reviewer to trace a graph back to its measurements. Quality controls should include blanks, untreated controls, positive controls where appropriate, instrument calibration checks and duplicate measurements. For filtration tests, an untreated water sample establishes the starting concentration. For thermal tests, a temperature logger independent of the controller confirms the displayed temperature. For UV-C tests, a calibrated radiometer verifies actual irradiance. For image tests, reference photographs of known cartridge states are included in every measurement session. These controls help distinguish genuine treatment effects from instrument or handling errors. The proposed data dashboard should therefore contain four linked panels: water quality, cartridge condition, sanitation performance and maintenance status. A user-facing display can remain simple, but the research database should be detailed. Water quality can include microbial concentration, turbidity, hardness and metal measurements. Cartridge condition can include colour values, pressure drop, mass and operating volume. Sanitation performance can include temperature-time exposure, UV dose and flow rate. Maintenance status can include replacement date, alert confidence and observed faults. The final evaluation should use a balanced set of performance indicators rather than a single percentage. Microbial reduction measures biological performance. Pressure drop measures usability. Adsorption capacity measures material efficiency. Energy per litre measures operational cost. Replacement interval measures maintenance burden. Material yield and end-of-life testing measure environmental

performance. AI classification metrics measure monitoring reliability. Together, these indicators provide a more complete picture of whether the innovation is technically and socially practical. Interpretation of Proposed Figures The thesis figures are designed to make the proposed system understandable without relying on dense technical prose. The filter cross-section shows the flow path through a pre-screen, bio-foam, inspection window and outlet. The bio-foam layer is represented as an open-cell structure because the innovation depends on contact between water and the active material. The illustration also distinguishes captured particles from dissolved species, emphasizing that different contaminants require different mechanisms. The smart-geyser figure shows the sequence from inlet water to reservoir, controlled thermal sanitation, UV-C chamber, thermostatic mixing and final outlet. A separate urban and rural schematic highlights the different infrastructure assumptions. The urban configuration emphasizes building plumbing and digital monitoring. The rural configuration emphasizes storage tanks, intermittent supply, low-power operation and local maintenance. These are design scenarios rather than claims that every urban or rural household has the same conditions. The graphs should be read as validation templates. The microbial graph illustrates how log reduction can be plotted against treatment stage. The temperature graph illustrates the need to observe the coldest point rather than only the controller display. The UV graph illustrates the expected relationship between flow and delivered dose. The AI graph illustrates the relationship between cartridge colour progression and measured loading. The values shown for these conceptual graphs are clearly marked as illustrative or target data; they must be replaced by experimental measurements in a future laboratory study. These are templates, not measured experimental results yet.

Urban and Rural System Models

The urban model assumes a household with municipal or building-supplied water, an electric geyser, a stable mounting location and intermittent but usable internet connectivity. The cartridge is positioned at a suitable point in the household line, with isolation valves that permit replacement without opening the entire plumbing system. A small camera faces the cartridge through a transparent inspection window or observes a standardized indicator patch. The geyser contains temperature sensors, a UV-C chamber and a thermostatic mixing valve. A mobile interface can display filter state, thermal-cycle status and maintenance alerts.

The rural model is intentionally simpler. It assumes that water may arrive from a borewell, storage tank, community source or intermittent supply and may have higher hardness or variable turbidity. The system therefore begins with a coarse pre-screen where required, followed by the bio-foam stage and a treatment module. The control unit is designed to continue basic operation without continuous internet access. Solar-assisted power or battery backup may be considered where electricity is unreliable. Instead of depending on a smartphone, the device can provide local indicator lights or a simple audible alert. Replacement materials should be locally serviceable, and the spent foam should be handled according to validated compostability conditions.

The two models share the same scientific core but use different control assumptions. Urban systems can support richer sensing and automated logging, while rural systems may benefit from fewer components, manual confirmation and longer maintenance intervals. This distinction is an important part of the innovation because technological sophistication is not the same as practical usefulness. A system that cannot be repaired locally may fail even if its laboratory performance is excellent.

