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Aquaponic System Dynamics: Nutrient Cycling, Nutrient Deficiencies and Integrated Health Management - A Critical Review

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Abstract

Aquaponics integrates aquatic animal production with soilless cultivation through the recovery of nutrients from aquaculture effluent. Its performance depends on interactions among fish nutrition, microbial transformations, plant demand and hydraulic design. This narrative review examines these interactions, with particular attention to nutrient deficiencies, water-quality management and the constraints on disease control in shared-water systems. Literature available on or before March 2025 is considered, including recent studies of complete ammonia oxidation and vermicompost-derived supplements. Hydroponic growing methods must be distinguished from coupled and decoupled system configurations because these classifications describe different aspects of production. Nutrient recycling does not ensure nutritional completeness: feed composition, solids removal, mineralization, pH and crop requirements jointly determine plant nutrient availability. Evidence from aquaponic and hydroponic experiments suggests that liquid vermicompost, vermitea and vermiwash may provide supplementary nutrients or biostimulant effects, but their preparation and composition vary and hydroponic responses cannot establish compatibility with fish or biofilters. Effective health management therefore requires diagnosis, prevention and attention to the consequences of interventions across compartments. Future research should combine nutrient mass balances, microbial functional measurements and replicated production trials to identify supplementation strategies that improve crop performance without compromising aquatic animal welfare or water quality.

Keywords: Aquaponics, Biosecurity, Nitrification, Nutrient availability, Vermicompost, Vermiwash

Introduction

Aquaculture development must reconcile demand for nutritious food with constraints on water, land, energy and waste management. These concerns underpin the blue transformation agenda described by FAO (2022). Recirculating aquaculture, biofloc and aquaponics offer different approaches to resource recovery. Biofloc research demonstrates opportunities to recover microbial biomass as fish nutrition, but its operating principles and stocking responses should not be transferred directly to aquaponics (Debbarma *et al*., 2022; Majhi *et al*., 2023). In aquaponics, the defining opportunity is to link aquatic animal production with plant cultivation through nutrient-bearing water.

Fish feed introduces nutrients into the system. Fish retain part of this input, while dissolved excretion and particulate wastes become potential resources for plants after appropriate biological and physical processing. Plant uptake removes selected nutrients, but it does not replace solids separation, biofiltration or oxygen supply. Aquaponics is consequently a managed production ecosystem rather than a self-balancing arrangement of fish and vegetables (Rakocy, 2012; Yep and Zheng, 2019). Its environmental and economic advantages depend on how effectively these components are matched.

Existing reviews describe aquaponic designs, adoption barriers and sustainability opportunities (Palm *et al*., 2018;

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Okomoda *et al*., 2023; Nair *et al*., 2025). Their breadth establishes the importance of integration, but operational decisions still require a clearer explanation of how nutrient availability, microbial function and health management constrain one another. This review addresses that decision problem through three questions: how does configuration alter the fate and availability of feed-derived nutrients; when does supplementation improve production without impairing biological treatment; and how can health interventions be selected without transferring risk between fish, plants and microorganisms? The review integrates these relationships and uses vermicompost-derived inputs to illustrate the distinction between nutrient supply, biostimulation and compatibility across the entire production system.

Scope and Historical Development

This critical narrative review considers publications available on or before March 2025. Sources were examined for relevance to hydraulic configuration, nutrient transformations, deficiency management, vermicompost-derived inputs and integrated health. Primary experiments were used to support treatment-specific statements, while reviews and book chapters supplied conceptual context. Evidence was compared according to production environment, intervention, comparator, measured outcome and transferability. No exhaustive database search, preregistered protocol or formal risk-of-bias instrument was applied. The resulting synthesis therefore identifies mechanistic relationships and evidence gaps rather than estimating pooled treatment effects or claiming comprehensive retrieval of all available studies.

Historical accounts frequently associate aquaponics with chinampas and other traditional combinations of aquatic resources and crop production. Such systems provide historical context for integrated farming but should not be equated with modern recirculating aquaponics. Contemporary development rests on engineered water circulation, biological filtration and controlled soilless cultivation (Rakocy, 2012; Okomoda *et al*., 2023). Research on integrated fish and plant production helped establish practical approaches to nutrient reuse under controlled conditions (Savidov *et al*., 2007).

In India, aquaponics is relevant to urban cultivation, protected horticulture and locations with restricted land or water availability. Adoption nevertheless requires reliable electricity, technical skills, appropriate species combinations and markets for both outputs. Bhanja *et al*. (2024) discussed these opportunities in the Indian context. Local demonstrations are valuable, but claims concerning commercial profitability or national adoption should be based on documented production and cost records rather than the existence of demonstration facilities alone.

Biological Components and Nutrient Transformations

1. Species Selection

The principal biological components are aquatic animals, crops and microorganisms. Commonly investigated fish include tilapia, carp and catfish, while lettuce, basil, mint and other leafy crops are frequently selected because of their relatively short production cycles. Fruiting crops can also be cultivated, although their nutrient demand and support requirements differ. Fish and plants should be selected jointly according to temperature, market value, crop duration and available treatment capacity (Palm *et al*., 2018; Nair *et al*., 2025).

