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Review Article

Nanotechnology Applications in Aquaponics: Feed Engineering, Nutrient Cycling Efficiency, and System Performance Optimization

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Abstract

Aquaponics integrates aquaculture and hydroponics within a recirculating system; however, achieving stable nutrient cycling and optimal system performance remains a major challenge due to limitations in nitrification efficiency, nutrient availability, and hydraulic performance. This review evaluates the role of nanotechnology as an engineering strategy to enhance nutrient transformation, improve feed utilization, and optimize overall system performance in aquaponic systems, with a particular focus on tilapia–lettuce production. Nano-enhanced feed formulations, including nano-silica and micronutrients, are examined for their ability to improve feed conversion efficiency, enhance nutrient retention, and reduce Total Ammonia Nitrogen (TAN) loading to biofilters. In parallel, nanostructured biofilter media are assessed for their capacity to increase specific surface area, promote biofilm development, and enhance nitrification kinetics. At the plant interface, nanofertilizers are evaluated for their role in improving micronutrient availability and nutrient uptake efficiency. This review adopts an engineering perspective by linking feed inputs, microbial processes, and plant uptake through mass balance and transport mechanisms. While nanotechnology offers significant potential to improve Nitrogen Use Efficiency (NUE) and system stability, concerns regarding nanoparticle toxicity, bioaccumulation, and long-term environmental impacts remain critical challenges. Future research should prioritize quantitative validation, system-scale integration, and safety assessments to support the sustainable implementation of nanotechnology in precision agriculture.

Keywords: Aquaponics, Biofilter, Nano-enhanced feed, Nanotechnology, Precision agriculture, Tilapia-lettuce production

1 Introduction

Due to growing interest in resource-efficient food systems, a new production method has gained traction that integrates animal protein production with vegetable cultivation while reducing water use and nutrient discharge [1]. Aquaponics is a recirculating food production system that integrates aquaculture and hydroponics, enabling the reuse of water and nutrients between fish and plants. While often described as a highly efficient nutrient-recycling system, its performance is constrained by imbalances in nutrient transformation, transport, and utilization processes. Nitrogen introduced through fish feeds is not fully converted into plant biomass, as a significant fraction is partitioned into dissolved nitrogen species, accumulates as solids, or gaseous losses [2]. Thus, aquaponic performance is more appropriately evaluated using a mass-balance framework, where feed input represents the primary nitrogen source and downstream processes determine its distribution across system compartments. Inefficiencies arise when there is a mismatch between nutrient release from fish metabolism, transformation through microbial processes, and plant uptake demand [3].

Nitrogen loading from feed is one of the primary drivers for assessing the amount of nitrogen introduced into aquaponics systems and affects how the nitrogen is utilized in those systems [3], [4]. As a result, nitrogen transformation paths and nitrogen use efficiency are some of the major issues considered for designing and managing aquaculture systems, as the performance of these systems is influenced by pH, dissolved oxygen, and hydraulic loading rate [4], [5].

Recent review articles highlight that aquaponic systems utilize fish feed formulations designed for traditional aquaculture; therefore, aquaponic systems will continue to experience nutrient shortages in their crops due to ineffective nutrient recycling [6].

To overcome these issues, along with those in traditional aquaculture, nanotechnology-based feed innovations are being investigated in aquaculture, as well as with the use of nanoparticles for feed supplementation and for the slow release of biologically active feed constituents, to increase the amount of nutrition delivered to the fish, bioavailability, and feed efficiency [7]. More broad reviews that are focused on aquaculture have also indicated that nanotechnology application in aquaculture can improve nutrition and digestibility of aquafeed; however, there is a need for continued investigation of safety, long-term fate, and environmental risks when applying nanotechnology in aquaculture [8]. Results from studies examining nutrition using nanoform of minerals for tilapia showed improved feed performance variables and reduced levels of nutrient residues in water, supporting the connection between nano-enabled nutrition and aquatic ecosystem health [9].

While much emphasis has been placed on the use of nanotechnology in aquaculture and a large amount of literature exists on the operational challenges encountered with aquaponics, an integrated system-based synthesis of nano-enabled feed strategies and their connection to the overall nutritional cycling efficiency of aquaponics, and metrics of engineering performance in NUE, nitrification stability, and productivity per unit of water and volume, continues to be lacking [10]. Nanotechnology represents a significant engineering approach for increasing feed utilization efficiency, accelerating nutrient cycling kinetics, and improving aquaponic system efficiency. This review was conducted as a structured narrative review focused on engineering-relevant nanotechnology applications in aquaponics. The collected literature presents a synthesis of the current state of research concerning the use of nanotechnology in aquaponics, with a focus on feed innovation, nutritional cycling efficiency, and system performance optimization, as well as identifying the research gaps that need to be addressed to enable safe, scalable, and engineering-relevant implementation.

2 Engineering Fundamentals of Aquaponics System

Aquaponics systems operate as integrated recirculating bioproduction platforms in which fish, microorganisms, and plants interact through continuous nutrient and water exchange. Fish metabolism and feed inputs generate organic waste and dissolved nutrients, which are subsequently transformed by microbial communities into plant-available forms. This coupling enables efficient resource utilization but also introduces complex dependencies between biological and engineering processes [11]. The sustainability of the fish and plants relies upon the continuous cycling of nutrients and the efficient reuse of water, as well as the activities of microorganisms to convert the waste produced by the fish into forms that can be utilized by the plants for uptake [12].

The engineering aspects of an aquaponic system are built upon the foundation of recirculating aquaculture system (RAS) principles. Aquaponic systems include culture tanks and the mechanical filtration, biological filtration, aeration, pumping, plumbing, and environmental monitoring components of the system as part of a closed-loop water management system. These subsystems are hydraulically connected, forming a closed-loop network in which water quality, nutrient availability, and system stability are governed by flow dynamics, reaction kinetics, and mass transfer processes [12].