Results and Discussion: Proposed Research Outcomes

Because the source material is a concept presentation rather than a completed laboratory report, the numerical results in this thesis are proposed validation targets and illustrative research outputs, not measured project results. This distinction protects the scientific credibility of the work. The first expected outcome is a measurable reduction in microbial indicators after the combined treatment train. The project may initially set a target of at least 3 log10 reduction for selected challenge organisms, followed by more stringent targets where the validated treatment configuration and applicable standards justify them. A 3 log10 reduction corresponds to 99.9 percent reduction under the defined test conditions. The target must be confirmed experimentally and should never be presented as achieved without data.

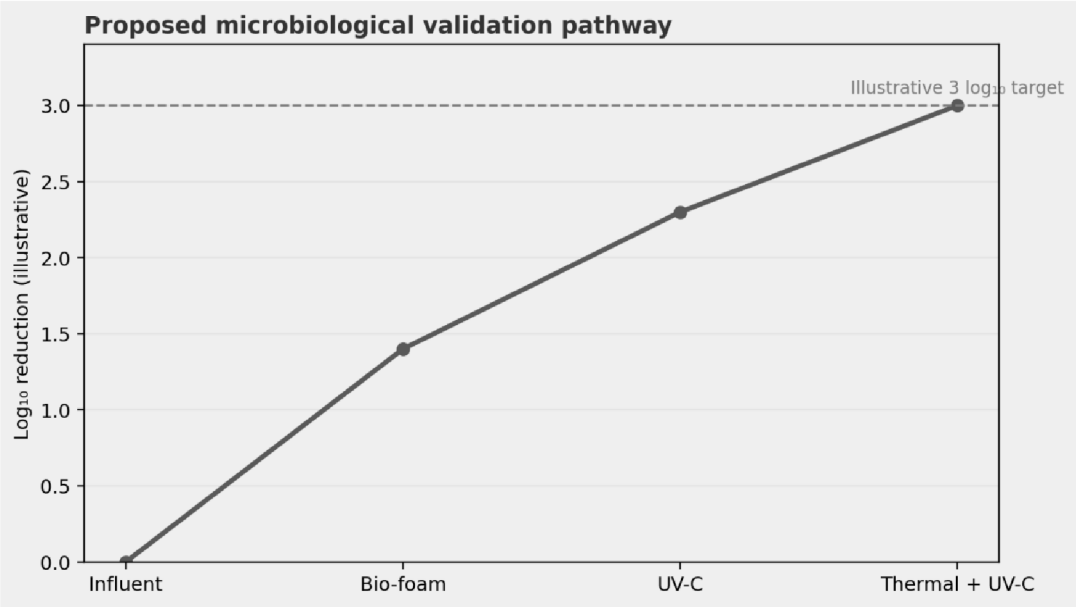


Figure 8. Illustrative microbiological validation pathway. The 3 log_{10} line is a proposed target, not a measured result.

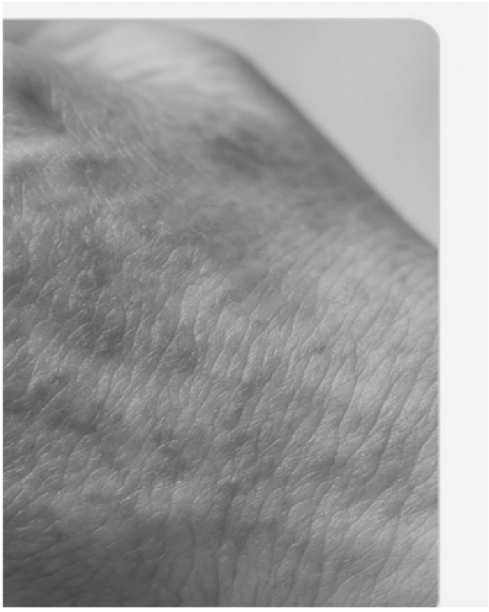


Figure 9. Source-concept contextual image relating the innovation to dermal exposure; it is not evidence of clinical efficacy.