2. Nitrification and Microbial Function

Nitrification protects fish from accumulation of reduced nitrogen and generates nitrate that can support plant growth. The conventional representation of ammonia oxidation by *Nitrosomonas* followed by nitrite oxidation by Nitrobacter is incomplete. Daims *et al*. (2015) demonstrated complete nitrification by Nitrospira, establishing that both oxidation steps can occur within a single organism. This discovery does not imply that all Nitrospira are complete ammonia oxidizers; their functional identity must be established rather than inferred solely from genus-level detection.

Direct aquaponic evidence further shows that microbial communities respond to operating conditions. Derikvand *et al*. (2024) found that inoculum and pH influenced ammonium removal and community development. Ammonia-oxidizing bacteria were prominent in systems operated at pH 7.6-7.8; whereas comammox *Nitrospira* were favored at pH 5.8-6.0. These results challenge the assumption that a single microbial pathway or pH prescription describes every aquaponic biofilter. They do not establish that low pH is appropriate for every fish species, inoculum or loading regime.

In the laboratory systems examined by Derikvand *et al*. (2024), initial ammonium accumulation with comammox-enriched inocula was reported as 47% and 69% of that in the respective ammonia-oxidizing-bacteria-enriched comparisons. These are relative accumulation values, not percentage removal efficiencies or evidence of equivalent increases in commercial yield. Inoculum effects were examined alongside pH and community composition changed during system establishment. Consequently, start-up performance, mature conversion capacity and crop response should be treated as separate endpoints. A low initial ammonium peak can be valuable for fish protection without proving greater long-term nutrient recovery.

The microbial contribution extends beyond nitrification. Heterotrophic organisms decompose organic material and release nutrients, while denitrification can remove nitrogen from the production system. High organic loading may increase oxygen demand and alter competition between microbial groups. Consequently, efficient nitrogen conversion and efficient nitrogen recovery are related but distinct objectives (Wongkiew *et al*., 2017; Kasozi *et al*., 2021). A system can maintain low ammonia while still losing a substantial fraction of feed-derived nitrogen through pathways other than crop uptake.

3. Biofilter Establishment

Mineralization and nitrification may compete indirectly for oxygen and suitable microbial attachment surfaces. Organic

carbon can support rapid heterotrophic growth, while ammonia oxidizers require appropriate oxygen and inorganic carbon supply. A supplement that raises soluble nutrient concentrations may therefore increase treatment demand at the same time. Conversely, aggressive removal of solids can improve hydraulic and oxygen conditions while exporting phosphorus and other potentially recoverable nutrients. These competing outcomes explain why evidence for nutrient enrichment cannot be interpreted independently of solids retention and aeration (Wongkiew *et al*., 2017; Eck *et al*., 2019; Kasozi *et al*., 2021).

Start-up should therefore be evaluated through measured ammonia and nitrite conversion rather than a fixed waiting period. Feeding and stocking must remain compatible with established treatment capacity. Stable aeration, suitable alkalinity and uninterrupted circulation support biofilter development. Sudden changes in feed loading, cleaning intensity or chemical exposure can disrupt a previously functional system (Kasozi *et al*., 2021).

Growing Methods and Hydraulic Configurations

Media beds, nutrient film technique and deep-water culture describe the plant-growing subsystem. Coupled and decoupled describe hydraulic relationships among production units. Vertical arrangements describe spatial organization, while hybrid designs combine growing methods. These categories should not be presented as mutually exclusive alternatives (Palm *et al*., 2018; Baganz *et al*., 2022).

1. Plant Growing Methods

Media beds support roots and provide colonization surfaces for microorganisms. Depending on loading and design, they may also retain solids, but their presence does not guarantee sufficient filtration. Accumulated organic matter can obstruct flow and create oxygen-poor zones. Flood-and-drain operation is one possible management strategy rather than a requirement for every media bed. In nutrient film technique, a shallow flowing nutrient solution supplies roots in channels; solids interception and reliable flow are particularly important. Deep-water culture suspends roots in an aerated water volume and requires adequate oxygen delivery to the root zone. Root size, crop duration and harvest practices should guide selection (Rakocy, 2012; Palm *et al*., 2018).

Table 1 separates plant-growing methods from spatial and combined arrangements; crop examples are conditional rather than exclusive.

2. Coupled and Independently Managed Loops

In coupled systems, water returns from the plant subsystem to the fish unit. This permits repeated reuse but makes supplementation and treatment decisions consequential for fish, crops and microorganisms simultaneously. Decoupled systems allow the fish and plant loops to operate with greater independence while retaining nutrient transfer from aquaculture to horticulture. They should not be described as entirely unrelated units: nutrient-bearing transfer remains the basis of integration (Kloas *et al*., 2015). Baganz *et al*. (2022) proposed the term on-demand coupled for this arrangement. Here, decoupled is retained for continuity with established usage, with the actual water connection specified.

Table 1: Plant growing methods and practical constraints

Method	Suitable crop examples	Main utility and limitation
Media bed growing method	Tomato, basil, leafy vegetables	Root support and microbial surfaces; retained solids can clog pores and deplete oxygen.
Nutrient film technique growing method	Lettuce, basil, small herbs	Efficient root access to flowing solution; vulnerable to interrupted flow and root obstruction.
Deep water culture or raft growing method	Lettuce, mint, leafy greens	Convenient harvesting and substantial water volume; root-zone aeration and solids control are necessary.
Vertical arrangement spatial organization	Small herbs and leafy crops	Uses vertical space; lighting uniformity, access and pumping head require assessment.
Hybrid arrangement combination of growing methods	Mixed crops matched to each unit	Combines growing methods; increases hydraulic and management complexity.

