A Research Framework for Oil Palm Trunk-Derived Biochar-Based Microbial Media Integrated with IoT-Enabled 3D-Printed Zero-Water Exchange Aquaculture Systems for Community Application

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ABSTRACT

This paper presents a research framework for the development and future validation of an Oil Palm Trunk (OPT)-derived biochar-based microbial medium integrated with an Internet of Things (IoT)-enabled, three-dimensionally printed Zero-Water Exchange Aquaculture System (ZWES) for community application. The framework responds to the combined challenges of water consumption, nitrogen accumulation, underutilised biomass, digital monitoring and the practical adoption of sustainable aquaculture technologies. Unlike a results paper, this manuscript reports no completed experimental measurements because the underlying research programme is scheduled for implementation from November 2026 over three years. The proposed methodology therefore defines reproducible operating conditions and validation criteria before experimentation. OPT will be converted to biochar using a controlled pyrolysis window of 400–600 °C under nitrogen, followed by candidate activation and washing protocols. Biochar will be characterised using proximate analysis, pH, ash content, Brunauer–Emmett–Teller surface area, scanning electron microscopy with energy-dispersive spectroscopy and Fourier-transform infrared spectroscopy. Microbial colonisation and nitrification will be compared with conventional Down-flow Hanging Sponge media, while an Up-flow Sludge Bed will provide a complementary denitrification stage. The IoT architecture proposes temperature, pH, dissolved oxygen, electrical conductivity and turbidity sensing, ESP32 edge acquisition, MQTT transmission, Node-RED processing and InfluxDB/Grafana visualisation. Microbial community analysis will use 16S rRNA V4 amplicon sequencing with 515F/806R primers and DADA2/SILVA-based bioinformatics. Community validation will use predefined participation, training, usability, maintenance, adoption-readiness and continued-use indicators, subject to institutional ethical approval. A preliminary techno-economic framework will quantify capital cost, operating cost, maintenance, energy, water and production indicators. The contribution is therefore a testable integration framework linking OPT biomass valorisation, biofilm-mediated nitrogen management, digital monitoring, additive manufacturing and community technology transfer rather than a claim of completed performance.

Keywords: biochar; zero-water exchange aquaculture; IoT monitoring; 3D printing; microbial nitrification; community aquaculture

INTRODUCTION

Aquaculture is increasingly important for food production and livelihoods, but intensive and low-exchange production can create persistent water-quality management challenges, particularly the accumulation of

ammonia and nitrite and the generation of nutrient-rich effluent. Zero-Water Exchange Aquaculture Systems (ZWES) seek to reduce routine water replacement by strengthening internal biological nitrogen management. The research programme underpinning this paper proposes a system in which biological treatment, digital monitoring, modular fabrication and community application are developed as one connected pathway.

Recent aquaculture studies demonstrate the importance of attached-growth biological treatment. Wandana et al. (2024), for example, reported a biofloc–Down-flow Hanging Sponge (DHS) configuration for zero-water-exchange aquaculture and demonstrated strong nitrogen removal under the tested experimental conditions. Biochar has also received increasing attention as a water-treatment and microbial-support material. Wong et al. (2024) reviewed applications of charcoal, activated charcoal and biochar in aquaculture and highlighted both potential applications and the need for further mechanistic and long-term evaluation. Dorner and Behrens (2024) further demonstrated that biochar can support biofilm-associated nitrification in an activated-sludge context.

The present framework extends these strands by focusing on Oil Palm Trunk (OPT), a locally relevant biomass resource, and by treating biochar development as a material-to-microbiology problem rather than assuming that biochar from another feedstock will perform equivalently. The framework also connects the selected medium with an Up-flow Sludge Bed (USB) denitrification stage, an IoT monitoring architecture and 3D-printed structural and hydraulic components. Importantly, the biochar is not proposed to be 3D printed; additive manufacturing is reserved for the system hardware.

Because the source grant is a prospective 2026–2029 research programme, the appropriate contribution at this stage is a reproducible research framework. The manuscript therefore defines proposed production parameters, characterisation methods, microbial and sequencing procedures, IoT architecture, community validation metrics and techno-economic indicators. These are design specifications to be tested, not experimental findings.

