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Biomass-Based Heating Systems for Temperature Regulation in Aquaponic Crop Production: Technologies, Sustainability, and Future Innovations

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ABSTRACT

Aquaponics integrates recirculating aquaculture and hydroponic crop cultivation within a closed-loop production system where fish waste is biologically transformed into plant-available nutrients. Despite its resource-efficiency advantages, temperature regulation remains a major technical constraint because fish, crops, and nitrifying microorganisms require stable thermal conditions for optimum performance. Conventional heating systems based on electricity and fossil fuels often increase production costs and weaken the environmental sustainability of aquaponics. This review critically examined the potential of biomass-based heating systems as renewable alternatives for temperature regulation in aquaponic crop production. The review synthesized evidence on biomass feedstocks, including agricultural residues, forestry by-products, animal wastes, biogas substrates, and dedicated energy crops, together with heating technologies such as biomass boilers, pellet and briquette burners, gasifiers, biogas units, combined heat and power systems, thermal storage, and hybrid biomass-solar configurations. Findings indicate that biomass heating can improve fish growth, crop productivity, nitrification efficiency, and year-round production when properly designed and controlled. Environmental benefits include waste valorization, reduced dependence on fossil fuels, and support for circular food-energy systems. However, outcomes depend strongly on feedstock quality, combustion efficiency, emission control, ash management, and system integration. Economic feasibility varies with capital cost, fuel availability, labor demand, maintenance requirements, and local energy prices. Emerging innovations such as IoT monitoring, AI-based optimization, predictive control, and digital twins offer new opportunities to improve performance and reliability. Major research gaps include limited direct experimental studies, lack of standardized design models, insufficient species-specific data, and policy barriers to adoption. Biomass heating therefore represents a promising pathway toward climate-smart and low-carbon aquaponic production, particularly in regions with abundant organic residues and rising demand for sustainable food systems.

Keywords: Aquaponics, Biomass heating, Temperature regulation, Sustainable agriculture, Renewable energy

INTRODUCTION

Aquaponics is an integrated food production system that combines recirculating aquaculture with hydroponic crop cultivation in a shared water cycle. In this system, fish waste supplies ammonia-rich nutrients, nitrifying bacteria convert ammonia into nitrate, and plants absorb the nitrate and other dissolved nutrients for growth. The process creates a biologically linked production environment in which fish, crops, and microorganisms function as interdependent components of one circular system [1, 2]. FAO describes aquaponics as an integrated fish–plant farming approach built around the nitrogen cycle, bacterial biofiltration, and water reuse. Aquaponic crop production has attracted increasing attention because it can reduce water consumption, limit nutrient discharge, and support food production in areas where arable land, freshwater, and soil fertility are constrained. Compared with conventional soil-based cultivation, aquaponics offers opportunities for controlled production of leafy vegetables,

herbs, and fruiting crops while simultaneously producing fish protein [3, 4]. The system is also relevant to urban agriculture, peri-urban food systems, and climate-smart farming because it allows food production in greenhouses, indoor units, and other controlled environments [2, 5]. Recent reviews continue to identify aquaponics as a promising sustainable food production method that links horticulture and aquaculture through circular nutrient and water flows. Temperature regulation is one of the most critical management requirements in aquaponic crop production because aquaponics depends on the simultaneous performance of fish, plants, and nitrifying microorganisms. Each biological component has an optimum temperature range, and poor thermal control can reduce fish feeding activity, impair plant growth, slow nitrification, and destabilize water quality. Fish metabolism, dissolved oxygen demand, microbial conversion of ammonia, root-zone nutrient uptake, transpiration, and crop development are all influenced by water and air temperature [1, 4].

The nitrification process is especially temperature-sensitive because nitrifying bacteria regulate the conversion of toxic ammonia and nitrite into nitrate, the major nitrogen form used by crops. Reduced nitrification efficiency can lead to ammonia or nitrite accumulation, which may stress fish and reduce system productivity [6, 7]. Recent work on aquaponic temperature regimes confirms that temperature is a key determinant of nitrification efficiency and overall aquaponic stability. Thermal regulation is also important for crop performance. Leafy vegetables such as lettuce, basil, and spinach generally respond strongly to root-zone and greenhouse temperature, while fruiting crops such as tomato, cucumber, and pepper require stable thermal conditions for flowering, fruit set, and biomass accumulation. In climates with cold nights, seasonal variation, or high diurnal temperature fluctuation, heating becomes essential for maintaining year-round productivity. Therefore, reliable and affordable heating technologies are central to the commercial viability of aquaponic crop cultivation.

Limitations of Conventional Heating Systems

Conventional heating systems used in greenhouses and controlled-environment agriculture often rely on electricity, diesel, natural gas, liquefied petroleum gas, or coal [8]. Although these systems can provide rapid and controllable heat, they are associated with high operational costs, dependence on external energy markets, and greenhouse gas emissions. Energy demand becomes especially significant in aquaponics because both water and air temperature may need to be regulated continuously to protect fish health, crop productivity, and microbial activity. Electric heating can be technically convenient but expensive where electricity tariffs are high or supply is unreliable. Fossil-fuel heating may offer high heat output but contributes to carbon emissions and exposes producers to fuel price volatility. These limitations are particularly severe for smallholder farmers, peri-urban producers, and commercial aquaponic enterprises in developing regions, where energy access and affordability can determine whether controlled-environment aquaponics is economically feasible [2]. Commercial aquaponics literature has repeatedly identified operational cost, technical complexity, and energy management as barriers to wider adoption. Another limitation concerns sustainability. Aquaponics is often promoted as a resource-efficient and environmentally responsible production system; however, the use of fossil-derived heat can weaken this sustainability claim. Heating strategies that reduce fossil energy dependence are therefore important for aligning aquaponic production with circular economy, low-carbon agriculture, and climate-resilient food system goals.

Potential of Biomass Heating Technologies

Biomass heating presents a renewable thermal-energy option for aquaponic crop production, particularly in systems that require stable water, root-zone, or greenhouse temperatures. Biomass refers to organic material derived from plants and animals, including crop residues, wood chips, sawdust, rice husks, maize cobs, animal manure, biogas substrates, and dedicated energy crops. These materials can be used directly through combustion or processed into pellets, briquettes, producer gas, or biogas for heat generation [9]. In aquaponic systems, the heat generated from biomass can be transferred through boilers, hydronic pipes, heat exchangers, or thermal storage units to regulate fish tanks, nutrient solutions, plant root zones, and greenhouse air temperatures. The use of biomass heating is especially relevant in agricultural regions where residues are abundant but underutilized. Feedstocks such as rice husks, coffee husks, sawdust, sugarcane bagasse, maize stalks, and pruning residues can serve as locally available energy sources, reducing dependence on fossil fuels and externally supplied electricity [10]. This approach strengthens the circular economy potential of aquaponics because organic residues from farming and agro-processing activities can be converted into useful heat instead of being discarded or openly burned. Biomass energy is therefore compatible with resource-efficient food production systems that seek to integrate waste valorization, renewable energy use, and local food production [2, 9].