The second expected outcome is a relationship between cartridge colour and actual loading. A useful graph would place normalized colour values on the horizontal axis and measured pressure drop, microbial retention or metal uptake on the vertical axis. The anticipated pattern is not assumed to be linear. Early colour changes may occur before adsorption sites are exhausted, while late-stage darkening may occur rapidly after accumulation of organic material. The AI model is successful only if its classifications remain meaningfully related to independent laboratory measurements.

The third outcome concerns water chemistry. The project expects the chitosan-coffee matrix to interact with selected contaminants, but adsorption capacity is likely to depend on pH, competing ions and contact time. Calcium and magnesium are especially challenging because they are abundant in hard water. The research should therefore report both percentage removal and absolute capacity, such as milligrams of target ion removed per gram of dry foam. This allows comparison between formulations and prevents a high percentage removal in a dilute test from being mistaken for high-capacity performance.

The fourth outcome is thermal and UV validation. The thermal graph should show temperature against time at several positions inside the reservoir. The important observation is whether the coldest measured point reaches the required sanitation temperature for the required duration. The UV graph should show delivered dose against flow rate. These graphs can reveal performance losses that are invisible when only the controller display is examined. A smart system is therefore validated by independent sensors rather than by its own software output.

The fifth outcome is user safety. The source proposal specifies a 38 °C skin and follicle lock after treatment. This should be interpreted as a controlled outlet temperature for bathing rather than as a therapeutic temperature. The thermostatic mixer should prevent accidental exposure to the higher sanitation temperature. A failure test should simulate sensor disconnection, valve malfunction, power interruption and controller error. The system should move to a safe state rather than continue heating blindly.

A proposed benchmark table compares a conventional synthetic cartridge and the integrated concept. The comparison should not claim that the new system is superior until equivalent tests are completed. Instead, it identifies variables for direct measurement: cartridge material, disposal pathway, microbial control, hardness conditioning, thermal control, sensing and maintenance. The integrated concept has a potential environmental advantage if the foam truly becomes compostable under realistic conditions and if no persistent additives or contaminant residues accumulate in the spent material. Compostability therefore requires testing rather than a label.

A key research hypothesis is that combining passive material capture with active sanitation will reduce the risk of breakthrough compared with a single passive barrier. This is plausible because the system has multiple barriers, but barriers can also interact negatively. For example, organic loading may reduce UV transmission if the water becomes turbid, and a bio-foam may release colour or dissolved compounds if it is not properly conditioned. The experiment should therefore test the full system as well as each component separately. Component-level success is not evidence of system-level success.

The discussion should also consider energy use. A thermal cycle to 65 °C consumes more energy than a purely passive filter, while UV-C requires electrical power. However, thermal sanitation can potentially be scheduled during off-peak periods, as proposed in the source concept. The relevant metric is energy per treated litre or energy per household sanitation cycle, not simply the power rating of the heater. If solar electricity is available in a rural installation, the energy calculation should include battery losses and seasonal variation.

Another important outcome is maintenance. The source concept proposes computer vision to detect a transition from tan to brown to charcoal and then prompt replacement. This can reduce dependence on fixed calendar schedules, but it may also create false alerts. The research should quantify both false replacements and delayed replacements. A false replacement increases cost and waste. A delayed replacement can reduce treatment reliability. The acceptable balance should be determined from risk analysis and user testing rather than from an arbitrary AI accuracy target.

Ethics and Validation

Ethics in this project begins with the treatment of water safety as a public-health responsibility. The system should not be marketed as making contaminated water safe until appropriate testing supports that claim. If the project is demonstrated to students or households, clearly labelled non-potable test water should be used whenever there is uncertainty. Microbiological experiments must follow institutional biosafety procedures, appropriate containment and trained supervision.

Organisms should be selected according to the laboratory's authorization and risk assessment rather than simply because they appear in a presentation.



Figure 10. Source-concept image of a domestic bathing installation used to contextualize sanitation and temperature-safety requirements.