Problem Statement, Research Gap and Novelty

Three linked research gaps motivate the framework. First, biochar performance is feedstock- and process-dependent; therefore, evidence from other lignocellulosic feedstocks cannot be directly transferred to OPT without characterisation and validation. Second, existing biochar-amended aquaculture studies commonly emphasise adsorption, water treatment or microbial responses, whereas the proposed work links material optimisation to a complete zero-water-exchange architecture containing nitrification, denitrification, sensing and modular fabrication. Third, technical feasibility does not by itself establish community applicability; the framework therefore includes structured user training, usability assessment, adoption-readiness indicators and a preliminary cost framework.

The novelty claim is intentionally narrower than claiming that biochar, IoT, 3D printing or zero-water-exchange aquaculture are individually new. The contribution proposed here is their integrated and testable configuration around OPT-derived biochar as a microbial support medium, with DHS as a biological benchmark, USB as a complementary nitrogen-removal stage, defined IoT data architecture, 3D-printed modular hardware and community validation. This goes beyond a general review such as Wong et al. (2024) by specifying a feedstock-specific development pathway, operational parameters and a validation protocol through which the proposed contribution can be empirically tested.

Objectives and Research Questions

The framework has three primary objectives:

1. To develop and optimise OPT-derived biochar as an alternative microbial support medium to conventional DHS for microbial colonisation and nitrification.
2. To integrate the optimised biochar medium with USB denitrification, IoT monitoring and modular 3D-printed structural and hydraulic components to form a ZWES prototype.

3. To establish a controlled and community-based validation framework covering water quality, microbial processes, aquaculture performance, digital reliability, usability, adoption readiness and preliminary techno-economic feasibility.

The corresponding research questions are:

4. Which OPT pyrolysis and activation conditions produce biochar characteristics suitable for microbial attachment and water treatment?
5. How does the nitrification performance of OPT-derived biochar compare with conventional DHS under controlled conditions?
6. Which microbial groups and surface-associated mechanisms are associated with ammonia oxidation and subsequent nitrite oxidation?
7. Can the integrated biochar–USB–IoT–3D-printed system maintain stable water-quality conditions under zero-water-exchange operation?
8. What community-level conditions, training requirements, operating burden and cost structure influence readiness for adoption?

LITERATURE REVIEW

Biochar in Aquaculture and Water Treatment

Biochar is a carbon-rich material produced by thermochemical conversion of biomass under oxygen-limited conditions. Its surface area, pore structure, mineral fraction, aromaticity and surface functional groups vary with feedstock and thermal processing. Wong et al. (2024) reviewed the use of char-based materials in aquaculture and identified applications involving water treatment, pollutant adsorption and system support, while also identifying the need for more mechanistic and long-term evidence. Consequently, the proposed framework does not assume that OPT biochar will behave like biochar derived from other materials.

Biochar as a Microbial Carrier

Biochar can function as a physical surface for microbial attachment and can modify local chemical conditions through adsorption, buffering and surface interactions. Dorner and Behrens (2024) reported enrichment of ammonia-oxidising bacteria on biochar surfaces and described biochar-associated pH microenvironments. A 2024 aquaculture study also reported associations between biochar addition and nitrifying microbial groups in intensive shrimp culture. These findings support investigation of biochar as a microbial carrier, but they do not establish the performance of OPT biochar in the proposed ZWES.

DHS as a Benchmark

DHS is an established attached-growth biological treatment configuration. Its use as the comparison benchmark is important because the research question is not whether biochar can support microbes in isolation, but whether a locally produced biochar medium can provide a technically credible alternative or complement to an established medium under comparable conditions.

D Printing and Digital Aquaculture

Additive manufacturing provides a route for customised hydraulic paths, media holders, sensor housings and modular structural components. Zhao et al. (2024) demonstrated a near-zero-discharge recirculating aquaculture system using a 3D-printed PLA honeycomb structure. The present framework differs by separating the biochar microbial medium from the printed hardware and by integrating IoT monitoring and community validation into the same development pathway.