Biomass heating may also improve the economic resilience of aquaponic enterprises. Energy demand is one of the major operating costs in controlled-environment agriculture, especially where heating is required during cold seasons or in high-altitude regions. Locally sourced biomass can reduce exposure to electricity shortages, fuel price volatility, and the high cost of conventional heating. This is particularly important for smallholder and commercial aquaponic systems in developing regions, where reliable and affordable energy access remains a major barrier to year-round production [1, 2]. Despite these advantages, biomass heating must be applied with appropriate technical and environmental safeguards. Incomplete combustion can produce carbon monoxide, volatile organic compounds,

particulate matter, nitrogen oxides, and other pollutants, which may affect human health and environmental quality [11, 12]. Poorly designed systems can also create problems related to ash disposal, feedstock moisture, combustion inefficiency, and temperature instability. Therefore, safe and sustainable use of biomass heating in aquaponics requires efficient boiler or burner design, properly dried feedstock, heat exchangers that prevent contamination of aquaponic water, emission-control devices, and reliable temperature-monitoring systems. When these conditions are met, biomass heating can support low-carbon, circular, and climate-resilient aquaponic crop production. Biomass energy can be integrated into aquaponic systems through indirect heating loops and heat exchangers (Figure 1).

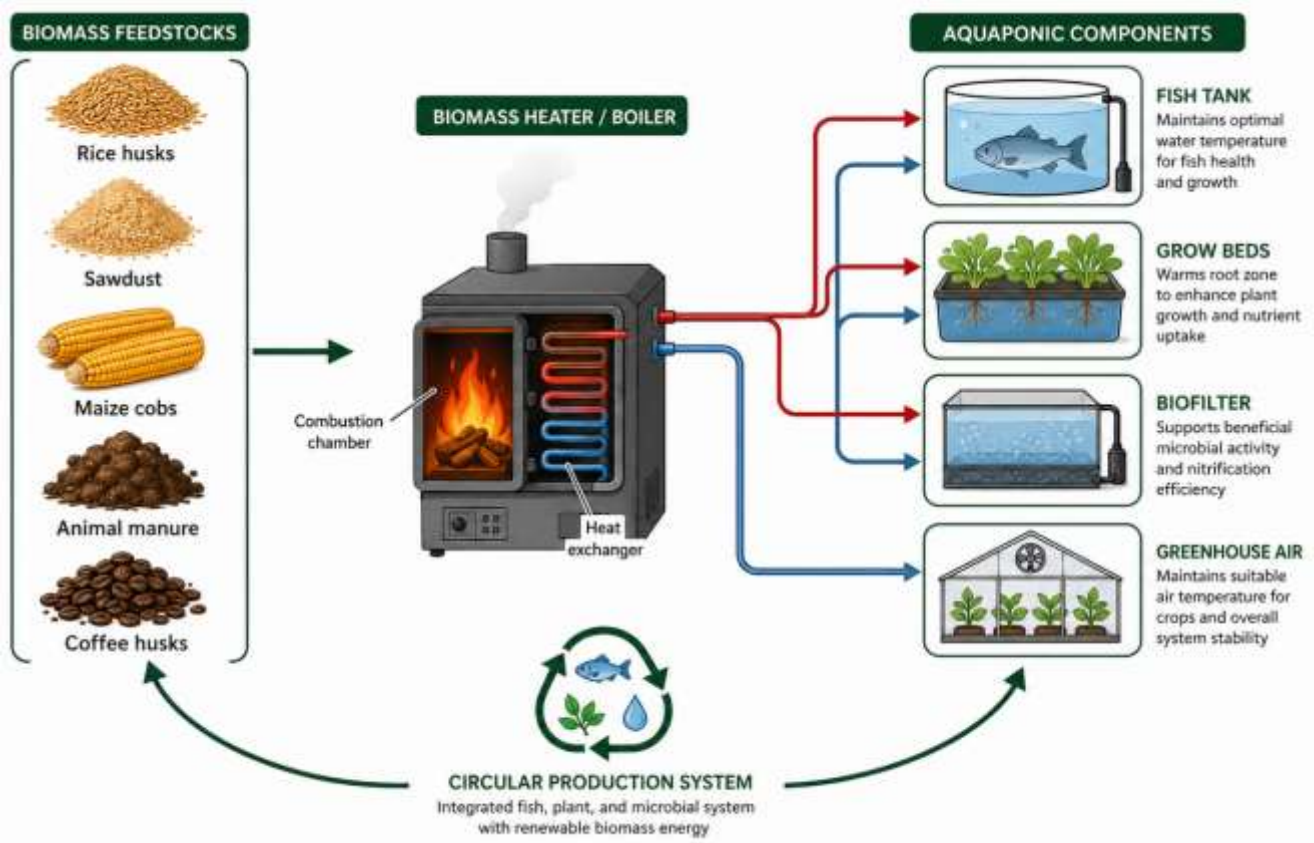

Figure 1: Integrated Aquaponic System with Biomass Heating Pathway
Conceptual integration of biomass feedstocks and heating technologies into aquaponic systems for fish, crop, and microbial temperature regulation. Adapted from [1, 2].

Review Rationale, Novelty, and Contribution

Despite growing interest in aquaponics and renewable energy, limited scholarly attention has been given specifically to biomass-based heating for aquaponic crop cultivation. Existing aquaponic reviews commonly focus on system design, nutrient cycling, water quality, fish–plant compatibility, and commercial challenges [2, 4, 13]. Energy discussions often address solar energy, electricity demand, greenhouse management, or general sustainability, while biomass heating remains insufficiently synthesized as a dedicated thermal regulation strategy. The novelty of this review lies in linking three research areas that are often treated separately: aquaponic crop production, temperature regulation, and biomass energy systems [14]. Such integration is important because thermal instability can reduce aquaponic productivity, while energy cost and sustainability remain major constraints to adoption. A focused review on biomass heating can clarify available technologies, suitable feedstocks, system integration options, environmental implications, economic feasibility, and research gaps. This review contributes to the literature through a critical synthesis of how biomass heating can support temperature-regulated aquaponic crop production. It also highlights the potential of biomass–aquaponics integration in regions with abundant agricultural residues, unreliable electricity, or rising demand for low-carbon food production. The review is expected to support researchers, greenhouse designers, aquaponic practitioners, renewable-energy engineers, and policymakers interested in sustainable food-energy systems.