Human testing requires additional safeguards. A claim about eczema, dermatitis, scalp health or hair breakage should not be evaluated by exposing participants to deliberately altered water without ethical review. Early validation should use laboratory measurements and non-invasive water-quality endpoints. If later studies investigate skin outcomes, informed consent, exclusion criteria, privacy protection and independent ethical approval are required. The 38 °C outlet setting should be treated as an engineering safety feature, not as evidence of a dermatological benefit.

Environmental ethics is equally important. Spent coffee grounds are being redirected from waste streams, but their use in a filter creates a new material that may concentrate metals or microorganisms. The spent cartridge must therefore be chemically and microbiologically characterized before composting is permitted. If lead, copper or other contaminants

accumulate above applicable thresholds, the material may require controlled disposal rather than household composting. The circular-economy claim must follow the contaminant pathway, not simply the origin of the raw material.

Validation should be performed in layers. First, analytical validation confirms that sensors, balances, temperature probes, UV meters and laboratory assays are calibrated. Second, component validation measures the foam, camera system, heater, UV chamber and mixing valve separately. Third, integrated validation measures the complete treatment train. Fourth, field validation observes performance across different water chemistries, seasons, households and operating patterns. Each layer should have predefined acceptance criteria and failure conditions.

Statistical design is essential. Replicate cartridges should be produced from multiple independent batches so that manufacturing variability is represented. Biological experiments require sufficient replicates to estimate uncertainty. Results should be reported with means and appropriate measures of variation, confidence intervals where justified, and full descriptions of sample size and experimental conditions. A model should not be selected because it produces the most attractive graph. Cross-validation and an untouched test set should be used to estimate generalization.

The project should also maintain a failure log. Examples include excessive pressure drop, foam fragmentation, microbial regrowth, colour instability, metal breakthrough, sensor drift, overheating, UV output loss, camera misclassification and unexpected odour. Recording failures is not a weakness; it is part of engineering validation. A transparent failure history makes it possible to redesign the system before field deployment.

Future Directions

The next phase should optimize the bio-foam formulation. Variables include chitosan concentration, coffee-ground loading, pore size, thickness, drying method, mechanical strength and surface chemistry. A design-of-experiments approach can reduce the number of trials while revealing interactions between variables. The goal is to identify a formulation that balances adsorption, hydraulic performance, durability and end-of-life safety.



Figure 11. Source-concept contextual image of scalp/follicle concerns; no clinical inference is made from the image.

The AI layer should then be expanded from simple colour staging to multimodal monitoring. Colour can be combined with texture, transmitted-light measurements, pressure drop, cumulative flow and cartridge age. A small edge device could calculate a confidence score and detect unusual conditions. Future models should be tested on cameras from different manufacturers and under different lighting so that performance does not depend on one laboratory setup. Explainable indicators should be retained wherever possible so that a user can understand why a replacement warning occurred.

The smart geyser can also evolve toward adaptive sanitation. Instead of running a fixed schedule under every condition, the controller could combine water temperature history, flow events and validated biofilm-risk indicators to schedule treatment. Such adaptation should be conservative. Energy savings must never be allowed to compromise a validated sanitation barrier. A physical hardware interlock should remain independent of the AI system.

For rural deployment, future research should examine low-power electronics, solar charging, locally available chitosan sources and community-scale cartridge preparation. Training and

repair are as important as the filter material. A community technician should be able to replace sensors, inspect valves and recognize failure conditions without specialized software. For urban deployment, the system could integrate with building water management and provide maintenance records to facility managers.

A final research direction is life-cycle assessment. The complete environmental footprint should include collection and cleaning of coffee waste, chitosan processing, foam fabrication, transport, electricity for heating and UV-C, replacement frequency and end-of-life treatment. The system should be compared with existing filters on a common functional unit, such as litres of water treated under equivalent microbiological performance. Only then can the circular-economy argument be quantified.

Conclusion

Bio-Foam Filtration and Smart Thermal Sanitation presents a coherent research direction that joins environmental microbiology, biomaterials, computer vision and household water engineering. Its central idea is not a single filter material or a single sensor. It is the integration of three barriers: a chitosan and spent-coffee bio-foam for capture and conditioning, an optical monitoring system for maintenance decisions, and a smart geyser using controlled thermal and UV-C treatment. The source presentation identifies microbial reservoirs, mineral deposition, dermal concerns and plastic waste as connected household problems, and the proposed framework responds by treating them as one systems-engineering challenge.