Sources: Rakocy (2012), Palm *et al*. (2018) and Nair *et al*. (2025)

Figure 1 distinguishes the hydraulic configurations and their shared dependence on nutrient transformations. Coupled operation exposes fish to the consequences of returning plant water; directed transfer into a separate plant loop

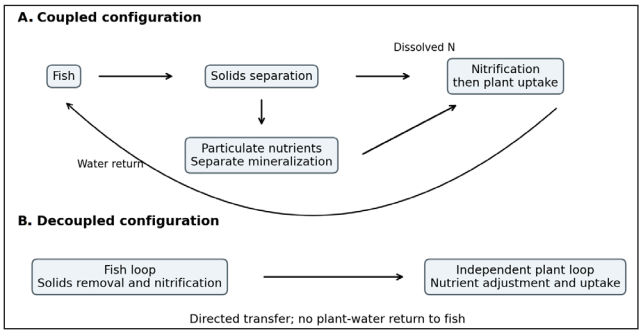


Figure 1: Conceptual water and nutrient pathways in coupled and decoupled aquaponics. Arrows indicate principal transfers; each production loop requires its own circulation and management. Mineralization output is a potential recovered nutrient input, not an automatic return stream. Original synthesis based on Kloas *et al*. (2015), Eck *et al*. (2019) and Baganz *et al*. (2022).

allows different operating conditions. Solids processing is shown separately because particulate nutrients do not become immediately available merely by entering a grow bed (Kloas *et al*., 2015; Eck *et al*., 2019; Baganz *et al*., 2022).

Independent control allows more crop-specific adjustment of nutrient concentrations and pH, while reducing the likelihood that plant treatments will be returned to the fish unit. However, these advantages introduce requirements for transfer control, additional infrastructure and management. Hydraulic separation alone neither guarantees pathogen exclusion nor demonstrates economic superiority. Comparisons should account for pumping, water replacement, heating, supplementation and labor, as well as harvestable output (Forchino *et al*., 2017; Yep and Zheng, 2019). Table 2 summarizes the management consequences of the main configurations.

Table 2: Hydraulic configurations and their management implications

Aspect	Coupled operation	Decoupled operation
pH and nutrient adjustment	Shared water constrains changes by fish and microbial tolerance.	Separate plant-loop control is a design capability; its yield benefit remains conditional.
Nutrient recovery	Repeated circulation permits reuse; solids still require capture or treatment.	Directed transfer can deliver treated effluent or mineralized nutrients; recovery must be measured.
Treatment flexibility	Returning water can expose all compartments.	Isolation can reduce return exposure; pathogens may still enter through transferred water or material.
Infrastructure	Shared circulation; treatment capacity must match combined loading.	Additional controls, transfer equipment and potentially separate aeration and dosing.
Evidence interpretation	Performance depends on species, loading and management.	Greater control does not establish universal superiority in yield, cost or environmental burden.

Sources: Kloas *et al*. (2015), Palm *et al*. (2018) and Baganz *et al*. (2022)

Water Quality and Operational Stability

1. Monitoring and Interpretation

Water-quality management links production with health. Monitoring should include temperature, dissolved oxygen, pH, alkalinity, total ammonia nitrogen, nitrite and nitrate. Electrical conductivity provides a useful indicator of dissolved ionic content but does not reveal which nutrients are deficient or excessive. Sampling frequency should increase during start-up, stocking changes, treatment events or unexplained reductions in feeding and growth (Wongkiew *et al*., 2017; Kasozi *et al*., 2021).

Total ammonia nitrogen comprises ammonium and un-ionized ammonia. Their relative proportions depend on pH and temperature, so a total concentration cannot be interpreted independently of these conditions. Nitrite accumulation can indicate an imbalance between ammonia and nitrite oxidation or a loss of treatment capacity. Nitrate is generally less acutely toxic but should not be regarded as harmless at every concentration or as evidence that all plant requirements are satisfied. Analytical reporting should specify whether concentrations are expressed as nitrogen or as the complete ion.

2. Oxygen, Temperature and pH

Dissolved oxygen supports fish respiration, root activity and aerobic nutrient transformations. Oxygen measured in a well-aerated fish tank may not represent conditions within a clogged bed or densely rooted channel. Water circulation and solids management should therefore be assessed alongside aeration. Temperature influences animal metabolism, plant growth, oxygen availability and microbial activity; suitable operating conditions are species- and system-dependent. Universal target values can obscure these interactions (Yildiz *et al*., 2019; Nair *et al*., 2025).

Nitrification consumes alkalinity and can progressively lower pH. Buffering must be selected with attention to the ions introduced, because repeated correction also changes nutrient composition. The effects of pH on nitrogen transformations have been demonstrated experimentally in media-based aquaponics (Zou *et al*., 2016). Adjustment should be gradual and informed by alkalinity and nutrient measurements, rather than used as an isolated response to a single abnormal reading.