Aim and Objectives of the Review

The aim of this review is to critically examine the role of biomass-based heating systems in regulating temperature for aquaponic crop production, with emphasis on technology options, sustainability benefits, operational challenges, and future research directions.

The specific objectives are to:

1. examine the importance of temperature regulation for fish, crops, and nitrifying microorganisms in aquaponic systems;
2. identify biomass feedstocks suitable for aquaponic heating applications;
3. evaluate biomass heating technologies, including boilers, gasifiers, briquette burners, pellet systems, biogas heaters, and hybrid systems;
4. assess how biomass heating can be integrated into aquaponic water, root-zone, and greenhouse heating systems;
5. analyze the environmental, economic, and operational implications of biomass heating in aquaponic crop cultivation;
6. identify research gaps and propose future directions for sustainable biomass-heated aquaponic systems.

METHODOLOGY

Review Design and Approach

This review adopted a structured narrative review approach supported by systematic search, screening, and synthesis procedures. The design was selected because the topic combines aquaponic crop production, biomass energy, greenhouse heating, thermal regulation, and sustainability assessment, which are discussed across different disciplinary fields. A structured review approach allows transparent identification, selection, and interpretation of relevant studies while also permitting critical discussion of technological, environmental, and economic issues [15, 16]. Reporting procedures were guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses, commonly known as PRISMA 2020, which provides updated guidance for identifying, selecting, appraising, and synthesizing evidence in review studies (figure 2) [17].

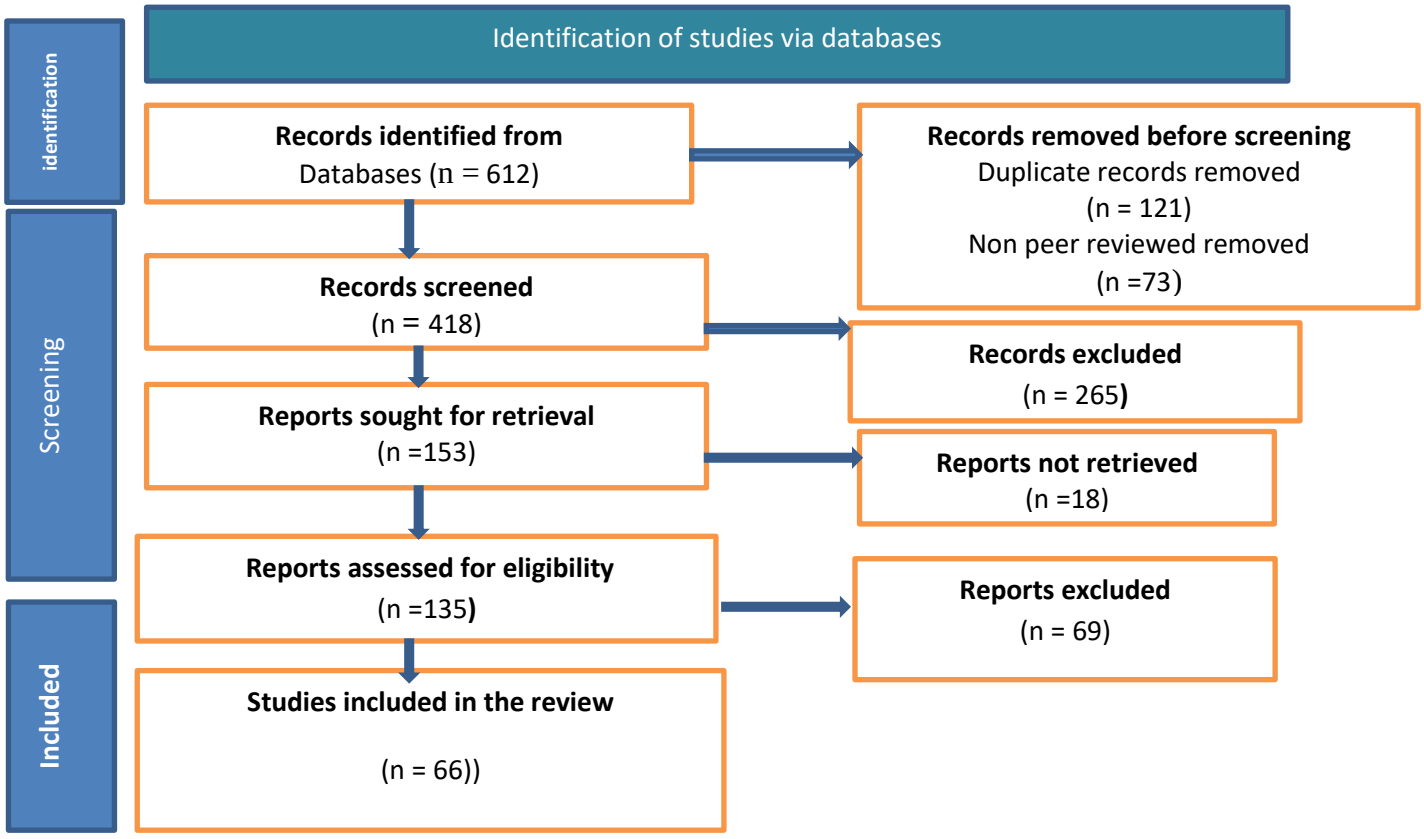

Figure 2: PRISMA

Literature Search Strategy

The literature search was designed to identify peer-reviewed studies, technical reports, and authoritative institutional publications related to biomass heating, aquaponics, crop production, and controlled-environment agriculture. Search terms were developed from four main concepts: aquaponics, biomass energy, heating technologies, and crop cultivation. The search focused on literature that discussed thermal regulation, greenhouse heating, renewable heat systems, fish-plant production, nitrification, energy efficiency, and circular bioeconomy applications. Reference lists of relevant review articles were also checked to identify additional studies not captured during database searching.

Databases Used

Relevant literature was searched from major academic databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, Google Scholar, PubMed, Taylor & Francis Online, MDPI, and Wiley Online Library. Additional materials were obtained from institutional sources such as the Food and Agriculture Organization of the United Nations, the International Energy Agency Bioenergy programme, and national energy agencies. The use of multiple databases was intended to improve coverage across agricultural science, aquaculture, renewable energy, environmental engineering, and sustainability research.