Expected Mechanisms of Nitrification on Biochar Surfaces

The framework proposes that nitrification on OPT-derived biochar will involve interacting physical, chemical and biological mechanisms. First, the porous surface may increase the available area for microbial attachment and biofilm formation. Second, surface functional groups and mineral components may influence ammonia

adsorption, local pH and substrate availability. Third, mature biofilms can develop spatial microenvironments in which ammonia oxidation and nitrite oxidation occur sequentially. These mechanisms are hypotheses to be tested rather than conclusions of the present paper.

Ammonia oxidation may involve ammonia-oxidising bacteria (AOB), particularly genera such as Nitrosomonas and Nitrosospira, and ammonia-oxidising archaea (AOA), including Nitrosopumilus and Nitrososphaera. In aquaculture biofilters, Nitrosomonas and Nitrospira lineages have been reported among important nitrifying populations, while Nitrosopumilus-related AOA have also been detected. The relative contribution of these groups is expected to depend on oxygen, pH, ammonia concentration, salinity and biofilm microenvironment. Comammox Nitrospira may also contribute to complete ammonia oxidation in suitable systems. The proposed 16S rRNA analysis will therefore screen community composition, while targeted functional-gene assays may be added if sequencing indicates a need for direct assessment of nitrification potential.

Mechanistically, the working model is: ammonia adsorption and diffusion into the biofilm → ammonia oxidation by AOA/AOB → nitrite production → nitrite oxidation principally by Nitrospira/Nitrobacter lineages → nitrate accumulation → transfer to the USB denitrification stage. Biochar may affect this pathway by altering attachment area, local pH, mass transfer and substrate retention. Importantly, biochar can also inhibit nitrification under some environmental conditions; therefore, the framework includes dose and process optimisation rather than assuming a universally positive effect.

Design-Stage Preliminary Feasibility Assessment

No preliminary laboratory measurements of OPT-derived biochar were available in the attached grant material. Accordingly, this section does not present invented values. Instead, it records the feasibility evidence available from published studies and defines the measurements that will establish material feasibility before system integration.

Feasibility domain	Evidence/design basis	Measurement to be generated	Decision criterion
Feedstock	OPT is identified in the research programme as the target biomass resource.	Moisture, ash, volatile matter, fixed carbon and biochar yield.	Select reproducible feedstock preparation and pyrolysis condition.
Material structure	Biochar performance is known to depend on porosity and surface chemistry.	BET surface area, pore volume, SEM–EDS and FTIR.	Identify candidates with stable structure and suitable surface characteristics.
Water interaction	Biochar may adsorb ammonia and alter local chemical conditions.	pH, EC, water-extractable ions and batch NH_4^+ sorption.	Exclude candidates causing unacceptable pH or leaching.
Biofilm support	Published studies show biochar can support nitrifying biofilms.	Biomass attachment, biofilm imaging and nitrification rate.	Select media based on reproducible microbial colonisation and nitrogen transformation.
System feasibility	ZWES requires stable nitrogen management.	NH_4^+-N, NO_2^--N, NO_3^--N, pH and DO time series.	Advance only candidates that maintain stable water-quality conditions.
Community feasibility	Adoption depends on usability, training and cost.	Training completion, task success, maintenance time, usability and willingness to continue.	Define readiness before wider deployment.

RESEARCH METHODOLOGY

Overall Research Design

The study is designed as a sequential research and development programme: (1) OPT preparation; (2) controlled pyrolysis and candidate activation; (3) physicochemical characterisation; (4) microbial colonisation; (5) nitrification testing against DHS; (6) USB integration; (7) IoT and 3D-printed hardware integration; (8) controlled ZWES validation; (9) community pilot; and (10) techno-economic assessment. Each stage has a predefined decision gate so that system integration occurs only after the preceding component meets its technical criteria.

Proposed OPT Pyrolysis Parameters

The following are proposed operating specifications for the experimental matrix, not completed process results. OPT will be washed or mechanically cleaned as appropriate, dried to constant mass, reduced to a controlled particle size and placed in a laboratory-scale fixed-bed or batch pyrolysis reactor. Pyrolysis temperature will be evaluated at 400, 500 and 600 °C. Nitrogen will be used as the inert purge gas, with oxygen exclusion verified through reactor operating procedures. A proposed residence-time matrix is 1, 2 and 3 h at target temperature, with heating rate recorded and kept constant within the experimental block. Biochar yield will be calculated from dry feedstock mass.