The interactions among pH, oxygen availability and nitrogen transformations illustrate the limitations of correcting water quality on the basis of a single variable. Raising pH may improve some microbial operating conditions yet increase the fraction of un-ionized ammonia at a given total ammonia concentration; lowering pH can improve availability of some plant nutrients while changing nitrifier selection and consuming buffering capacity. Temperature modifies both metabolic oxygen demand and oxygen solubility. Thus, corrective action should be based on concurrent measurements and recent loading history. A stable pH with declining alkalinity may indicate reduced buffering reserve, whereas a satisfactory bulk oxygen measurement can coexist with oxygen limitation in organic deposits (Zou *et al*., 2016; Wongkiew *et al*., 2017; Derikvand *et al*., 2024).

3. Monitoring Technology

Sensors can identify trends and equipment failures,

but calibration and manual checks remain necessary. Chandramenon *et al*. (2024) combined sensing with experiments involving earthworms and freshwater replenishment. Their results illustrate that replenishment and biological additions must be evaluated together; monitoring technology improves observation but does not by itself establish the cause of a production response.

Nutrient Deficiencies and Targeted Supplementation

1. Nutrient Inputs and Recovery

Fish feed is formulated principally to meet fish requirements, which differ from crop requirements. A nutritionally adequate fish diet may therefore generate an effluent deficient in selected plant nutrients. Nutrient partitioning among fish biomass, dissolved water, retained solids and losses determines what reaches the roots. Phosphorus dynamics and nitrogen budgets illustrate the need to evaluate mass balance rather than assume that feed nutrients become quantitatively available to plants (Cerozi and Fitzsimmons, 2017; Maucieri *et al*., 2020).

Eck *et al*. (2019) distinguished the readily dissolved nutrient fraction from particulate nutrients that require microbial mineralization. Mechanical removal protects water quality but exports nutrients unless the captured solids are treated separately. A mineralization unit therefore creates a potential recovery pathway, although its output must be assessed for nutrient concentration, residual organic load and suitability for return to the production loop. Nutrient recovery should be quantified as a fraction of inputs rather than inferred from elevated concentrations alone; a high concentration can also reflect restricted uptake or low water replacement.

Nutrient management must also account for crop identity and harvest stage. In a comparison involving lettuce, mint and mushroom herb, Nozzi *et al*. (2018) found different responses to supplementation. Lettuce achieved its highest yield with additional micronutrients, iron, phosphorus and potassium, whereas the other crops required less supplementation. Yield and nutritional quality did not necessarily change in parallel. Earlier comparisons of lettuce under aquaponic and hydroponic production similarly provide a basis for evaluating both output and quality (Pantanella *et al*., 2012).

2. Deficiency Diagnosis

Visible symptoms provide a starting point for diagnosis, but chlorosis, necrosis and stunting can also result from root damage, unfavorable pH, low oxygen or disease. Tissue analysis and water chemistry should be used where feasible to distinguish inadequate supply from impaired uptake. Essential macronutrients include nitrogen, phosphorus, potassium, calcium, magnesium and sulfur; micronutrients include iron, manganese, zinc, copper, boron, molybdenum, chlorine and nickel. Carbon, hydrogen and oxygen are acquired principally through carbon dioxide and water rather than conventional mineral fertilization (Sonneveld and Voogt, 2009).

3. Supplement Selection

Iron illustrates the distinction between total concentration and availability. Chelate stability and solution pH influence its usefulness to plants. Kasozi *et al*. (2019) reviewed supplementation strategies and the differing suitability of iron sources. A fixed concentration without specification of source, crop and operating conditions is therefore an incomplete recommendation. Calcium and potassium additions used for buffering should likewise be included in nutrient accounting. Calcium-based lime is not automatically an appropriate treatment for magnesium deficiency and slowly soluble materials cannot be assumed to correct an acute deficiency at the required rate.

Table 3 summarizes differential diagnosis of common nutrient deficiencies. Symptoms are indicative rather than conclusive; corrective doses should be determined from the confirmed deficiency, crop requirements and system configuration.

Table 3: Common plant nutrient deficiencies and diagnostic priorities

Nutrient and mobility	Indicative symptoms and likely causes	Diagnostic measurements and response
N, relatively mobile	Older-leaf chlorosis; low available N or excessive crop demand.	Measure dissolved N, feeding and biomass; inspect roots before increasing inputs.
P, relatively mobile	Restricted growth or purpling; low release from solids or precipitation.	Measure soluble P and pH; examine solids exports and mineralization.
K, mobile	Older-leaf marginal damage; inadequate feed-derived K or ionic imbalance.	Measure K alongside Ca and Mg; use a compatible supplement if deficient.
Ca, poorly remobilized	Young-tissue deformation or tipburn; inadequate supply or transport.	Evaluate water Ca, roots and transpiration conditions; avoid concentration-only diagnosis.
Mg, mobile	Older-leaf interveinal chlorosis; low Mg or cation imbalance.	Measure Mg, K and Ca; calcium-only lime cannot supply Mg.
Fe, poorly remobilized	Young-leaf interveinal chlorosis; poor availability at unsuitable pH.	Assess pH, iron source and tissue status; select an appropriate stable chelate.