Search Keywords and Boolean Operators

Search strings were developed using Boolean operators to combine related terms. Examples of search combinations included:

aquaponics AND biomass heating, aquaponic system AND temperature regulation, aquaponics AND greenhouse heating, biomass boiler AND greenhouse agriculture, biomass energy AND controlled, environment agriculture, biogas heating AND aquaculture, renewable heat AND aquaponic crop production, thermal regulation AND nitrification AND aquaponics, biomass gasification AND greenhouse heating, circular economy AND aquaponics AND biomass.

Truncation and phrase searching were applied where supported by the database. For example, terms such as "biomass heat*," "aquaponic crop*," "greenhouse thermal regulation," and "renewable heating system*" were used to capture variations in terminology.

Inclusion and Exclusion Criteria

Studies were included when they met at least one of the following criteria: they addressed aquaponic crop production, temperature regulation in aquaponics, biomass-based heating technologies, greenhouse heating, renewable thermal energy, or energy use in controlled-environment agriculture. Peer-reviewed articles, review papers, experimental studies, conference papers, technical reports, and institutional publications were considered eligible when they provided relevant scientific or technical information. Studies were excluded when they were unrelated to aquaponics, crop production, biomass energy, or heating systems. Publications were also excluded when they lacked sufficient methodological detail, were not written in English, duplicated another record, or focused only on unrelated renewable technologies without connection to heating, agriculture, aquaculture, or controlled environments. Opinion pieces, non-scientific webpages, and publications without identifiable authorship or institutional credibility were not prioritized.

Screening and Selection of Articles

The screening process followed three stages. First, duplicate records were removed. Second, titles and abstracts were examined to determine relevance to biomass heating, aquaponics, crop cultivation, temperature regulation, and sustainability. Third, full-text articles were reviewed to confirm eligibility and extract relevant information. The screening logic was aligned with PRISMA 2020 principles, which emphasize transparent reporting of record identification, screening, eligibility assessment, and final inclusion [17].

Data Extraction Procedure

Data were extracted using a structured matrix. The extracted information included author names, year of publication, study location, research design, aquaponic system type, crop species, fish species, biomass feedstock, heating technology, temperature range, energy performance, crop yield response, fish performance, environmental outcomes, economic findings, and major limitations. For review and policy documents, information was extracted on technology classification, sustainability implications, adoption barriers, and future research needs.

Quality Assessment of Selected Studies

The quality of selected studies was assessed using criteria adapted from established review and appraisal frameworks. Experimental studies were evaluated according to clarity of objectives, system description, sampling design, measurement reliability, data analysis, and relevance to aquaponic heating. Review papers were assessed according to search transparency, scope, synthesis quality, and strength of conclusions. Mixed-method and interdisciplinary studies were assessed using principles consistent with the Mixed Methods Appraisal Tool, which is widely used for evaluating qualitative, quantitative, and mixed-method studies [18]. Methodological transparency and

reproducibility were also considered important quality indicators, consistent with systematic review guidance [15, 17].

Data Synthesis and Thematic Analysis

The extracted literature was synthesized thematically rather than statistically because the available studies differ in design, scale, feedstock type, technology configuration, crop species, fish species, and performance indicators. The synthesis focused on six main themes: temperature requirements in aquaponics, biomass feedstock availability, biomass heating technologies, integration of heating systems into aquaponics, sustainability implications, and techno-economic feasibility. This approach allowed comparison of evidence across disciplines and supported identification of research gaps, technological constraints, and future development pathways [16].

Limitations of the Review Methodology

The methodology has several limitations. First, direct studies on biomass-heated aquaponic systems remain limited, so evidence from greenhouse heating, aquaculture heating, biomass energy, and controlled-environment agriculture was used where directly relevant. Second, differences in system scale, climate, fish species, crop type, heating technology, and feedstock quality limited direct comparison among studies. Third, some technical reports and institutional publications may not have undergone peer review, although they were included when they provided authoritative information. Fourth, the exclusion of non-English publications may have omitted relevant regional studies. These limitations indicate the need for more experimental and long-term studies on biomass heating specifically designed for aquaponic crop production.

Fundamentals of Temperature Management in Aquaponics

Thermal Requirements of Aquaponic Systems

Temperature management is a central requirement in aquaponics because the system depends on the simultaneous performance of fish, crops, and nitrifying microorganisms. Aquaponics operates as a biologically integrated production unit in which fish release metabolic waste, nitrifying bacteria convert ammonia into plant-available nitrate, and crops absorb nutrients from the recirculating water. Temperature affects each of these processes directly, making thermal regulation essential for biological stability, nutrient conversion, fish welfare, and crop productivity [1, 2]. Aquaponic systems require a balanced temperature range rather than a temperature optimized for only one organism. Fish generally determine the water-temperature requirement, crops are influenced by both root-zone and air temperature, and nitrifying bacteria require conditions that support ammonia and nitrite oxidation. Poor temperature control can reduce fish feeding, slow microbial activity, decrease nutrient uptake, lower dissolved oxygen availability, and increase the risk of system imbalance [1, 6]. Temperature stability is therefore more important in aquaponics than in single-component hydroponic or aquaculture systems because thermal stress in one component can affect the entire production chain. Optimum thermal ranges differ among aquaponic organisms and crops (Table 1).

Table 1: Temperature Requirements of Major Aquaponic Components

Component	Recommended Temperature Range (°C)	Effect of Low Temperature	Effect of High Temperature	Reference
Nile tilapia	25–30	Reduced growth, low feeding	Stress, oxygen depletion	[1]
Lettuce	18–24	Slow growth	Bolting, bitterness	[4]
Tomato	20–26	Poor flowering	Fruit abortion	[4]
Nitrifying bacteria	25–30	Reduced nitrification	Oxygen limitation	[6]

Temperature Requirements of Fish Species

Fish are poikilothermic organisms, meaning their body temperature and metabolic activity depends strongly on the surrounding water temperature. Water temperature influences feed intake, digestion, growth rate, immune response, oxygen demand, and survival. Warm-water species such as Nile tilapia generally perform well at higher temperatures, while cool-water species such as trout require lower temperatures and higher dissolved oxygen concentrations [1]. Species selection must therefore match the intended crop type, local climate, and available heating or cooling capacity. Tilapia is widely used in aquaponics because it tolerates a relatively broad range of water-quality conditions and grows efficiently in warm water. However, low temperatures can suppress tilapia feeding, slow growth, and increase susceptibility to stress. In contrast, cold-water fish such as trout may be unsuitable for warm greenhouse aquaponics unless cooling systems are available. This creates a design challenge because the ideal temperature for fish may not always match the optimum temperature for plants or bacteria. Effective aquaponic management therefore requires compromise temperature ranges that support acceptable performance across all biological components [1, 19].