Effective system operation requires the removal of solid waste, followed by biological conversion of dissolved nitrogen compounds through nitrification. Biofilters provide a high surface area for microbial colonization, supporting the growth of ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB), which convert toxic ammonia into nitrate. The efficiency of this process depends on factors such as dissolved oxygen, pH, temperature, and biofilm characteristics [13]. Biofilters within aquaponic systems utilize media with high surface area for the nitrification process to provide nitrate to the plants, preventing the accumulation of toxic TAN while producing plant-available nitrogen in an integrated system [14], [15]. The pump selection and plumbing design impact hydraulic retention time, head pressure, and energy efficiency. Hydraulic design plays a critical role in determining system performance. Flow rate, hydraulic retention time (HRT), and reactor configuration influence nutrient transport, substrate availability, and contact time between microorganisms and substrates. Poor hydraulic design can lead to short-circuiting, stagnant zones, and increased boundary layer resistance, all of which reduce mass transfer efficiency and limit system performance. [16], [17]. Together, these engineered subsystems comprise the infrastructure that supports aquaponic systems and provide the foundational elements for the incorporation of advanced technologies into aquaponic systems, such as nano-enhanced feed systems and nutrient cycling optimization.

2.1 *System architecture and engineering concepts*

Aquaponic systems are engineered as integrated recirculating bioproduction platforms that combine aquaculture and hydroponics through bio-mediation of the nutrient cycling of the system (Figure 1). Aquaponics is an extension of the method of aquacultural engineering that incorporates a hydroponic plant nutrient recovery unit into the system as it relates to the design of a hydraulic, nutritionally sustainable, and biochemically stable aquaculture system. Thus, aquaponics is an integrated recirculating aquaculture system (RAS) with a plant nutrient recovery unit that is governed by hydraulic stability, the kinetics of nutrient transformation, and the operational efficiency of the system [18]. Generally, aquaponic systems are a series of interconnected unit operations, including fish rearing tanks, solids removal components, biofiltration units, hydroponic production modules, and sump-based recirculation systems [19]. The overall system operates as a series of coupled reactors that meet mass balance criteria within which nitrogen enters the system through feeding fish and is partitioned between fish biomass, dissolved inorganic nitrogen species, solids, plant biomass, and denitrification [20]. Several quantitative modeling and mass balance approaches have been used to evaluate the efficiency of nutrient distribution and recovery of recirculating aquaponics systems that help inform design decisions regarding flow rates, retention times, and component sizes [21].

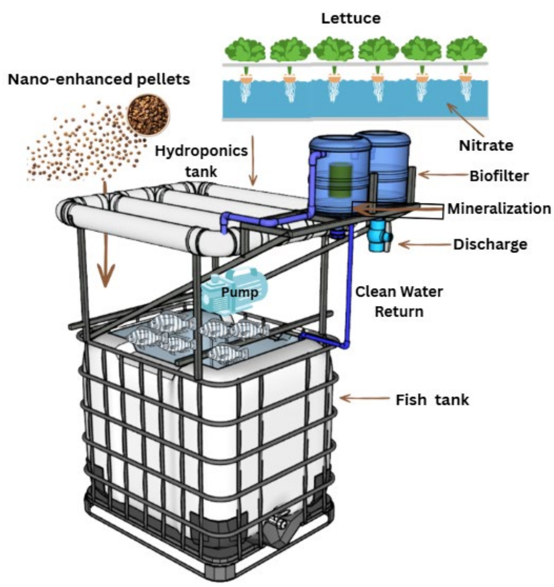

Figure 1. Diagram of the aquaponics system work.

The performance of biofilters is essential to the stability of the overall system. Specific surface area and biofilm density are key factors that influence nitrification, with additional contributing factors being hydraulic loading, temperature, pH, and dissolved oxygen. Specific surface area, biofilm density, and all other factors that influence high-nitration performance include substrate transport to biofilm and microbial kinetics. Guidelines for biofilter design and performance in aquaculture engineering are primarily based on these water quality parameters as well as specific design constraints [4], [22].

The hydraulic design of the aquaponic systems connects all subsystems through hydraulic residence time (HRT) and total recirculation flow (Q), which dictate the delivery of nutrients to plants as well as substrate loading to biofilters [23]. Results from empirical optimization studies in recirculating aquaponic systems demonstrate that plant-to-fish size ratios and hydraulic loading rates materially affect both plant production and nutrient removal; therefore, consideration of both flow rates and reactor size should be viewed as design variables rather than fixed parameters [24].

Oxygen transfer engineering is another important factor that affects nitrification in aquaponic systems due to the large amount of oxygen required for nitrification. The standard stoichiometric relationship for total ammonia nitrogen (TAN) oxidation to nitrate is 4.57 g O_2/g NH_3-N, which assumes that both the ammonia and nitrite forms of nitrogen are oxidized to nitrate. The aeration capacity of the aquaponic system should provide sufficient oxygen to both the fish for respiration and the microorganisms that oxidize TAN to prevent TAN accumulation afnd the subsequent hindrance of nitrification [25].

2.2 *Process kinetics, mass transfer, and nutrient transformation dynamics*

Hydraulic-coupled bioreactor petroleum aquaculture technology operates as a nutrient (N) optimum ecosystem that functions through (a) biological reaction kinetics, (b) mass transfer across a liquid boundary layer, and (c) hydraulic residence time and recirculation transport. These three mechanisms interact to determine the proportion of total ammonia nitrogen (TAN) retained as toxic TAN; nitrogen, as TAN, is oxidized to nitrate; and nitrogen, as nitrate, is recovered as N_2O [26].

2.2.1 Nitrogen transformations kinetics

Nitrogen transformation in an aquaponic system is governed by biological and physicochemical processes, with nitrification as the primary pathway for converting toxic ammonia into plant-useable nitrate. Nitrification is a strictly aerobic microbial process, carried out by ammonia-oxidizing and nitrate-oxidizing microorganisms.