Parameter	Proposed specification	Purpose
Temperature	400, 500 and 600 °C	Map the effect of carbonisation severity.
Atmosphere	Nitrogen purge / oxygen-limited reactor	Provide controlled pyrolysis conditions.
Residence time	1, 2 and 3 h at target temperature	Evaluate thermal severity and material stability.
Heating rate	Target 5–10 °C min^{-1}; final value recorded	Standardise thermal history.
Feedstock	Prepared OPT, dried to constant mass	Reduce moisture-related variability.
Particle size	Proposed 5–10 mm screening fraction	Improve heat-transfer consistency.
Yield	Dry biochar mass / dry OPT mass × 100	Quantify conversion efficiency.

Proposed Biochar Activation Protocols

Activation will be treated as a controlled comparison rather than assumed to improve performance. Three candidate routes will be screened: (A) unactivated pyrolysis biochar; (B) mild water washing followed by drying; and (C) thermal/steam activation where equipment permits. Chemical activation using strong acids or bases is not selected as the primary community-oriented route because residual chemicals and washing requirements would complicate field deployment. For each candidate, activation conditions, mass loss, pH and leachable ions will be recorded. Activation will only be retained if it improves the material criteria without creating unacceptable leaching or handling requirements.

Candidate	Proposed protocol	Purpose / decision
A: Raw biochar	Use directly after cooling, sieving and sterile/clean handling as appropriate.	Baseline material.

B: Water-washed biochar	Wash with deionised water until wash-water pH/EC stabilise; dry at ~105 °C.	Reduce soluble ash and initial leachates.
C: Steam/thermal activated biochar	Steam or inert-gas activation at approximately 700–800 °C for a defined activation time after pilot equipment verification.	Increase accessible porosity; retain only if benefit outweighs energy and yield penalty.

Biochar Characterisation

Candidate biochars will be characterised before biological testing. Proximate analysis will quantify moisture, volatile matter, ash and fixed carbon. pH and electrical conductivity will be measured in water extracts. BET analysis will quantify specific surface area and pore characteristics. SEM–EDS will assess morphology and elemental composition, while FTIR will identify major surface functional groups. Where resources permit, additional analyses may include CHNS/O elemental composition, X-ray diffraction, cation exchange capacity and total polycyclic aromatic hydrocarbons or other relevant contaminants. The purpose is to link processing conditions to microbial-support suitability and environmental safety.

Microbial Colonisation and Nitrification Testing

Biochar candidates and DHS controls will be placed in parallel biological test units under comparable hydraulic and water-quality conditions. After inoculation and acclimation, the systems will be monitored for ammonia, nitrite and nitrate transformation. Biofilm attachment will be assessed using biomass measurements and microscopy where appropriate. The primary decision variables will be ammonia oxidation rate, nitrite oxidation, nitrate formation, time to stable nitrification, biofilm retention and operational stability. The final statistical model will be selected after the experimental design and replication structure are confirmed.

S RRNA Sequencing and Bioinformatics

The proposed microbial-community workflow will target the V4 region of the prokaryotic 16S rRNA gene using the 515F/806R primer pair, which is widely used for bacterial and archaeal community profiling. The current Earth Microbiome protocol uses 515F/806R for the V4 region, and published workflows demonstrate paired-end Illumina sequencing with this primer set. The proposed sequencing platform is Illumina MiSeq with 2 × 250 bp paired-end reads, subject to final facility availability and library quality.

Proposed laboratory steps are: (1) collect biofilm and water samples using sterile procedures; (2) extract DNA using a validated microbial DNA extraction kit; (3) quantify and quality-check DNA; (4) PCR amplify V4 using 515F and 806R with indexed adapters; (5) include negative controls and, where feasible, a mock community; (6) purify and normalise amplicons; (7) sequence on Illumina MiSeq; and (8) process raw reads using QIIME 2 with DADA2 for denoising, paired-end merging and chimera removal. Taxonomy will be assigned using a current SILVA reference database. Alpha diversity, beta diversity and differential taxonomic patterns will be related to water-quality and nitrification variables. If direct functional inference is insufficient, targeted amoA qPCR for AOA/AOB and nxrA/nxrB assays for nitrite oxidation may be added as a complementary method.