Temperature Requirements of Crops

Crop temperature requirements in aquaponics depend on plant species, growth stage, root-zone conditions, and greenhouse climate. Leafy vegetables such as lettuce, basil, spinach, and leafy brassicas are commonly grown because they have relatively short production cycles and moderate nutrient requirements. Fruiting crops such as tomato, cucumber, eggplant, and pepper generally require greater nutrient availability, more stable environmental control, and longer production periods [4]. Temperature affects seed germination, root development, nutrient uptake, photosynthesis, transpiration, flowering, fruit setting, and final yield. Low temperatures can slow plant growth and nutrient absorption, while excessive temperatures can cause physiological stress, leaf tip burn, bolting in leafy vegetables, flower abortion, and reduced crop quality. Root-zone temperature is especially important in aquaponics because plants absorb nutrients from recirculating water rather than soil. Thermal instability in the nutrient solution can therefore reduce nutrient uptake efficiency and weaken crop performance even when air temperature appears suitable [4, 1].

Temperature Effects on Nitrifying Bacteria

Nitrifying bacteria are responsible for converting ammonia excreted by fish into nitrite and then nitrate, which is the primary nitrogen form absorbed by plants. This biological filtration process is temperature-sensitive and is essential for preventing ammonia and nitrite toxicity in fish tanks. The main nitrifying groups include ammonia-oxidizing bacteria and nitrite-oxidizing bacteria, both of which require suitable temperature, dissolved oxygen, alkalinity, and pH conditions to function effectively [1]. Nitrification generally increases as temperature rises within a suitable biological range, although the response depends on biofilter type, dissolved oxygen, ammonia concentration, and microbial community structure. Zhu and Chen [6], reported that temperature influenced nitrification rates in fixed-film biofilters and that the effect varied under oxygen-limited and total ammonia nitrogen-limited conditions. Recent aquaponic studies also indicate that nitrifying bacteria commonly perform best within moderate warm-water ranges, while low temperatures reduce ammonia conversion and high temperatures can inhibit microbial activity [6, 7]. As a result, temperature management is necessary not only for crop and fish growth but also for maintaining stable biofiltration.

Thermal Stress and System Productivity

Thermal stress reduces aquaponic productivity through several interconnected mechanisms. In fish, suboptimal temperatures can reduce appetite, slow growth, increase feed conversion ratio, weaken immunity, and raise mortality risk. In plants, thermal stress can reduce photosynthetic efficiency, nutrient uptake, biomass accumulation, marketable yield, and produce quality. In biofilters, low or fluctuating temperatures can reduce nitrification efficiency, leading to ammonia or nitrite accumulation and poor water quality [1, 6]. Temperature also affects dissolved oxygen. Warmer water holds less oxygen, while fish and microorganisms require more oxygen as metabolic activity increases. This imbalance can create oxygen stress during warm periods, particularly in densely stocked systems. Cold conditions, on the other hand, may suppress microbial conversion and plant uptake, causing nutrient accumulation or imbalance. Stable temperature management therefore improves system productivity by supporting fish growth, crop development, microbial activity, and water-quality control at the same time. Temperature influences fish metabolism, plant growth, and nitrification simultaneously (Figure 3).

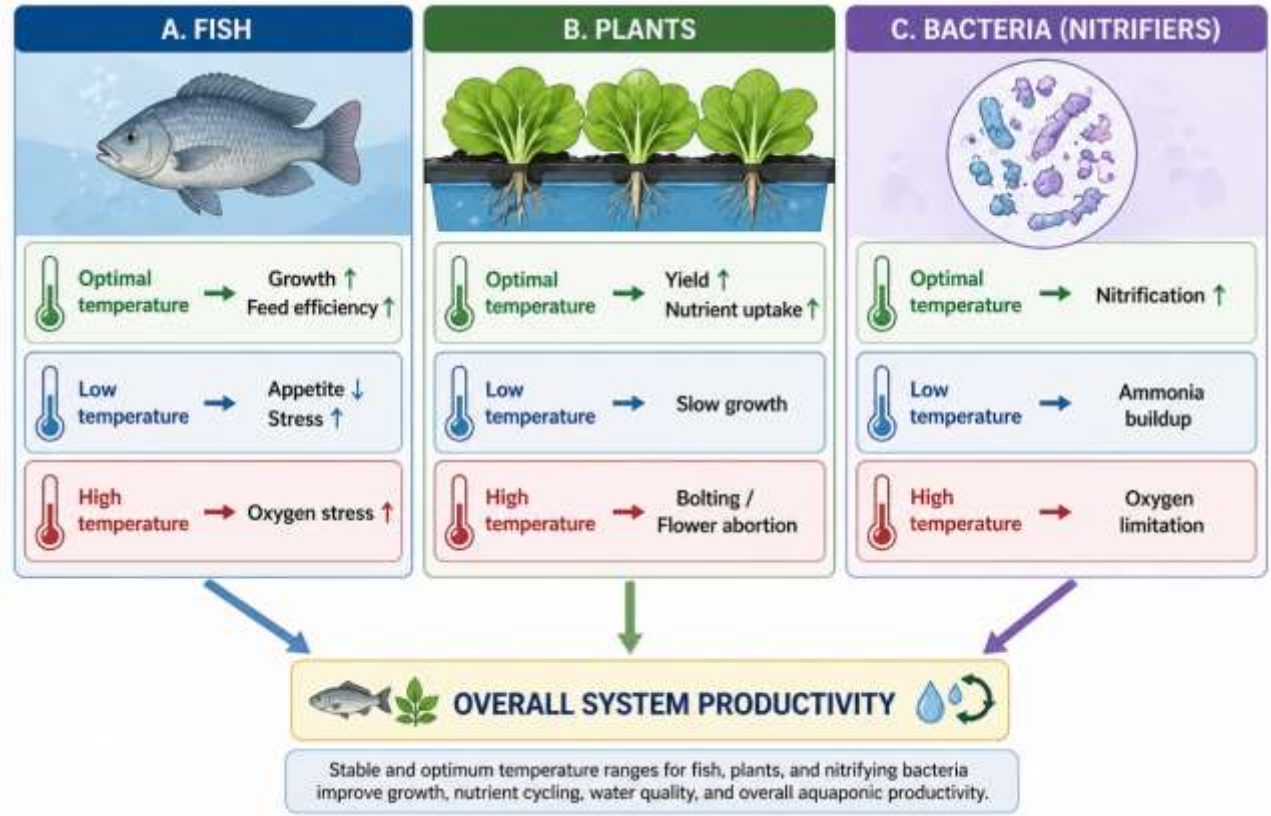

Figure 3: Effects of Temperature on Aquaponic Biological Components
Biological responses of fish, plants, and nitrifying bacteria to temperature variation in aquaponic systems. Based on [6, 1, 4].