Sources: Sonneveld and Voogt (2009), Eck *et al*. (2019), Nozzi *et al*. (2018) and Kasozi *et al*. (2019)

For an individual element, the relevant accounting boundary is input in feed, replacement water and supplements minus removal in harvested fish, harvested plants, discharged water and exported solids, with the remainder representing accumulation or unmeasured pathways. This balance should be calculated from nutrient masses over a defined period rather than from water concentrations alone. For nitrogen, gaseous pathways may contribute; for phosphorus, precipitation, sorption and solids export are especially relevant. Increasing crop uptake efficiency therefore requires information on both nutrient recovery and losses (Cerozi and Fitzsimmons, 2017; Maucieri *et al*., 2020; Eck *et al*., 2019).

Cation interactions further complicate diagnosis. Potassium, calcium and magnesium should be interpreted together because changing one input can alter the balance available to roots. Calcium-associated tipburn can reflect transport limitations even where water calcium is measurable; whereas iron chlorosis can persist when total iron is present but poorly available. Electrical conductivity cannot distinguish these mechanisms. A useful diagnostic sequence combines symptom location and tissue age with root inspection, pH, nutrient-specific analysis and, where possible, tissue composition. Repeated supplementation based solely on visual symptoms may increase salinity without correcting the underlying nutrient limitation (Sonneveld and Voogt, 2009; Kasozi *et al*., 2019).

Supplementation should follow a sequence of diagnosis, source selection, controlled addition and reassessment. Solids mineralization may recover useful nutrients, but excessive organic loading can impair oxygen conditions. Decoupled operation provides greater freedom to formulate plant solutions, whereas coupled operation requires explicit evaluation of fish and biofilter tolerance (Kloas *et al*., 2015; Nozzi *et al*., 2018).

Vermitea, Vermiwash and Earthworm Integration

1. Product Identity and Composition

Vermicompost-derived inputs offer a possible route to recover nutrients from organic residues, but product names do not identify a uniform composition. Vermicompost tea generally refers to an aqueous extract of processed material, while vermiwash often denotes liquid obtained by passing water through an active earthworm bed. Terminology varies between studies. Zarei *et al*. (2018) showed that both source material and extraction approach affected product characteristics, with teas generally richer in nutrients than corresponding vermiwashes under their conditions. Preparation, dilution, aeration, storage and nutrient composition should therefore accompany any description of use.

2. Evidence from Aquaponics

The strongest distinction is between efficacy and compatibility. A crop response establishes efficacy only for the measured plant outcome; maintenance of selected water-quality variables establishes compatibility only within the tested exposure and monitoring period. Neither alone demonstrates economic advantage nor complete disease prevention. Accordingly, the evidence is interpreted at the level of the actual intervention, avoiding substitution of pond-fertilization or hydroponic findings for aquaponic tests.

Direct aquaponic evidence is available from Küçükağtaş and Kurtoğlu (2024), who investigated liquid vermicompost in systems containing common carp, pepper, lettuce and beans. Foliar and water applications were compared with untreated controls over 90 days. At the tested concentration of 1 ml L^{-1}, the authors reported no adverse effects on the measured water-quality parameters. This supports further investigation of supplementation under specified conditions, but does not establish that every liquid vermiproduct is safe at the same nominal dose. Product composition and exposure frequency remain important to interpretation.

Research conducted by Küçükağtaş and Kurtoğlu (2024) also reported preliminary adverse responses at higher concentrations, with 2 ml L^{-1} associated with changes in fish behavior and lettuce condition, while 1.5 ml L^{-1} was associated with increased turbidity. These observations may provide an initial reference for further investigation of vermiwash application in aquaponic systems; however, their applicability to other systems and dosing conditions requires further evaluation. However, the commercial product evaluated in the study should not be assumed to be equivalent to farm-prepared vermiwash, as differences in composition and preparation may influence its effects.

3. Evidence from Hydroponics

Hydroponic evidence supports potential plant responses while also revealing limitations. Jaikishun *et al*. (2018) examined vermicompost and vermiwash derived from neem and lime in lettuce cultivation. Jiang *et al*. (2023) reported changes in maple pea growth, nutrient uptake and root-associated microbial communities following vermicompost tea application. These experiments demonstrate biological activity in soilless cultivation, but neither establishes compatibility with fish or nitrifying biofilters.

Rehman *et al*. (2024) provided a useful counterpoint to claims that untreated vermitea is a complete nutrient solution. In *Diplotaxis muralis*, enhanced vermitea with lower pH and higher electrical conductivity supported better performance than the standard formulation. Because several solution properties differed, the response should not be attributed exclusively to microbial stimulation or a single nutrient. The practical lesson is that product formulation and nutrient availability can determine whether a vermi-liquid supports or restricts plant growth.

Quantitative results from Jiang *et al*. (2023) illustrated the need to identify the comparator and endpoint. After 26 days, the 20% vermicompost-tea treatment produced stem length of 30.91 cm compared with 24.25 cm in the control. Stem-and-leaf fresh mass reached 1.25 g and differed significantly from the control ($p<0.01$); root fresh mass was 0.91 g compared with 0.59 g, also significant at this concentration ($p<0.01$). These short-duration seedling responses demonstrate treatment-associated growth effects, not a validated commercial yield response or safe

aquaponic application rate. Nutrient enrichment and shifts in microbial communities occurred simultaneously, making it difficult to attribute the observed responses to either mechanism independently.