Item	**Proposed specification**
Target	Prokaryotic 16S rRNA gene, V4 region
Primers	515F: GTGYCAGCMGCCGCGGTAA; 806R: GGACTACNVGGGTWTCTAAT
Platform	Illumina MiSeq, paired-end 2 × 250 bp (proposed)
Controls	Extraction blank, PCR negative control and optional mock community
Processing	QIIME 2; DADA2 for denoising/ASV generation
Taxonomy	SILVA reference database

Community metrics	Observed ASVs, Shannon diversity, Bray–Curtis/weighted UniFrac as appropriate
Functional follow-up	Optional amoA and nxr qPCR if justified by results

Exact Proposed IOT Sensor and Dashboard Architecture

The reviewer-requested IoT specification is addressed by defining a baseline hardware and software architecture. These are proposed engineering selections and may be changed after procurement and calibration testing; the paper does not claim that the hardware has already been deployed.

Variable	**Proposed sensor / measurement route**	**Acquisition and validation**
Temperature	DS18B20 digital waterproof temperature sensor	ESP32 digital input; compare periodically with calibrated reference thermometer.
pH	Atlas Scientific EZO-pH circuit with compatible industrial pH probe	UART/I²C interface; two- or three-point calibration as specified by probe manufacturer.
Dissolved oxygen	Atlas Scientific EZO-DO circuit with compatible DO probe	UART/I²C; calibration and periodic reference checks.
Electrical conductivity	Atlas Scientific EZO-EC circuit with compatible conductivity probe	UART/I²C; standard solution calibration.
Turbidity	DFRobot SEN0189 or equivalent optical turbidity sensor	Analog input; verify against prepared turbidity standards.
NH_4^+-N / NO_2^--N / NO_3^--N	Laboratory colorimetric/standard analytical methods during development; optional ISE probes after validation	Used as laboratory reference data for sensor calibration and model development.
Edge controller	ESP32	Local timestamping, sensor polling, buffering and Wi-Fi communication.
Transmission	MQTT over Wi-Fi; TLS authentication where supported	Publish/subscribe messaging to local or cloud broker.
Processing	Node-RED	Data validation, alarm rules, transformation and device-status monitoring.
Database	InfluxDB	Time-series storage.
Dashboard	Grafana	User-facing trend plots, alarm panels and system status.
Alerts	Node-RED rule engine via email/SMS/selected messaging gateway	Threshold-based notification; thresholds defined after fish and system requirements are established.

The dashboard will present current values, historical trends, sensor status, data completeness, threshold alarms and maintenance reminders. A local data buffer will be used so short network interruptions do not automatically create data loss. The proposed architecture is deliberately modular so that sensor models can be substituted after calibration without changing the higher-level data structure.

D-printed ZWES Integration

3D printing will be used for modular structural and hydraulic components such as media holders, sensor mounts, flow distributors, pipe interfaces and selected reactor housings where material compatibility is confirmed. PLA or another validated polymer will be considered according to mechanical strength, water exposure, temperature and food-contact requirements. The biochar will remain a separate microbial medium. Each printed component will be documented by material, infill, layer height, print time, mass and fabrication cost so that manufacturability can be incorporated into the techno-economic assessment.