The process occurs in two sequential steps :

1. Ammonia oxidation ($NH_3 \rightarrow NO_2^-$)
2. Nitrate oxidation ($NO_2^- \rightarrow NO_3^-$)

In Biofilter media, nitrification is an aerobic biological process carried out by ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB), responsible for conducting nitrification reactions. Generally, the rate of ammonia oxidation follows a Monod kinetic type reaction pattern, which is based on the limitations imposed by substrate availability and growth constraints on the microbial population within the biofiltration system [22]. This relationship describes how substrate availability limits nitrification kinetics in biofilm systems.

$$r = r_{max} \frac{S}{k_s + S} \quad (1)$$

Where:

r= nitrification rate (mg N·L⁻¹·day⁻¹)

r_{max}= maximum rate (mg N·L⁻¹·day⁻¹)

S = ammonium concentration (mg NH_4^+-N·L⁻¹)

K_S = half-saturation constant (mg NH_4^+-N·L⁻¹)

Mechanistic modeling of nitrification processes in recirculating systems employs Monod kinetics to represent growth and substrate uptake. Mass transfer coefficients, biofilm diffusion resistance, and hydraulic constraints together observed conversion rates. Enhanced media surfaces and nano-scale modifications reduce diffusion limitations, increase effective reaction rates, and mitigate build-up environments unfavorable to nitrifiers [4], [27]. Nitrification efficiency was influenced by temperature, pH, dissolved oxygen, and biofilm surface area due to the acid and alkalinity consumed at 7.1 mg $CaCO_3$ per mg NH_4^+ without buffering. Progressive pH decline can inhibit microbial activity and impair nutrient availability to plants and, therefore, depends not only on microbial activity but also on system-level engineering parameters such as aeration and hydraulic flow [27].

2.2.2 Nitrogen mass balance framework

The performance of aquaponic systems can be quantitatively evaluated using a nitrogen mass balance approach:

$$N_{in} = N_{fish} + N_{plant} + N_{solids} + N_{gas} \quad (2)$$

Where:

N_{in}= nitrogen input (g N·d^{-1})
N_{fish}= nitrogen retained in fish biomass (g N·d^{-1})
N_{plant}= plant nitrogen uptake (g N·d^{-1})
N_{solids}= solids removal losses (g N·d^{-1})
N_{gas}= gaseous losses (g N·d^{-1})

The biofilter performance is mostly affected by the amount of feed that is converted. Typically, 60-70% of feed nitrogen is released as dissolved waste, primarily as total ammonia nitrogen (TAN), which must be converted through nitrification by plants. Inefficiencies occur when nitrogen accumulates in intermediate forms before plant uptake. Therefore, an effective means of balancing the amount of feed input, the available biofilter capacity, and the size of the plant growing area is necessary to achieve Nitrogen Use Efficiency (NUE) [28]

2.2.3 Hydraulic retention time (HRT) and reactor design

Hydraulic residence time (HRT) governs the interaction time between substrates and biofilms and determines nutrient delivery frequency to plant roots [15].

$$\text{HRT} = \frac{V}{Q} \tag{3}$$

Where:

V = reactor volume (m^3)
Q = volumetric flow rate (m^3 h^{-1})
HRT = time constant (h)

A process-oriented design approach treats aquaponics as a set of parallel unit operations, with HRTs tuned to better match biofilter kinetics and plant uptake demands. Experimental studies in aquaponic NFT systems demonstrate that hydraulic loading rate directly affects nutrient distribution and plant productivity, indicating that reactor hydrodynamics must be engineered according to crop demand and system configuration. Flow uniformity is equally significant: short-circuiting and stagnant zones increase boundary-layer thickness, reducing effective mass transfer to biofilms and plant roots [29]. Beyond bulk flow, nutrient transformation is influenced by mass transfer limitations, particularly in boundary-layer resistance at biofilm surfaces, oxygen diffusion constraints, and non-uniform flow distribution. These transport limitations reduce effective substrate availability to microorganisms and plant roots, even when bulk concentrations are sufficient. Therefore, system performance depends on coupling reaction kinetics with transport processes, rather than biological processes alone [30].

2.2.4 Oxygen mass transfer and system stability

Oxygen availability is a constraint in aquaponic systems, as it directly affects both fish respiration and microbial nitrification. The oxygen transfer rate (OTR) is expressed as [25]:

$$OTR = k_L a(C^* - C) \tag{4}$$

Where:

$k_L a$= volumetric mass transfer coefficient (s^{-1})
C^*= saturation DO (mg/L)
C = bulk DO concentration (mg/L)

Complete oxidation of ammonia requires 4.57 g O_2 per g NH_4^+-N, indicating a significant oxygen demand in biofiltration units. Maintaining dissolved oxygen levels above 5 mg.L^{-1} is required for stable nitrification [31]. Insufficient aeration reduces nitrification rates and may shift microbial communities toward incomplete pathways [22]. Therefore, aeration systems must be designed to meet both biological oxygen demand (BOD) and nitrification demand under high feeding rates.

2.2.5 Nutrient transport and plant uptake dynamics

Plant nutrient assimilation depends on diffusion and convection transport mechanisms. Nutrient flux toward the rhizosphere can be calculated using Fick's Law [32]:

$$J = -D\frac{dC}{dx} \tag{5}$$

Where:

J= nutrient flux (mg·m^{-2}·s^{-1})
D= diffusion coefficient (m^2·s^{-1})
$\frac{dC}{dx}$= concentration gradient

Mass transfer limitations occur when boundary layers thicken due to low turbulence, even if bulk nutrient concentrations remain sufficient [33]. Therefore, hydraulic design directly influences nutrient uptake efficiency and overall system productivity. Diffusion and mass flow determine nutrient delivery to root surfaces, and diffusion limitations occur in external nutrient supply to transport to the uptake interface [34]. In hydroponic flow environments, insufficient turbulence can limit nutrient delivery to roots and constrain uptake. Even when bulk solution concentrations are experimentally, nutrient solution flow rate has been shown to influence nutrient uptake and plant growth through transport and fixing effects near the root surface [35], [36]. Recent system-level analyses further emphasize that balancing fish feed input, biofilter conversion capacity, and plant growing area is essential for maximizing nitrogen use efficiency (NUE) and preventing nutrient imbalance in an integrated aquaponics system.

3 Nanotechnology Applications in Aquaponics

Nanomaterials represent an engineering strategy for enhancing the transformation and mass transfer of nitrogen in aquaponics by changing physicochemical properties at the feed, biofilter, and plant interfaces, rather than simply optimizing biological parameters as with traditional methods. This modification leads to both a change in the nitrogen source term and a change in the capacity of nitrogen to react in the overall system mass balance [37]. From a systems perspective, nanotechnology affects aquaponics through three primary pathways: (1) feed engineering, (2) biofiltration, and (3) plant interface. These interventions collectively influence nitrogen cycling dynamics and overall system efficiency.