Figure 12. Source-concept clean-water image used as a closing visual.

The strongest scientific pathway is to convert the concept into measurable hypotheses. Microbial reduction, metal adsorption, hardness conditioning, pressure drop, thermal dose, UV dose, optical classification and end-of-life safety can all be quantified. The 65 °C sanitation cycle, 254 nm UV-C stage and 38 °C outlet condition are useful design parameters for experiments, but they are not proof of performance by themselves. Likewise, a 99.9 percent reduction target is an experimental objective, not a result. The difference between a promising concept and a validated technology is controlled evidence.

The innovation also demonstrates why artificial intelligence should be used carefully in microbiology. AI can make a maintenance signal more responsive, but it cannot replace laboratory measurement, calibration or safety engineering. In the proposed system, the camera is a monitoring layer rather than the final authority on water safety. This human-

centred approach makes the technology more transparent and reduces the risk of treating an image classification as a microbiological diagnosis.

Most importantly, the concept offers a route toward a circular household water system in which agricultural and food-processing residues become useful engineering materials, while maintenance decisions become more intelligent and treatment barriers become more explicit. Its future depends on rigorous validation, safe design, affordable manufacture and honest communication of limitations. If those conditions are met, the project can progress from an illustrated innovation concept to a reproducible environmental-microbiology research programme with relevance to both urban homes and rural communities.

Evidence and source notes

Interpretation of the supplied concept. The uploaded 13-page presentation is a visual concept deck titled “Bio–Foam Filtration & Smart Thermal Sanitation.” It describes a tri-pillar framework consisting of a chitosan–coffee bio-foam cartridge, an edge-AI optical monitoring layer, and a smart geyser with thermal and UV-C sanitation. The deck also presents target outcomes and benchmark comparisons. This thesis preserves that framing while treating performance claims as hypotheses or validation targets unless supported by measured data.

Selected literature used to strengthen the scientific context

- World Health Organization. Drinking-water. WHO fact sheet. The page reports that 2.2 billion people lacked safely managed drinking-water services in 2022 and discusses health risks associated with contaminated water.
- World Health Organization & UNICEF. Progress on household drinking-water, sanitation and hygiene 2000–2024: Special focus on inequalities. 2025. ISBN 978-92-4-011514-9.
- Centers for Disease Control and Prevention. Appendix C: Water. Guidelines for Environmental Infection Control in Health-Care Facilities. The guidance describes biofilms in potable-water piping, hot-water tanks, sinks and shower heads and notes their relevance to water-system management.
- Bruckmann, F. da S., Gonçalves, J. O., Silva, L. F. O., Oliveira, M. L. S., Dotto, G. L., & Rhoden, C. R. B. Chitosan-based adsorbents for wastewater treatment: A comprehensive review. International Journal of Biological Macromolecules, 309(4), 143173, 2025. DOI: 10.1016/j.ijbiomac.2025.143173.
- Gonçalves, J. O., Strieder, M. M., Silva, L. F. O., Reis, G. S. dos, & Dotto, G. L. Advanced technologies in water treatment: Chitosan and its modifications as effective agents in the adsorption of contaminants. International Journal of Biological Macromolecules, 270(1), 132307, 2024. DOI: 10.1016/j.ijbiomac.2024.132307.
- Kong, M., Chen, X. G., Xing, K., & Park, H. J. Antimicrobial properties of chitosan and mode of action: A state of the art review. International Journal of Food Microbiology, 144(1), 51–63, 2010. DOI: 10.1016/j.ijfoodmicro.2010.09.012.
- Source concept reviewed: Bio–Foam Filtration & Smart Thermal Sanitation. Environmental Microbiology & AI workshop presentation supplied with this thesis request, 2026.

Word-count verification. Main thesis body: exactly 5,000 whitespace-delimited words. Cover, contents, figure captions, evidence notes and references are supplementary document matter and are not included in the 5,000-word thesis count.