INTEGRATED PROCESS FLOW

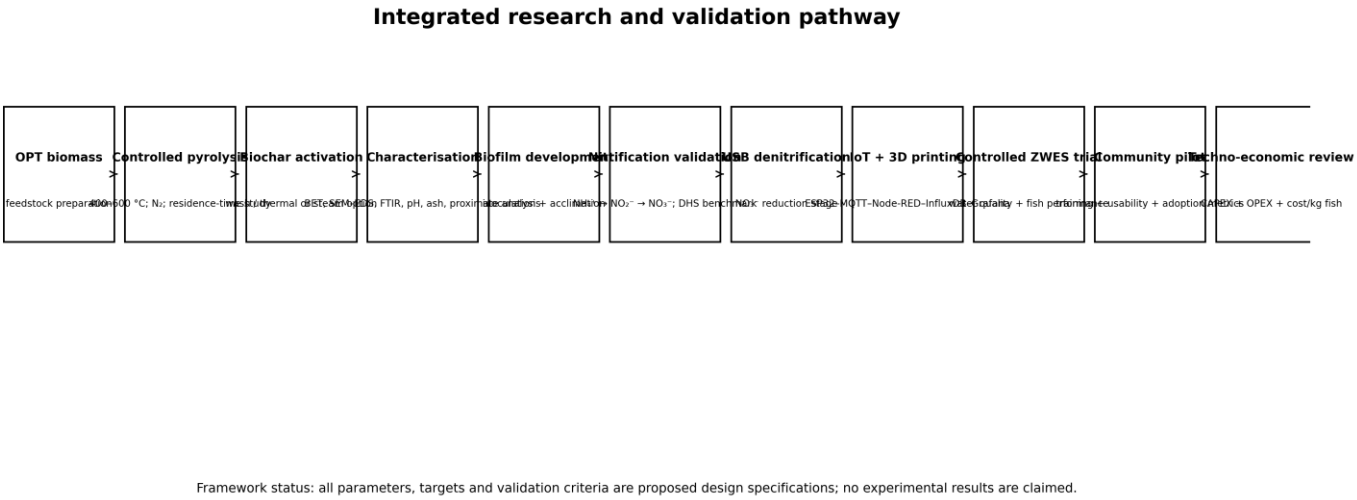


Figure 1. Proposed integrated research and validation process from OPT feedstock to community application.

The process flow is intentionally staged. Material candidates are not advanced to the integrated aquaculture system solely because they have favourable physicochemical properties; they must first demonstrate acceptable microbial colonisation and nitrogen-transformation behaviour. Likewise, a technically functioning prototype is not considered community-ready until training, usability, maintenance and economic indicators have been assessed.

Controlled System Validation Framework

Validation dimension	Primary indicators	Proposed measurement frequency / method	Framework decision
Water quality	NH_4^+-N, NO_2^--N, NO_3^--N, pH, DO, temperature, EC	Continuous for sensor variables; laboratory nitrogen analysis at defined sampling intervals.	Assess stability and nitrogen transformation.
Biofilm	Attached biomass, microscopy, microbial composition	Scheduled sampling during acclimation and steady-state periods.	Select media supporting stable biofilm.
Aquaculture	Fish growth, specific growth rate, survival, feed conversion, biomass gain	Routine weighing and production records at predefined intervals.	Assess production compatibility.
Hydraulics	Flow rate, pressure/head	Routine operational	Assess maintainability.

	loss, clogging	checks and logged pump performance.	
IoT	Data completeness, sensor drift, transmission uptime, alarm response	Automated logging plus scheduled calibration.	Assess digital reliability.
Energy/resource use	Electricity, make-up water, maintenance materials	Metered or recorded throughout trials.	Support cost and sustainability assessment.
Safety	Biochar leachates, abnormal pH/DO, equipment faults	Predefined risk checks.	Stop or modify unsafe conditions.

Community Validation, Training and Ethics

The community component will be implemented only after technical validation and the required institutional approvals. Because the attached grant does not specify a final number of participating households or farms, the following are proposed planning targets rather than fixed study results. A pilot involving approximately 10–15 participating households or smallholder/community fish-farming units may be used for the initial field phase, subject to site suitability, recruitment and ethics approval.

Community metric	**Proposed target/indicator**	**Data collection**
Pilot scale	Approximately 10–15 households/farm units, subject to approval and recruitment	Participant/site register.
Training duration	Two days (approximately 8–12 contact hours) plus supervised start-up support	Attendance, task checklist and competency assessment.
Training content	System operation, water-quality interpretation, IoT dashboard use, routine maintenance, troubleshooting and safety	Pre/post knowledge checklist and practical task observation.
Usability	Task-completion rate, time required for routine tasks, perceived ease of use	Structured questionnaire + observation.
Maintenance burden	Minutes per routine maintenance task; frequency of sensor cleaning/calibration; downtime	Maintenance log.
Adoption readiness	Proportion expressing intention to continue, perceived usefulness, affordability and confidence	Post-pilot survey/interview.
Continued-use indicator	Proportion continuing operation at 3 months after supervised handover, where feasible	Follow-up visit/log review.
Technology acceptance	Perceived usefulness, ease of use, trust in monitoring and willingness to recommend/continue	Likert-scale instrument plus qualitative comments.
Economic acceptance	Acceptable initial cost, recurring cost and perceived benefit	Cost questionnaire/interview.