3.1 *Nanoencapsulation of nutrients and functional additives*

Fish diets often contain oxygen-sensitive bioactives, which can leach out and are difficult to absorb by the intestines. Nanoparticle coating of unstable nutrients prevents nutrient loss, as well as controls the release of these nutrients throughout the gastrointestinal tract so that they are available longer to the fish. An increased amount of available nutrients to fish corresponds with increased growth and feed conversion [38].

A study on chitosan-vitamin C nanoparticles added to the diet of tilapia demonstrated that tilapia fed the nanoparticles had improved growth, antioxidant levels, immune response, and resistance to disease. This study showed that nanoparticles can be used to improve the absorption of unstable micronutrients without having to increase the total amount of the micronutrient in the feeding program [39]. A second study using nanoparticles with Nile tilapia demonstrated similar improvements in growth and feed conversion and provided evidence that nanoparticles may provide superior delivery of micronutrients in aquaculture systems experiencing high levels of stress [40].

The increased feed conversion and immunological status improvements demonstrated in feed investigations with nanoparticles suggest one way to potentially reduce the generation of nitrogenous waste within interconnected aquaponic systems, therefore reducing biofilter loading and improving the stability of nitrification in aquaponic systems (Table 1).

Table 1. Effects of nano-enhanced feed additives on tilapia performance and system-level nutrient cycling.

Nanoparticle Type	Effect in Tilapia	System Level Impact	References
Chitosan-Vitamin C nanocomposite	↑ Growth rate (~10-18%); ↑ antioxidant enzyme activity (SOD, CAT ↑15–30%)	↓ Nitrogen excretion (~10–20%); ↓ TAN loading to biofilter ; improved system stability	[40]
Chitosan nanoparticles	↑ Survival rate (~5–12%); ↑ immune response (lysozyme activity ↑20–40%)	Reduced production variability; improved biomass retention; more stable nitrogen input profile	[41]
ZnO nanoparticles	Dose-dependent growth increase (~8–15% at optimal levels); toxicity observed at high doses	Requires controlled dosing; potential oxidative stress may disrupt microbial processes if overdosed	[42]
Silica nanoparticles	↑ Feed conversion efficiency (FCR ↓10–20%); ↑ nutrient digestibility	↑ Nitrogen retention efficiency; ↓ TAN generation (~15–25% reduction); reduced biofilter loading	[43]
Dietary nanoparticles	↑ Nutrient bioavailability; ↑ feed utilization efficiency (~10–15%)	Moderates upstream nitrogen loading; improves nitrogen use efficiency (NUE); enhances system integration	[44]

3.2 *Feed formulation component in nano-enhanced aquafeeds and preparation*

The individual feed components significantly define nutritional adequacy and downstream effects on water quality in the aquaponic system. The formulation combines hydrocolloid binding (CMC), mineral structuring bentonite, silica, and sugar pelleting aid as molasses with banana peel as a circular bioresource ingredient and amino-acid supplementation to meet tilapia requirements [45].

3.2.1 Bentonite

Bentonite is commonly considered an adhesive compound additive, and its maximum levels of 3% for all species are established. This factor provides a basis for improved pellets' integrity, being well-bound. In aquafeeds, improved durability reduces fines and nutrient leaching, which can lead to more organic pollutants and increased total ammonia nitrogen (TAN) concentrations in recirculation systems. Thus, approximately 1% on a 100 g Ration provides both adhesive technological binder and creates a more stable pellet in water when fed to fish [46].

3.2.2 Nano-silica

Nano-silica has been investigated in aquaculture feeds as a functional additive; its small particle size and large specific surface area may modify digestive interactions, improve nutrient accessibility, and influence gut morphology and physiological status. Earlier tilapia work suggested that dietary nano-silica could improve protein digestibility and feed utilization, but the aquaponic relevance of these findings must be interpreted cautiously because most available evidence comes from aquaculture rather than integrated fish–plant systems. Mechanistically, the reported benefits of nano-enabled feed additives in fish are often associated with improved nutrient absorption, enhanced digestive enzyme activity, better intestinal condition, or greater antioxidant and immune competence, all of which may indirectly reduce dissolved nutrient losses to the water.

Recent tilapia studies with other nanoparticle systems likewise show that performance responses are dose-dependent rather than uniformly beneficial. The chitosan nanoparticles improved growth, antioxidant defenses, and disease resistance in Nile tilapia, with the best performance observed at 5 g/kg, while cautioning that toxicity remains a concern and that safe application rates must be linked to particle properties. Similarly, nano-phosphorus supplementation improved tilapia growth while reducing phosphorus residues in water, supporting the idea that nano-enabled feeds can alter waste release as well as fish performance. In the context of aquaponics, these findings justify discussing nano-silica as a potential upstream strategy for moderating nutrient discharge, but they do not yet prove whole-system improvement. Nano-silica should be presented as a promising but still under-validated feed engineering tool whose aquaponic value depends on inclusion rate, nanoparticle characterization, fish response, downstream water quality effects, and long-term recirculating-system safety. Nano-silica has been associated with improved digestive enzyme activity and enhanced intestinal morphology, contributing to increased nutrient absorption efficiency. However, its effects are dose-dependent, with optimal performance observed at low inclusion levels (1-3 mg/kg feed), while higher concentrations may induce oxidative stress. Additionally, potential release into recirculating water raised concerns regarding environmental accumulation and interactions with microbial biofilms [43], [47].

3.2.3 Carboxymethyl cellulose (CMC)

The use of carboxymethyl cellulose as a hydrocolloid binder significantly adds to the cohesiveness and water stability of pellets by forming polymeric networks when hydrated. When used in aquaculture feed, the class of hydrocolloid binder (including CMC) can help maintain the water stability of a pelleted diet and has been shown to provide a feeding response to tilapia based on inclusion levels and processing conditions [48]. In extruded tilapia diets, CMC has been evaluated at 4 g/kg (0.4%), demonstrating its ability to serve as a point of reference for other binders used in modern Tilapia pellets [49]. When CMC is used with other binders such as molasses and bentonite, the binder effects of all binders appear to exhibit synergistic effects when combined; this provides practical benefits for minimizing fines and nutrient loss through leaching from pelleted diets in recirculating systems [50].