Preparation differences provide a plausible explanation for divergent results. Rehman *et al*. (2024) prepared enhanced vermitea at a 1:5 vermicompost-to-water ratio and adjusted pH to 5.8-6.3; the standard preparation involved further extraction to 1:10 and remained at pH 7.5-8.0. Plants were evaluated after approximately 45 days. Concentration and pH therefore changed together, so improved performance cannot isolate an independent microbial or hormonal effect. Zarei *et al*. (2018) likewise demonstrated source-dependent chemistry; whereas Ortega-Torres *et al*. (2023) tested additions against a background of complete fertilization. The studies answer different questions: adequacy of a nutrient formulation, variability of an extract and response to supplementation, respectively.

Ortega-Torres *et al*. (2023) evaluated vermiwash and vermileachate products as complements to complete fertilization in hydroponic lettuce. Growth and stress-related enzyme activities responded to treatment. Such findings support investigation of biostimulant or elicitor effects, but changes in antioxidant enzymes are not equivalent to demonstrated resistance against a pathogen. Simeon and Bugawisan (2023) also compared vermitea and nutrient-solution combinations in non-circulating pechay cultivation. Their study broadens the range of crop examples, although it remains hydroponic evidence and should carry less weight than replicated trials directly measuring fish, plant and biofilter responses.

4. Earthworms and Pond Fertilization

Earthworm integration into a grow bed is a separate intervention from dosing a prepared extract. Chandramenon *et al*. (2024) compared standard aquaponics with an earthworm-containing system and examined freshwater replenishment. The design highlights possible interactions between waste processing and water management. In contrast, Kumar and Godara (2019) studied solid vermicompost as pond fertilizer for Indian major carps. Pond food webs and fertilization rates differ fundamentally from recirculating aquaponics; those results cannot justify applying pond-scale doses to fish tanks.

5. Distinguishing Nutrient Effects from Biostimulation

The evidence supports three propositions with different levels of confidence. First, vermiproducts can supply nutrients, although their concentrations and availability are variable. Second, plant growth and biochemical responses can accompany their application, but most comparisons do not separate nutrient supply from changes in pH, organic compounds and microorganisms. Third, direct evidence of fish-plant-biofilter compatibility remains much narrower than the hydroponic evidence for plant response. The aquaponic trial of Küçükağtaş and Kurtoğlu (2024) is therefore more relevant to exposure compatibility than the larger number of plant-only studies, but its unit inconsistencies and product specificity constrain operational interpretation.

A discriminating experiment would compare an untreated control, a mineral treatment matched for measured available nutrients and the vermiproduct at the same nutrient loading and pH. Microbial or organic-fraction manipulations could then examine possible biological effects, provided that sterilization or filtration does not introduce uncontrolled chemical changes. Replication must occur at the independent production-system level; multiple plants or water samples within one loop are subsamples. Fish survival alone is insufficient: feeding behavior, growth, root health, ammonia and nitrite conversion, oxygen demand and edible-tissue quality should be evaluated together. These are proposed research requirements rather than outcomes already established by the reviewed studies.

6. Requirements for Practical Use

Taken together, these studies support a cautious research pathway: characterize the product, quantify the nutrient contribution and test its effects within the intended hydraulic configuration. Treatment comparisons should separate nutrient supply from possible biostimulation by including nutrient-matched controls. Measurements should include oxygen demand, nitrogen conversion, plant composition and fish performance. Table 4 distinguishes the principal evidence types.

Integrated Health Management

1. Diagnostic Framework

Aquaponic health management should distinguish infectious disease from nutritional disorders, toxic exposure and environmental stress. Loss of appetite, surface gasping, abnormal swimming and damaged fins are not specific diagnoses. Water quality and equipment function should be checked promptly, followed by examination of affected animals and appropriate diagnostic testing. Nutrient deficiency can reduce resilience, but it should not be treated as the cause of every infectious outbreak (Yildiz *et al*., 2019).

Ammonia and nitrite toxicity arise from exposure conditions rather than infection. Responses should address loading, biofilter performance, oxygenation and water exchange where appropriate. Organic accumulation can produce localized oxygen depletion and reduced compounds, reinforcing the importance of solids removal. Abrupt temperature change is another stressor that requires environmental correction. These conditions belong in a water-quality and welfare discussion rather than a list of microbial diseases.

2. Fish Infections and Treatment Constraints

Infectious conditions include bacterial, parasitic and oomycete diseases. Saprolegnia is an oomycete and cotton-like lesions should not be assumed to identify the causative agent without examination. Similarly, fin erosion or gill damage may have several causes. Treatment selection must follow diagnosis and account for species, food-fish status, local authorization and exposure of the wider system. The original approach of listing antibiotics or chemicals as