Ethical approval will be obtained before any community recruitment or participant data collection. The final protocol will be submitted to the relevant institutional ethics committee at UTeM and, for animal experimentation, to the institutional animal-care/ethics authority required by UTeM and applicable Malaysian requirements. Community participants will receive an information sheet and provide informed consent. Participation will be voluntary, withdrawal will be permitted without penalty, and personal identifiers will be separated from analytical datasets. No claim of ethical approval is made in this framework before the formal review and approval process has occurred.

PRELIMINARY TECHNO-ECONOMIC AND COST-BENEFIT FRAMEWORK

At the framework stage, a full cost-benefit result cannot be calculated because procurement prices, measured energy demand, biochar yield, system lifetime and production performance are not yet available. The study will therefore use a preliminary techno-economic assessment (TEA) structure that can be populated during prototype development and pilot operation.

Cost/benefit category	Variables to record	Proposed metric
Biochar production CAPEX	Reactor, gas system, dryer, grinder/sieve and safety equipment	RM per kg usable biochar; equipment depreciation.
Biochar OPEX	OPT preparation, electricity/fuel, N_2, water, labour and activation	RM per kg usable biochar.
3D printing CAPEX/OPEX	Printer, polymer, electricity, labour and component replacement	RM per component and RM per system.
IoT CAPEX/OPEX	Sensors, ESP32, gateways, networking, server/cloud and replacement probes	RM per monitored system per year.
Aquaculture OPEX	Feed, electricity, pumping, water make-up, maintenance and labour	RM per kg fish produced.
Water benefit	Water exchanged/made up compared with baseline	L water per kg fish and estimated water cost avoided.
Production benefit	Biomass gain, survival and feed conversion	kg fish per cycle; RM gross margin.
Maintenance	Sensor cleaning/calibration, media replacement and repair	RM per month and hours per month.
Environmental/circular benefit	OPT diverted from low-value disposal/use; reduced effluent	kg OPT valorised; water/effluent reduction.
Overall feasibility	CAPEX, annual OPEX, revenue/benefit and replacement cost	Simple payback period and sensitivity analysis, when data are available.

The TEA will compare at least three scenarios: baseline community aquaculture with conventional water exchange, the proposed ZWES with biochar media, and the proposed ZWES with the DHS benchmark. Sensitivity analysis will vary biochar yield, electricity price, sensor replacement interval, system lifetime, fish price and production performance. This structure prevents a favourable economic conclusion from being inferred solely from technical novelty.

Community and Social Innovation Dimension

Positioning the paper within IJRISS requires the engineering intervention to be connected explicitly to community implementation. The framework treats adoption as a socio-technical outcome: users must be able to operate the system, interpret monitoring information, perform routine maintenance and perceive sufficient benefit relative to cost and effort. The community pilot therefore does not merely demonstrate the machine; it generates evidence about the conditions under which the technology can become a usable community practice.

The proposed evaluation combines quantitative indicators with structured user feedback. Quantitative measures include training completion, task success, maintenance time, data-dashboard use, downtime, intention to continue and continued use after handover. Qualitative feedback will be used to identify barriers

involving skills, trust, affordability, connectivity, maintenance and perceived usefulness. This approach connects technological performance with human capability and local implementation requirements.

Expected Outcomes and Contribution

Because this is a framework paper, the following are expected outputs and validation outcomes, not completed findings:

- An experimentally characterised OPT-derived biochar formulation or formulation range suitable for further microbial-media testing.
- A reproducible pyrolysis and activation protocol with documented yield, physicochemical properties and safety-related checks.
- Comparative evidence on microbial colonisation and nitrification relative to DHS, including microbial-community information.
- An integrated ZWES prototype combining biochar microbial media, USB denitrification, IoT monitoring and modular 3D-printed hardware.
- A validated data architecture linking sensor observations with laboratory water-quality measurements.
- A community validation dataset covering training, usability, maintenance, adoption readiness and continued use.
- A preliminary techno-economic model capable of supporting future commercialisation and scale-up decisions.