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3.2.4 Molasses

Molasses is utilized as both a pelleting aid and an enhancer of palatability. This product aids adherence of particles during conditioning, while crystallized sugar solidifies pellets when drying. Increased palatability enhances consistency of feed consumption and decreases the number of rejected feeds, therefore reducing lost nutrients. In 50 g of molasses per 1000 g of feed (5%) can improve pelleting processes and quality of pellets [51].

3.2.5 Banana peel

The 20 g banana peel per 1000 g feed (2%) with the integration of agro-byproducts. The stronger tilapia evidence shows that molasses fermented banana peel replaces fishmeal up to 50% without negatively affecting growth performance [52]. This supports two defensible statements in a review: (1) banana peel fermented is a feasible ingredient stream for tilapia feeds, and (2) low inclusion levels of 2% are conservative and destabilize performance, while still supporting bioeconomy framing [53].

3.2.6 Amino acid

The 4 g amino acid mix per 1000 g feed (0.4%) with the engineering goal of improving protein utilization, since amino acid imbalance increases deamination and nitrogen excretion. An updated comprehensive review of Nile tilapia amino acid requirements provides the appropriate nutritional basis for amino acid correction strategies, emphasizing that requirements remain a common source of protein utilization [54]. In an aquaponic mass balance, improved amino acids increase nitrogen retention in fish biomass, reducing the nitrogen source that becomes TAN and thereby lowering biofilter loading. Amino acid supplementation in tilapia diets is calibrated to the essential requirements based on fish size and growth stage, with supplemental crystalline amino acids that contain 0.1-1 % of the diet based on the protein quality and ingredient composition, as recommended in nutritional requirements [55].

3.2.7 Commercial feed base

Keeping a commercial feed base (Figure 2) constant while adding small fractions of binder ingredients in a consistent performance stability approach, the base feeds anchor protein, lipids, vitamins, and mineral adequacy, while the added component, pellet stability, and nutrient utilization efficiency [44]. Protein-rich fish feed is the primary source of nitrogen in aquaponics systems, as it is then converted to nitrate NO_3 from ammonia NH_3, with plants then assimilating the nitrogen [27]. Nutrition and feeding rates of fish are crucial in generating a controlled amount of waste from fish, controlling how nutrients in aquaponics are accumulated and assimilated into plants, showing that feed development influences how much nitrogen is available and waste produced [54]. Further studies on the flow of nitrogen through crops and tilapia prove there is a direct relationship between how fish feed is used and nitrogen use efficiency downstream [56]. Aquaponics performance and nitrogen recovery are influenced by both biological and technological analyses of fish use systems [57].

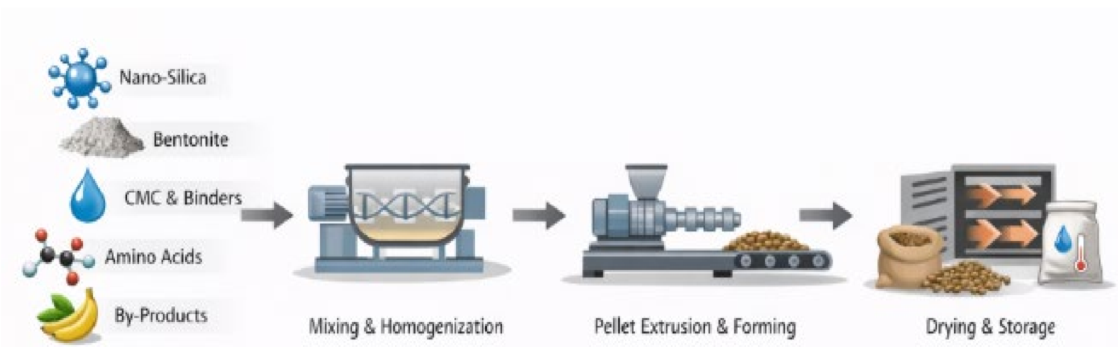

Figure 2. Feed formulation and processing workflow for nano-enhanced aquaponic feeds.

4 Nanotechnology in Nutrient Cycling and Biofiltration

Nanotechnology introduces materials-engineering strategies that enhance microbial attachment, adsorption capacity, and catalytic efficiency within aquaponic biofiltration units. Unlike conventional plastic media, nanostructured substrates increase reactive surface area and modify interfacial properties, directly influencing nitrification kinetics and nutrient capture efficiency (Figure 3). Nitrification within the aquaponic biofilter

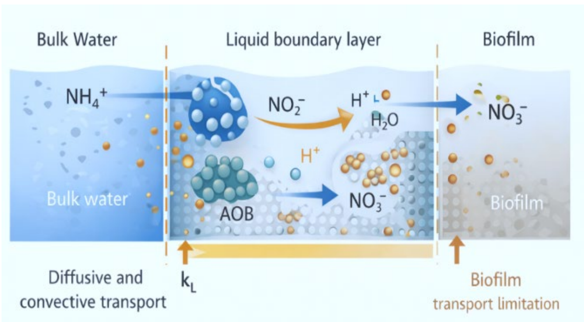

Figure 3. Nitrogen transformation in aquaponic biofilters.