Seasonal and Climatic Constraints

Seasonal and climatic variation strongly influences aquaponic performance, especially in greenhouse, outdoor, or low-cost systems. Cold nights, rainy seasons, winter periods, high-altitude conditions, and large day-night temperature differences can reduce water temperature below the preferred range for warm-water fish and nitrifying bacteria. In such cases, heating becomes necessary to maintain fish welfare, nitrification efficiency, and crop production. Conversely, hot climates may require shading, ventilation, evaporative cooling, or crop and fish species adapted to high temperatures [1, 2]. Seasonal thermal instability also affects economic performance. Reduced growth during cold periods can extend production cycles, increase feed and labor costs, and reduce market supply consistency. Reliable heating systems are therefore important for year-round aquaponic production, particularly in commercial systems that require stable harvest schedules. Biomass heating can be relevant in this context because it offers a renewable heat source that may be locally available in agricultural regions with abundant crop residues and organic wastes.

Biomass Energy Resources for Aquaponic Heating

Definition and Classification of Biomass

Biomass refers to renewable organic material derived from plants, animals, and biological wastes that can be converted into useful energy. It includes agricultural residues, forest residues, wood-processing wastes, animal manure, food-processing residues, municipal organic wastes, and dedicated energy crops (U.S. Energy Information Administration [EIA], 2024; Food and Agriculture Organization of the United Nations [FAO], 2024). Biomass can be burned directly to produce heat or converted into solid, liquid, or gaseous fuels such as pellets, briquettes, bio-oil, producer gas, and biogas [17]. For aquaponic heating, biomass resources can be classified into four major categories: agricultural residues, forestry and wood-based biomass, animal waste and biogas substrates, and dedicated energy crops. Solid biomass such as rice husks, maize cobs, sawdust, wood chips, coffee husks, and sugarcane bagasse can be used in boilers, gasifiers, or briquette-burning systems. Wet biomass such as manure and food-processing wastes is more suitable for anaerobic digestion, which produces biogas for heat generation [20, 21]. This classification is important because feedstock type influences heating value, moisture content, ash production,

combustion efficiency, storage requirements, and suitability for aquaponic thermal regulation. Multiple agricultural and agro-industrial residues can serve as heating fuels (Table 2).

Table 2: Biomass Feedstocks Suitable for Aquaponic Heating

Feedstock	Source	Heating Use	Advantages	Limitation	Reference
Rice husks	Rice mills	Boiler fuel	Abundant	High ash	[20]
Sawdust	Sawmills	Pellets, burners	High calorific value	Dust handling	[11]
Maize cobs	Farms	Direct combustion	Low cost	Seasonal supply	[21]
Animal manure	Livestock farms	Biogas	Waste management	Digester needed	[22]
Coffee husks	Agro-processing	Briquettes	Local residue	Variable moisture	[20]

Agricultural Residues

Agricultural residues are among the most promising biomass resources for aquaponic heating because they are widely produced in farming regions and are often underutilized. Common examples include rice husks, maize stalks, maize cobs, wheat straw, coffee husks, groundnut shells, cotton stalks, sugarcane bagasse, and pruning residues. These materials can be converted into heat through direct combustion, gasification, pelletization, or briquetting [20, 21]. The use of agricultural residues in aquaponic heating can support waste valorization and reduce dependence on fossil fuels. FAO [20] identifies crop residues and manure as important resources for sustainable bioenergy development in agrifood systems. IRENA [21] also emphasizes that agricultural residues can contribute to renewable energy supply when collection, processing, and use are managed sustainably. In aquaponics, these residues can provide heat for fish tanks, nutrient solution, root zones, or greenhouse air through heat exchangers and hot-water circulation systems. However, agricultural residues differ considerably in fuel quality. Moisture content, ash content, particle size, bulk density, and calorific value affect combustion performance and heat output. Rice husks, for example, may have high ash and silica content, which can increase slagging and ash-handling problems. Proper drying, size reduction, densification, and combustion-system design are therefore necessary to achieve stable and efficient heating.

Forestry and Wood-Based Biomass

Forestry and wood-based biomass includes firewood, wood chips, sawdust, bark, branches, thinning residues, logging residues, and sawmill offcuts. These materials are widely used for thermal energy because properly dried wood generally has good combustion properties and can be handled more easily than many loose agricultural residues. Wood-based biomass can be used in biomass boilers, pellet burners, gasifiers, and hydronic heating systems for greenhouse and water heating. Sawmill residues are particularly useful where timber-processing industries generate large quantities of sawdust, bark, and offcuts. These residues can be converted into pellets or briquettes to improve bulk density, storage efficiency, transport, and combustion control. IEA Bioenergy [11] notes that biomass pre-treatment, including densification, can improve the quality and logistics of solid biomass supply chains. In aquaponic systems, such fuel upgrading is valuable because temperature stability is required to protect fish, crops, and nitrifying bacteria. Sustainable sourcing remains essential. Excessive removal of forest residues can reduce soil organic matter, nutrient cycling, biodiversity, and long-term forest productivity. Wood-based biomass should therefore be sourced from managed forests, sawmill by-products, pruning residues, or legally approved waste streams rather than from unsustainable fuelwood extraction [20, 11].

Animal Waste and Biogas Sources

Animal manure and other wet organic wastes can be converted into biogas through anaerobic digestion. Biogas consists mainly of methane and carbon dioxide and can be burned to generate heat for aquaponic systems. Suitable substrates include cattle manure, pig manure, poultry litter, fish-processing wastes, kitchen wastes, and agro-industrial organic residues [20, 21]. Biogas heating is relevant to aquaponics because it can provide a cleaner and more controllable heat source than raw solid biomass combustion. It also supports waste management by converting manure and organic wastes into useful energy while producing digestate that may be used as fertilizer outside the aquaponic water loop after appropriate treatment. Seglah *et al.* [22] reported that animal manure can support sustainable biofuel production when properly managed. Direct contact between biogas digestate and aquaponic water should be avoided unless strict treatment and safety controls are applied. Digestate may contain pathogens, high ammonia concentrations, salts, suspended solids, and organic matter that can disturb fish health and water quality. A safer approach is to use biogas only as a thermal-energy source, transferring heat through boilers, heat exchangers, or closed hot-water loops.