Table 4: Evidence for vermicompost derived inputs and limits to transfer

System	Intervention and experimental comparison	Outcome and evidence limitations	Study/ References
Product characterization	Cow manure, leaf meal and mixed beds; paired tea and wash characterization. No fish or crop efficacy trial.	Composition depended on feedstock; tea generally richer. Chemistry does not establish production efficacy.	Zarei *et al*. (2018)
Lettuce hydroponics	Neem- and lime-derived vermiproducts compared with commercial solution.	Reported favorable growth; preparation-specific result, with no fish or biofilter test.	Jaikishun *et al*. (2018)
Maple pea hydroponics	Tea concentration series including 20%; control comparison; 26-day growth evaluation.	At 20%, root fresh mass 0.91 versus 0.59 g ($p<0.01$). Nutritional and microbial effects not independently isolated.	Jiang *et al*. (2023)
Lettuce hydroponics	Mesh/direct vermiwash and leachate combinations supplementing complete fertilization.	Growth and enzyme responses; does not test sole-fertilizer replacement or pathogen suppression.	Ortega-Torres *et al*. (2023)
Pechay hydroponics	Four treatments, three reported replicates: SNAP alone, tea alone, full combination and half combination. Tea alone 100 ml/ 10 L.	Treatment differences in growth and plant weight; plant-only evidence. Replicate independence needs scrutiny before synthesis.	Simeon and Bugawisan (2023)
Diplotaxis muralis hydroponics	Standard tea 1:10 at pH 7.5-8.0; enhanced tea 1:5 at pH 5.8-6.3; Hoagland comparison; about 45 days.	Enhanced formulation outperformed standard tea; concentration and pH confounded. No fish exposure.	Rehman *et al*. (2024)
Carp, lettuce, pepper and bean aquaponics	Nine systems; three groups with three system replicates; 90 days; water or foliar commercial liquid vermicompost versus control. Methods: 1 ml L-1.	No adverse measured water-quality effects at selected dose; preliminary higher-dose responses and inconsistent units limit dosing transfer.	Küçükağtaş and Kurtoğlu (2024)
Aquaponics	Earthworm-containing versus standard testbeds; phases with and without 19% freshwater replenishment.	Reported productivity changes after replenishment: 2.83% and 5.54%, respectively. Not an extract trial; treatment and system effects require care.	Chandramenon *et al*. (2024)
Major-carp ponds	Solid vermicompost pond fertilization, including 10,000 kg ha-1year-1, against other manures and control.	Growth response concerns pond food webs; rates cannot be transferred to recirculating aquaponics.	Kumar and Godara (2019)

universal remedies is unsuitable for a coupled production environment (Yildiz *et al*., 2019; Folorunso *et al*., 2021).

Table 5 distinguishes infectious disease, nutritional disorders and environmental or toxic causes of impaired fish health. It deliberately avoids universal chemical prescriptions.

Prevention includes sourcing healthy stock, quarantine where practicable, avoiding overcrowding, maintaining appropriate feeding and removing mortalities promptly. Dedicated equipment and controlled movement between units reduce opportunities for pathogen transfer. Where treatment is necessary, a separate treatment unit can limit unintended exposure of crops and biofilters, although decisions must still consider animal welfare and appropriate disposal of treatment water.

3. Plant Health and Food Safety

Plant pest and disease management presents similar constraints. Folorunso *et al*. (2021) emphasize monitoring, cultural control and biological approaches while evaluating the risks of chemical runoff. A product described as natural or organic is not necessarily harmless to aquatic organisms or microorganisms. Foliar application changes the exposure route but does not eliminate runoff. Shared-water systems therefore require attention to application method, drainage and possible return to fish tanks.

Root-zone disease deserves particular attention because recirculating water can connect susceptible plants. The plant-pathogen chapter in the supplied aquaponics volume identifies *Pythium* and *Phytophthora* as important water-

Table 5: Fish health problems and appropriate first management priorities

Problem and category	Indicative findings	Priority response
Nutritional disorder	Poor growth or abnormal condition; nonspecific signs	Review diet quality, ration and storage; investigate other causes.
Ammonia or nitrite toxicity	Respiratory distress or abnormal behavior	Measure water chemistry; assess oxygen, feeding load and biofilter function.
Oxygen depletion or sulfide exposure	Gasping; oxygen-poor zones and accumulated wastes	Restore suitable oxygen conditions and address solids accumulation; isolate fish when necessary.
Temperature stress	Behavioral or feeding changes after thermal disturbance	Check temperature history and stabilize conditions gradually.
Saprolegniosis	Cotton-like growth; often associated with stress or damaged tissue	Confirm oomycete involvement and underlying stress; obtain species-appropriate treatment advice.
Bacterial fin erosion or columnaris-like disease	Fin, skin or gill lesions	Confirm diagnosis; correct husbandry and use targeted authorized treatment where indicated.
Trichodinid or velvet-like parasitic disease	Excess mucus, rubbing or respiratory distress	Microscopic examination and parasite identification; treatment in an appropriate isolated unit.

Sources: Yildiz *et al*. (2019) and Folorunso *et al*. (2021)

associated oomycetes, alongside fungal pathogens such as *Fusarium* (Stouvenakers *et al*., 2019). Root discoloration or wilting must be differentiated from oxygen deficiency and nutrient stress. Removing affected plant material, managing drainage and preventing introduction through seedlings or equipment are complementary measures. Evidence that a microbial preparation alters defence-enzyme activity does not establish pathogen suppression without challenge tests and measurements of disease severity.

Figure 2 summarizes the central argument: management acts on shared chemical and biological pathways, so a local improvement must be evaluated against its consequences for the whole production system.