4.1 *Nano-enhanced biofilter media*

An aquaponics system's overall performance depends on how well biofilters provide effective surface area, stable biofilm structure, and efficient diffusion of substrates and transfer of oxygen [58]. Although conventional plastic carriers provide a structural base for nitrifying bacteria to accomplish molecular mass transfer across the biofilm interface, the large interfacial area and high mass transfer resistances limit the total performance of these conventional carriers as biofilters [59]. Conversely, nanostructured materials alter the limiting characteristics of conventional substrates by increasing their surface roughness, increasing the adsorption capacity of the substrate, and improving the efficiency of microbial attachment to the substrate [60]. Conventional biofilter carriers in aquaponics are limited not only by total geometric surface area but also by transport phenomena occurring at the biofilm–water interface. Boundary-layer resistance can slow substrate transport from bulk water to nitrifying biofilms, while oxygen diffusion constraints become more pronounced as biofilm thickness increases or when flow distribution is uneven. Short-circuiting, stagnant zones, and insufficient turbulence can therefore reduce effective nitrification even when nominal surface area appears adequate. From an engineering standpoint, nanostructured or roughened surfaces are of interest because they may alter wettability, interfacial area, sorption behavior, and early-stage microbial attachment. However, these potential benefits should be separated from proven aquaponic outcomes; evidence from related biofilm systems suggests plausible mechanisms, but direct long-term aquaponic validation remains limited [61]. Nanostructured materials address these challenges by increasing specific surface area, enhancing microbial attachment, and reducing diffusion resistance. As a result, nano-enhanced media can improve nitrification kinetics and overall biofilter performance.

4.1.1 Nanostructured zeolites

Nanostructured or modified zeolites may contribute to aquaponic water treatment through two distinct mechanisms that should not be conflated. First, zeolites can remove ammonium through physicochemical ion exchange, thereby temporarily lowering dissolved TAN. Second, when used as biofilter support media, they may also provide a colonization surface for nitrifying microorganisms, enabling biological oxidation of ammonia to nitrate under aerobic conditions. These are complementary but different processes: ion exchange provides immediate ammonium buffering, whereas nitrification converts TAN into a more plant-available and less toxic nitrogen form. Ammonium sorption should therefore be treated as a buffering or capture function, not as nitrification itself. The properties of specific zeolite examples include substantial cation exchange capacity (CEC) and a strong affinity for ammonium. Multiple ways to extract ammonium, in addition to biological oxidation processes, take place simultaneously within the biofilter system of the zeolite substrate. The use of modified zeolites and nanomaterials can also enhance rates of ammonium removal from aqueous and wastewater matrices through the addition of specific surface area and sorption kinetics onto a zeolite material [62]. Within recirculating aquaculture systems (RAS), zeolite within the system has been effective at providing buffering capacity for ammonia inundation events, maintaining nitrification activity during periods of fluctuating loading to the treatment facility, and providing protective equipment for nitrifying species against the effects of inhibitory substances arising from transient incidents.

4.1.2 Graphene media

Carbon nanomaterials and graphene oxide (GO) have a specific surface area of about 1000 $m^2.g^{-1}$, and good surface chemistry characteristics to adhere to microbial [63]. In biofilm reactor experiments, different substrates that had been modified with graphene proved to accelerate biofilm formation and stimulate microbial activity in the biofilms that were formed [64]. The resultant improved interfacial properties and higher rates of electron transfer between the substrate and the microbes may help to increase nitrifier colonisation density and thus potentially increase the maximum effective nitrification rate. Even though their use is still maturing in aquaponics, wastewater biofilms have demonstrated that they are functionally significant in nitrogen removal systems [65].

4.1.3 Nano-silica substrates

Silica biofilm carriers and other engineered surfaces have been shown to enhance microbial attachment and improve nitrogen removal efficiency in biofilm reactors. The surface roughness, wettability, and physicochemical modifications influence the initial adhesion and subsequent biofilm development, which are determinants of reactor performance in moving bed biofilm systems [66]. Increased roughness and hydrophilicity promote stable biofilm formation and higher biomass retention, facilitating sustained nitrification and nitrogen transformation capacity under varied loading conditions, as demonstrated by systematic analyses of carrier surface properties showing the significant role of wettability and micro-texture in microbial adhesion and biofilm development in engineered biofilm systems [67].

4.2 *Catalytic nanomaterials for nutrient capture*

Magnetic iron oxide nanoparticles exhibit strong phosphate adsorption capacity through a ligand exchange mechanism. Phosphorus removal and recovery using iron oxide nanomaterials is well documented in wastewater systems. Integration into aquaponic loops offers potential for selective phosphorus capture and reintroduction into hydroponic subsystems [68].

Magnetic nanoparticles enable rapid nutrient and contamination separation using external magnetic fields due to high magnetic responsiveness and surface adsorption capacity. This facilitates controlled nutrients without interrupting recirculation flow for efficient pollutant capture and recovery. The strong magnetic responsiveness of magnetic nanomaterials facilitates the efficiency of aquaponic recirculation [69]. Catalytic and adsorptive nanomaterials provide a potential extension of aquaponic nutrient recovery beyond nitrification by targeting phosphorus and micronutrient capture. However, their application in aquaponics remains largely inferential from wastewater and nutrient-recovery studies [70]; therefore, future work should evaluate recovery efficiency, regeneration capacity, nanoparticle stability, and long-term compatibility with fish, plants, and biofilter microorganisms in recirculating systems.

5 Nanofertilizers in the Plant Component of the Aquaponic System

The productivity of aquaponic plants is correlated to nitrification and nutrient efficiency during uptake from fish wastes. Nitrate will not limit productivity in aquaponics systems when balanced aquaponics are maintained, but iron (Fe), potassium (K), and calcium (Ca), in addition to micronutrient deficiencies, will limit plant growth, such as in lettuce production systems. A water-research review on iron management and supplementation in aquaponics suggests that when there is not enough Fe present, it limits the ability of aquaponics growers to effectively manage the systems because the amount of Fe available is dependent upon the source, along with the conditions associated with the iron chelation, and the pH level of the aquaponics system. The material science strategy developed within the nanofertilizer products enables aquaponics operational efficiencies related to nutrient delivery efficiencies, nutrient uptake kinetics, and nutrient stability when used with recirculating aquaponics systems. Although aquaponic water can supply substantial nitrogen, plant productivity in coupled systems is often constrained by deficiencies in iron, potassium, and some micronutrients rather than by nitrate alone. This is particularly important when evaluating nanotechnology in the plant unit, because the potential role of nanofertilizers in aquaponics is not to replace the fish-derived nutrient stream, but to correct release mismatches and micronutrient bottlenecks within recirculating conditions.