Energy Crops and Dedicated Biomass Feedstocks

Dedicated energy crops are plants cultivated specifically for bioenergy production. Examples include elephant grass, switchgrass, miscanthus, short-rotation willow, eucalyptus, bamboo, and other fast-growing grasses or woody crops. These feedstocks can provide a planned and relatively predictable biomass supply for farms that require regular

heating. Energy crops may be useful for larger aquaponic enterprises, especially where agricultural residues are seasonal or insufficient. However, their sustainability depends on land availability, water demand, fertilizer use, biodiversity impacts, and competition with food production. FAO [20] emphasizes that bioenergy development should be assessed in relation to food security, land use, and environmental sustainability. For this reason, dedicated biomass production is most suitable where marginal land, degraded land, agroforestry systems, or integrated farm planning can support biomass supply without reducing food-crop production.

Feedstock Availability, Storage, and Pre-Treatment

Reliable biomass heating depends on consistent feedstock availability, stable fuel quality, and proper storage. Biomass supply varies with cropping seasons, harvest periods, transport distance, competing uses, labor availability, and market demand. Poor storage can increase moisture content, reduce calorific value, promote fungal growth, and cause dry-matter losses. IEA Bioenergy [11] identifies dry-matter loss and moisture variation as major concerns during biomass storage. Pre-treatment improves biomass fuel performance and may include drying, chopping, grinding, screening, pelletizing, briquetting, torrefaction, and leaching. Drying improves combustion efficiency, while pelletizing and briquetting increase bulk density and make fuel handling easier. IEA Bioenergy [11] reports that biomass pre-treatment can improve supply-chain efficiency and fuel quality for thermochemical conversion. In aquaponic heating, pre-treatment is particularly important because unstable heat production can expose fish, crops, and nitrifying bacteria to harmful temperature fluctuations.

Biomass Energy Potential in Developing Regions

Developing regions have strong potential for biomass-based aquaponic heating because agricultural residues, livestock wastes, forestry by-products, and agro-processing residues are often abundant. Many of these materials are discarded, openly burned, or left to decompose, resulting in lost energy value and environmental pollution. FAO [20] highlights the potential of residues from agrifood systems, including manure, crop residues, forest-management residues, food-processing wastes, and municipal organic wastes, for sustainable bioenergy production. Biomass heating can improve aquaponic viability in developing regions by reducing dependence on unreliable electricity, imported fuels, and expensive conventional heating systems. It can also support rural employment, local energy security, circular economy development, and climate-smart food production. IRENA [21] notes that agricultural residues can contribute to renewable energy expansion when supported by appropriate collection systems, technology choices, and sustainability safeguards. Several constraints must be addressed before biomass heating can be widely adopted in aquaponics. These include inefficient combustion technologies, limited technical skills, feedstock seasonality, poor storage infrastructure, air-pollution risks, weak policy support, and high initial investment costs. Sustainable biomass-heated aquaponics therefore requires careful matching of local feedstock resources with efficient heating technologies, emission-control systems, training, and supportive energy-agriculture policies.

Biomass Heating Technologies for Aquaponic Systems

Biomass Boilers

Biomass boilers are among the most practical technologies for supplying heat to aquaponic systems because they convert solid biomass into hot water or steam that can be circulated through heat exchangers, pipes, or greenhouse heating loops. Suitable fuels include wood chips, pellets, briquettes, sawdust, rice husks, maize cobs, coffee husks, and other agricultural residues. In aquaponics, biomass boilers can heat fish tanks, nutrient solutions, root zones, and greenhouse air without allowing combustion gases to contact the aquaponic water directly. Biomass boiler systems are especially useful in cold climates or high-altitude regions where aquaponic water temperatures fall below the optimum range for fish, crops, and nitrifying bacteria. Greenhouse biomass heating studies show that biomass systems can support crop production while reducing dependence on fossil fuels and conventional heating systems [23]. A biomass-heated greenhouse study in China reported that biomass heating improved greenhouse production economics compared with unheated greenhouse conditions [23]. Boiler performance depends on fuel moisture content, combustion efficiency, heat-transfer design, ash handling, and emission control. Poorly dried fuel reduces thermal efficiency and increases smoke, carbon monoxide, and particulate emissions. Efficient biomass boilers should therefore include controlled air supply, insulated combustion chambers, heat exchangers, chimney systems, ash-removal units, and temperature-control devices.

Pellet and Briquette Burners

Pellet and briquette burners use densified biomass fuels produced from sawdust, crop residues, husks, grasses, or agro-industrial wastes. Densification improves bulk density, fuel uniformity, handling, storage, and feeding into combustion units. This makes pellets and briquettes more suitable than loose residues for automated or semi-automated aquaponic heating systems. Pellet burners are appropriate for systems requiring more precise temperature control because fuel feeding can be regulated mechanically. Briquette burners may be more suitable for smallholder aquaponic farms where low-cost locally produced fuels are available. Biomass pre-treatment and densification are recognized as important strategies for improving the logistics and quality of solid biomass supply chains [11]. For aquaponics, pellet and briquette burners can be connected to water jackets, boilers, or heat

exchangers to provide indirect heating. Indirect heating is important because smoke, ash, and combustion residues must not enter the fish or plant water loop. The main limitations of pellet and briquette systems include fuel-quality variation, ash accumulation, burner maintenance, and the need for reliable fuel supply.

Biomass Gasification Systems

Biomass gasification converts solid biomass into producer gas through partial oxidation at high temperatures. The resulting gas can be burned for heat or used in engines for electricity and heat generation. Gasification generally offers higher fuel flexibility and cleaner combustion potential than direct burning when the system is properly designed and operated [24]. Gasification can support aquaponic systems in two ways. First, producer gas can be burned in a thermal unit to heat water or greenhouse air. Second, producer gas can fuel an engine-generator in a combined heat and power configuration, producing both electricity and recoverable heat. This is useful for aquaponics because pumps, aerators, sensors, and control systems require electricity, while fish tanks and greenhouses may require heat. However, biomass gasification is technically more complex than simple combustion. Tar formation, gas cleaning, feedstock moisture, particle size, and reactor design strongly affect performance. Small-scale aquaponic farms may face difficulties with operation and maintenance unless simplified and robust gasifier designs are used.