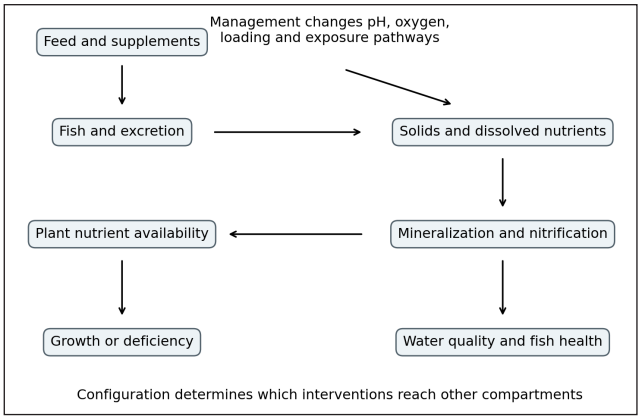


Figure 2: Integrated nutrient-microbial-health framework. Nutrient addition can support plants while increasing biological treatment demand; configuration controls the propagation of effects between compartments. Original conceptual synthesis based on Wongkiew *et al*. (2017), Eck *et al*. (2019), Kasozi *et al*. (2021) and Folorunso *et al*. (2021).

An integrated diagnostic sequence starts with the distribution and timing of signs, followed by water chemistry and equipment checks. If an environmental cause is identified, correction and response monitoring take priority. Persistent or spreading lesions require organism-specific examination and, where appropriate, diagnostic testing. Any proposed treatment is then assessed for its exposure route, likely effects on fish and plants and potential disruption of nitrification. Where isolation is feasible, it reduces the number of biological compartments exposed but does not remove the need to confirm efficacy. This sequence links Table 5 to prevention rather than treating it as a prescription list (Yildiz *et al*., 2019; Folorunso *et al*., 2021).

Microbial richness should not be equated with microbiological safety. Beneficial nutrient transformations can coexist with undesirable organisms and taxonomic detection alone does not establish either pathogenicity or disease suppression. Kasozi *et al*. (2021) described the complexity of aquaponic microbial communities. Hygiene during cultivation and harvest remains necessary, particularly for vegetables consumed raw. Vermiproducts introduced from outside the system should be evaluated as additional biological and chemical inputs rather than presumed protective agents.

Sustainability and Research Priorities

Aquaponics can reduce waste discharge and recover nutrients, but its overall performance depends on energy demand, infrastructure, feed inputs, supplementation and product markets. Life-cycle comparisons showed why the production boundary matters when judging sustainability (Forchino *et al*., 2017). Additional revenue from vegetables does not automatically translate into higher profit once labor, heating, pumping and crop losses are included (Yep and Zheng, 2019; Nair *et al*., 2025).

Comparisons should report environmental burdens per defined output and explain how burdens are allocated between fish and crops. Water saved within the production

loop does not describe energy required for heating, pumping or aeration. Likewise, recovering a nutrient from solids can reduce fertilizer demand while introducing treatment costs. Forchino *et al*. (2017) provided a basis for evaluating alternative aquaponic techniques through life-cycle assessment; their comparison should not be interpreted as a universal ranking of coupled and decoupled systems. Economic studies should distinguish capital investment, recurring costs and sensitivity to fish and vegetable prices rather than extrapolating profitability from biological yield.

Future research should first establish comparable nutrient budgets across fish, water, solids and crops. Reporting feed composition, feeding rate, stocking biomass, plant density, water replacement and supplement inputs would improve interpretation of configuration effects. Second, microbial studies should connect community composition with measured conversion rates and system resilience. The findings of Daims *et al*. (2015) and Derikvand *et al*. (2024) demonstrated why functional diversity must be incorporated into biofilter design assumptions.

Third, vermitea and vermiwash trials require reproducible preparation protocols, nutrient-matched controls and independent system replication. Long-term measurements are needed to distinguish transient growth stimulation from sustained nutrient sufficiency and to detect accumulation or changes in treatment capacity. Fourth, health-management research should assess whole-system consequences of interventions, including nitrification, root health and edible-product quality. Finally, regional studies should evaluate operational reliability and costs under local climatic and market conditions, especially where electricity interruptions or high temperatures constrain adoption (Bhanja *et al*., 2024).

Conclusion

Aquaponic productivity and system stability depend on the interactions among hydraulic design, nutrient availability and microbial processes. An intervention that improves crop nutrition can simultaneously alter oxygen demand, nitrogen conversion and fish exposure; health management must therefore be evaluated across compartments. The reviewed evidence supports crop-specific supplementation and recognizes a broader nitrifying community than the conventional two-organism model. It also shows that vermiproduct formulation and experimental comparator strongly influence apparent benefits. Hydroponic growth responses establish potential plant utility, whereas direct aquaponic compatibility remains product- and exposure-specific. The principal unresolved question is whether standardized vermiproducts can improve nutrient recovery and crop performance beyond nutrient-matched mineral controls without impairing fish welfare or biofilter function. Independent system replication, nutrient mass balances and integrated health endpoints are needed to answer that question. Greater control in decoupled systems offers management flexibility, but its economic and environmental value must be demonstrated under the intended production conditions.

Ethical Statement

The author declares that no generative artificial intelligence tools were used in drafting or preparing this manuscript. The manuscript was written, interpreted and revised solely by the author, who takes full responsibility for its content.

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