Recent aquaponic evidence supports the importance of targeted micronutrient management: in a media-bed aquaponic system, chelated iron supplementation of 1–2 mg.L^{-1} for every 20 days, improved lettuce performance and increased nitrogen utilization efficiency, with the highest reported nitrogen utilization rate reaching 33.95% compared with 28.61% in the unsupplemented control. More broadly, recent reviews on slow- and controlled-release nanofertilizers show that nano-enabled formulations can reduce nutrient leaching, prolong nutrient availability, and improve nutrient-use efficiency compared with conventional soluble fertilizers. Nevertheless, direct aquaponic studies on nanofertilizers remain scarce; thus, their potential in aquaponics should be framed as a targeted micronutrient-delivery strategy requiring validation for crop response, residual accumulation, and compatibility with fish and microbial communities [71].

5.1 *Nano-NPK systems*

Conventional soluble nutrient supplementation in aquaponic plant units is not synchronized with plant demand, in a recirculating system where nutrient residence time is constrained by hydraulic turnover. Controlled-release nano-NPK systems are designed to moderate this mismatch by slowing nutrient dissolution and extending nutrient availability through nano-structured [72]. Recent reviews on slow and controlled-release nanofertilizers emphasize that these systems can improve nutrient use (NUE) by reducing leaching losses and delivering nutrients in a more sustained manner than conventional formulations [73]. The release behavior of nano-enabled fertilizers is commonly approximated using first-order kinetics [74].

$$\frac{dM}{dt} = -k_r M \quad (6)$$

Where:

M = mass remaining in the carrier
k_r= released constant

6 System Performance Optimization with Nano-Enhanced Feed Pellets

System performance optimization in aquaponic systems has long been established as a multifaceted challenge involving integration of aquaculture engineering and plant science, along with a microbial ecology component [75]. Unlike traditional production methods, aquaponics functions as a tightly integrated, recirculatory system where inputs supply nutrients via the fish to drive growth of both the fish and plants and to provide for the system's water processing needs. Optimizing these systems is not a matter of maximizing any one aspect of the system but managing the trade-offs between the overall productivity of the system, stability of the system, and efficient use of resources throughout the entire system [76].

There has been a continual theme throughout the collective bodies of information indicating that feed inputs are a key factor influencing the overall performance of aquaponic systems. Those who have studied the aquaponic systems have pointed out that the feed inputs control the amount of nutrients deposited into the plant and create the overall carrying capacity of the system for fish [77]. The Southern Regional Aquaculture Center recommends feed inputs be properly managed because improper management of feed inputs can lead to underfeeding the growing plants and creating nutrient limitation, while overfeeding leads to excess organic material and a spike in ammonia levels within the system [78]. Assessments of commercial aquaponic systems have further shown that the feeding cost and feed conversion rate are the two primary factors driving productivity and profit.

As a result of these factors, there is a real need for very precise feed management methods to address these problems. Nanotechnology-based feed additives have emerged as a viable option to enhance nutrient utilization due to the underlying mechanisms of nanotechnology that increase surface area, increase solubility of feed, and provide controlled release properties. In fact, there have been several studies documenting that the use of nano minerals and nano-encapsulated nutrients has resulted in improved digestive efficiency and digestive absorption when added to an aquaculture diet [79]. Furthermore, the use of nano zinc oxide as a supplement in aquaculture diets has proven to enhance growth and immune function by increasing the efficiency of total mineral absorption from the diet by the fish [80]. These new technologies are aimed at reducing the levels of nutrients excreted from aquaculture systems and thus reducing both the organic loading and ammonia production inherent within recirculating systems. By improving feed conversion with nano-enhanced pellets, the nitrogen dynamics of aquaponics will be significantly impacted by both reduced waste and lower ammonia levels, therefore putting less load on the biofilters and resulting in more stable nitrification processes. Efficient nitrification is imperative for converting ammonia to nitrate, which represents the primary form of nitrogen used by plants [81], [82]; therefore, the maintenance of stable microbial populations is essential in maintaining both the nutrients and quality of water in aquaponic systems. Therefore, through the reduction of excess ammonia production by feeding nano-enhanced feeds, microorganisms in the system will benefit indirectly through stabilization and reduction of toxic accumulations. In addition, utilizing nano-encapsulation technologies will result in the released nutrients and various bioactive materials being available to assist in system performance. For example, nano-encapsulated chitosan-based feeds have been shown to increase the absorption of vitamins and phytochemicals, lengthening their physiological availability and enhancing the overall health of fish [83]. Increased fish health will result in reduced susceptibility to diseases and, consequently, decreased mortality rates, and therefore greater stability of total biomass and improved economic performance. Beyond the fish benefits, the productivity of plants will also be positively affected by the changes in the nutrient profile of the fish waste from feeding products that include nano-enhanced pellets.

Aquaponic plants use dissolved nutrients derived from the metabolic processes of the feed. Improved nutrient assimilation efficiency will lead to a higher percentage of nutrients being converted into biological forms than into waste forms [84]. It is believed that feed efficiency contributes to the productivity and profitability of commercial aquaponics; thus, the use of advanced feed formulations may yield financial benefits. However, when high levels of nanoparticle inclusion occur, there exists a potential for both environmental and biological concerns associated with them; therefore, the optimization of the use of nano-enhanced feeds must also keep in mind the possibility of toxic effects and bioaccumulation within beneficial microbial populations. In many aquatic systems, dose-dependent effects have been demonstrated, with beneficial effects occurring at low concentrations and adverse effects occurring as the concentration of nanoparticles increased [85]. Since the water in aquaponics systems is in continuous recirculation and accumulation, if not properly managed, both the nitrifying bacteria and the plant roots in the aquaponics system will suffer from the impact of this accumulation. Aquaponics, the use of nano-enhanced feed pellets in the optimization of aquaponics systems, must also take into consideration the capacity of the system in biofilter size, hydraulic retention times, rates of plant uptake, and energy maximization. Therefore, optimizing the feed efficiency of aquaculture by advanced feed formulations will likely produce similar results for the reduction of waste production from the source [86]. The literature reviewed supports the use of nano-enhanced feed pellets as a means of improving aquaponic systems by enhancing nutrient bioavailability, reducing waste production, stabilizing microbial populations, and improving fish health; however, successful implementation will require careful design of the optimal inclusion rates and long-term assessments of their environmental safety. Future research should focus on comprehensive system assessments that integrate nano-nutrition with hydraulic design, microbial ecology, and plant responses to maximize the benefits of utilizing nanotechnology as a sustainable aquaponics production method.