Contribution beyond Prior Reviews

The framework contributes beyond prior reviews in four specific ways. First, it makes OPT feedstock the explicit material-development object rather than treating biochar as a generic category. Second, it connects pyrolysis/activation conditions to physicochemical characterisation, biofilm formation and nitrogen transformation in a staged decision pathway. Third, it integrates the selected microbial medium with a specified IoT and modular 3D-printing architecture rather than discussing these technologies separately. Fourth, it defines community and economic validation metrics so that technical feasibility can eventually be assessed alongside practical adoption. The paper therefore proposes a testable socio-technical framework rather than claiming that the integrated system has already been validated.

DISCUSSION

The principal methodological implication of the framework is that biochar should not be evaluated only as an adsorbent. For ZWES application, the desired function is sustained microbial support under continuous water treatment. A candidate that has high surface area but releases excessive soluble material, destabilises pH, clogs hydraulically or performs poorly under biofilm conditions would not be considered suitable simply because of its material properties. The staged decision gates therefore link material science to biological and system-level performance.

The microbial mechanism section also prevents an overly simplified interpretation of nitrification. Ammonia oxidation can involve AOB and AOA, while nitrite oxidation and, potentially, complete ammonia oxidation involve other nitrifying groups. Biochar may influence these communities through attachment area, local pH, adsorption and mass transfer, but the direction and magnitude of the effect are context dependent. Published evidence includes both enhancement and inhibition of nitrification following biochar addition in different systems. The proposed experiments are therefore designed to measure rather than presume the direction of the effect.

The IoT layer is similarly treated as an operational tool rather than an end in itself. Sensor calibration, drift, missing data and network interruptions can undermine a digital monitoring system even when the biological process is sound. The proposed architecture includes local buffering, laboratory reference measurements and maintenance indicators to distinguish biological changes from sensor artefacts.

Finally, the community component is necessary because a technically validated system may still fail to achieve practical adoption if its capital cost, maintenance burden, connectivity requirements or user interface are inappropriate. The framework consequently evaluates training, usability, maintenance and continued-use indicators together with engineering performance.

LIMITATIONS AND FUTURE RESEARCH

The main limitation is the absence of completed experimental data. The proposed pyrolysis temperatures, residence times, activation conditions, sensor models, sequencing workflow and community targets are framework specifications and must be validated experimentally. They should not be interpreted as established optimal values. The final experimental design may modify these specifications after pilot tests, equipment verification, ethics review and resource assessment.

Future work will generate the missing empirical evidence, including OPT biochar yield and characterisation, microbial colonisation, nitrification and denitrification performance, fish-production outcomes, IoT reliability, community acceptance and cost data. Long-term media durability, regeneration/replacement, contaminant safety, life-cycle impacts and scale-up should be assessed before commercial or large-scale community deployment.

CONCLUSION

This manuscript presents a revised research framework for developing OPT-derived biochar-based microbial media within an IoT-enabled, 3D-printed Zero-Water Exchange Aquaculture System for community application. The framework directly addresses the methodological gaps identified during review by defining proposed pyrolysis and activation conditions, physicochemical characterisation, a specified IoT architecture, a detailed 16S rRNA sequencing workflow, nitrification mechanisms, community validation indicators, ethical requirements and a preliminary techno-economic structure.

No experimental results are reported because the underlying programme has not yet generated the required datasets. This is a deliberate feature of the manuscript: all numerical targets and operating parameters are presented as proposed specifications or validation criteria, not as findings. The expected contribution is a reproducible pathway through which OPT biomass valorisation, microbial nitrogen management, digital monitoring, additive manufacturing and community adoption can be evaluated within one integrated research design.

Ethical Considerations

No human-participant or animal-experiment result is reported in this framework paper. Before implementation of community participation or animal trials, the research team will obtain the relevant institutional approvals. Human participation will require informed consent and confidential handling of personal information. Fish experimentation will follow the applicable institutional animal-care and welfare requirements. The manuscript does not claim that such approval has already been granted.

Data Availability

No experimental dataset is available from this framework paper. Data generated during subsequent implementation will be quality-checked and stored in the project database. Non-confidential datasets may be shared through a repository or publication after consideration of intellectual-property, confidentiality and collaborator requirements.

Conflict of Interest

The authors declare that there is no known conflict of interest associated with this research framework.

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