6.1 *Limitations and system-level constraints*

Despite the reported benefits, several limitations constrain the application of nanotechnology in aquaponics systems. Nanoparticle accumulation in recirculating water may lead to chronic exposure of microbial communities, potentially inhibiting nitrification. Dose-dependent toxicity has been observed, where beneficial effects at low concentrations transition to oxidative stress.

The benefits of nano-enabled interventions in aquaponics must be balanced against biosafety and implementation constraints. In recirculating systems, nanoparticles are not discharged immediately; instead, they may accumulate in water, solids, biofilms, and potentially edible biomass, making long-term exposure more relevant than short single-dose trials. Recent reviews show that engineered nanomaterials can alter aquatic microbial community structure and suppress functions essential to nutrient cycling. Metal nanoparticles such as silver and copper can inhibit enzymatic activities linked to nitrogen transformation, and a recent study reported that 2 mg.L^{-1} AgNPs suppressed nitrification in a biological nitrogen removal system by up to 90%. These findings are especially relevant to aquaponics because biofilter microbiomes are central to TAN conversion and overall system stability [87]. Beyond biological risk, commercialization is also constrained by cost, limited field-scale evidence, and regulatory uncertainty. Recent reviews of nanotechnology in aquaculture note persistent gaps in oversight across food and feed frameworks and recommend Safe-by-Design approaches together with stronger analytical monitoring [88]. Therefore, any engineering assessment of nanotechnology in aquaponics should include not only performance claims but also particle characterization, exposure pathways, microbial compatibility, recirculating-system accumulation, techno-economic feasibility, and regulatory compliance [89].

6.2 *Feasibility of implementation*

The feasibility of applying nanotechnology in aquaponic systems depends on technical performance, economic viability, environmental safety, and operational compatibility. From an engineering perspective, nano-enabled feed additives and nanostructured biofilter media can be integrated into existing systems with minimal infrastructure modification, offering practical advantages in improving system efficiency. Studies have shown that nanotechnology can enhance feed utilization, water quality, and overall aquaculture productivity, thereby reducing nitrogen waste generation and improving nutrient cycling efficiency [90]. These improvements may lower total ammonia nitrogen (TAN) loading and reduce biofilter design requirements, leading to potential cost savings in aeration and system operation [91]. However, economic feasibility remains dependent on the cost of nanoparticle synthesis, formulation, and controlled application, which may limit large-scale adoption. In addition, system design must consider nanoparticle fate and transport, including accumulation in recirculating water and sludge streams [92]. Environmental and regulatory concerns are also critical, as nanoparticle toxicity and ecological risks have been reported in aquaculture systems, particularly at higher concentrations [93]. Therefore, while nanotechnology presents clear technical advantages, its practical implementation in aquaponics requires a balance between performance improvements, cost-effectiveness, and environmental safety.

6.3 *Future research directions*

Future research should focus on advancing nanotechnology applications in aquaponics through integrated experimental, modeling, and system-level approaches [94]. A key priority is the development of quantitative validation frameworks incorporating mass balance and kinetic modeling to evaluate nutrient cycling efficiency under realistic operating conditions. Although recent studies demonstrate improvements in nutrient recovery, microbial processes, and system efficiency, many findings remain derived from controlled or component-level studies rather than fully integrated aquaponic systems [95]. Long-term investigations are needed to assess system stability, nutrient transformation, and microbial interactions within biofilters, particularly in recirculating environments where continuous operation influences microbial community dynamics and nutrient conversion efficiency. Recent reviews emphasize that optimizing nutrient recovery and microbial processes remains a key challenge for achieving stable aquaponic performance. Furthermore, research should explore the coupling between feed inputs, microbial processes, and plant nutrient uptake to ensure system-wide integration. While advances in nanotechnology and smart agriculture have demonstrated improved nutrient delivery and plant productivity, their integration within aquaponic systems is still limited and requires further investigation [96]. Field-scale validation is essential to evaluate operational performance, scalability, and economic feasibility under commercial conditions. Current literature highlights that achieving consistent productivity, economic viability, and system stability remains a major limitation in aquaponics, particularly when transitioning from experimental setups to real-world applications. Therefore, future research should prioritize system-scale validation, long-term performance assessment, and sustainable system design to enable practical and efficient implementation of advanced technologies in aquaponic production systems.

7. *Conclusions*

This review demonstrates that nanotechnology provides a promising engineering approach for enhancing aquaponic system performance through improvements in nutrient cycling efficiency, feed utilization, and system integration. The application of nano-enabled feed formulations, nanostructured biofilter media, and nanofertilizers contributes to measurable gains in nitrogen use efficiency (NUE) by reducing total ammonia nitrogen (TAN) loading, enhancing nitrification kinetics, and improving plant nutrient uptake. However, despite these advantages, the practical implementation of nanotechnology in aquaponics remains constrained by several critical challenges. Key research gaps include the need to understand long-term nanoparticle accumulation in recirculating systems, which may affect water quality and system stability; the interactions between nanoparticles and biofilter microbiomes, particularly their impact on nitrifying bacteria and overall microbial community dynamics; and the lack of field-scale validation and commercialization studies, as most existing evidence is derived from controlled or laboratory-scale experiments. To address these limitations, future research should prioritize the development of quantitative system-level validation frameworks using mass balance and kinetic modeling, long-term environmental and microbial assessments to evaluate nanoparticle fate and ecological impact, integrated studies examining the coupling of feed inputs, microbial processes, and plant uptake within aquaponic systems, and field-scale trials and techno-economic analyses to determine scalability and commercial feasibility. Overall, while nanotechnology holds significant potential to optimize aquaponic systems, its successful application will depend on a balanced approach that integrates engineering performance, environmental safety, and practical implementation.

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Author Contributions

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Conflicts of Interest

The authors declare no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare no AI tool was used in this work.

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