Biogas Heating Units

Biogas heating units use methane-rich gas produced through anaerobic digestion of animal manure, food waste, crop residues, or agro-processing wastes. Biogas can be combusted in burners, boilers, or combined heat and power units to provide thermal energy for aquaponic systems. Biogas is particularly suitable for farms that already generate livestock manure or organic wastes. Biogas heating can support circular food-energy systems because organic wastes are converted into usable energy instead of being discarded. Stable digester temperature is important for biogas productivity, and studies on biodigester heating show that heat management improves anaerobic digestion stability and performance [25]. In aquaponics, biogas should be used as an external heat source rather than being directly introduced into the water system. Heat can be transferred through boilers, hot-water pipes, or heat exchangers. Digestate should not be added directly to fish tanks or hydroponic beds without proper treatment because it may contain pathogens, suspended solids, high ammonia, and salts that could harm fish and disturb water quality.

Combined Heat and Power Systems

Combined heat and power systems generate electricity and useful heat from a single fuel source. In biomass-based CHP systems, solid biomass or biogas can fuel engines, turbines, or gasification-based generators. The electricity can power pumps, aerators, lighting, sensors, and automation devices, while the recovered heat can warm fish tanks, greenhouses, or nutrient solutions. CHP is relevant to aquaponics because aquaponic systems require both electrical and thermal energy. The U.S. Environmental Protection Agency describes CHP as an efficient and reliable approach for producing power and thermal energy from one fuel source, with potential to reduce energy costs and greenhouse gas emissions compared with separate generation [11]. Biomass CHP systems are more suitable for medium- to large-scale aquaponic enterprises because they require higher capital investment, technical skills, and regular maintenance. Their feasibility depends on continuous heat demand, stable biomass supply, engine efficiency, load matching, and the value of displaced electricity and fuel.

Heat Exchangers and Hydronic Heating

Heat exchangers are essential for safely transferring heat from biomass combustion or biogas systems into aquaponic water without contaminating the production system. A heat exchanger separates the combustion side from the aquaponic water side, allowing heat transfer while preventing smoke, ash, oils, metals, or combustion by-products from entering fish tanks or plant beds. Hydronic heating systems circulate hot water through pipes, coils, radiators, or under-bench loops. In aquaponics, hydronic systems can heat fish tanks, sump tanks, nutrient solutions, greenhouse floors, or root zones. This method provides more uniform heating than direct air heating and can be integrated with thermostats, pumps, valves, and thermal storage tanks. Heat-exchange design is important because fouling, scaling, corrosion, and clogging can reduce efficiency. Biogas engineering studies identify heat exchangers as important components for recovering and transferring heat, although fouling and low-temperature heat recovery remain technical challenges [26].

Thermal Energy Storage Integration

Thermal energy storage improves biomass-heated aquaponic systems by storing excess heat and releasing it when temperatures decline. Storage can reduce fuel consumption, improve temperature stability, and prevent overheating during periods of high heat production. Common storage options include insulated water tanks, rock beds, phase-change materials, sand beds, and greenhouse thermal mass. Water-based thermal storage is particularly suitable for aquaponics because water has high heat capacity and can be integrated with hydronic heating loops. Sensible and latent heat storage systems are widely discussed in greenhouse energy studies because they help address the mismatch between heat supply and heat demand [27]. Thermal storage is also valuable in hybrid renewable systems because it improves energy reliability when solar radiation or biomass combustion output fluctuates. For aquaponic crop production, thermal storage helps maintain stable water and root-zone temperatures during cold nights, cloudy

periods, or temporary interruptions in biomass combustion. This stability supports fish welfare, nitrification, and crop growth.

Hybrid Biomass-Solar Heating Systems

Hybrid biomass-solar heating systems combine solar thermal or photovoltaic technologies with biomass heating. Solar energy can provide heat or electricity during sunny periods, while biomass serves as a backup or complementary energy source during cloudy weather, nighttime, or cold seasons. This combination improves energy reliability and reduces continuous biomass consumption. Hybridization is attractive because solar energy is intermittent, while biomass can be stored and used when needed. Recent reviews on solar-biomass-energy-storage systems show that hybrid renewable configurations can improve energy security and system reliability compared with single-source renewable systems [28]. In aquaponics, a hybrid system may include solar collectors, biomass boilers, hot-water storage tanks, heat exchangers, circulation pumps, and automated temperature controllers. Such systems are especially suitable for remote, rural, and peri-urban farms where grid electricity is expensive or unreliable. The main challenges include high initial cost, technical complexity, maintenance requirements, and the need for accurate system sizing. Technology selection depends on scale, automation level, and feedstock type (Table 3).

Table 3: Comparison of Heating Technologies for Aquaponics

Technology	Fuel Type	Automation	Best Scale	Advantages	Limitation	Reference
Biomass boiler	Chips, pellets	Medium	Commercial	Stable heat	High capital cost	[23]
Pellet burner	Pellets	High	Medium-large	Precise control	Fuel cost	[11]
Briquette stove	Briquettes	Low	Smallholder	Cheap	Manual feeding	[21]
Gasifier	Residues	Medium	Large	CHP possible	Technical complexity	[24]
Biogas heater	Methane gas	Medium	Farm-integrated	Clean combustion	Digester management	[29]

Integration of Biomass Heating into Aquaponic Production

Greenhouse-Based Aquaponics

Greenhouse-based aquaponics requires stable thermal conditions because fish, crops, and nitrifying microorganisms function within the same production environment. Temperature instability can reduce fish feeding, slow nitrification, limit nutrient uptake, and reduce crop yield. Greenhouses improve environmental control, but heat losses through glazing, ventilation, and night-time radiation often make supplementary heating necessary in cold seasons or high-altitude regions [1, 2]. FAO describes aquaponics as an integrated system involving fish culture, plant production, bacteria, nitrification, and system balancing, all of which are influenced by environmental management. Biomass heating can be integrated into greenhouse aquaponics through hot-water boilers, biomass burners, buried heat exchangers, hydronic pipes, or warm-air distribution systems. A greenhouse biomass-heating study in China demonstrated that biomass flue gas could be used as a thermal medium through a buried soil heat exchanger to improve the greenhouse thermal environment [23]. In aquaponics, however, indirect heat transfer is preferable because smoke, ash, and combustion residues must not contact fish water or crop nutrient solutions.

Recirculating Aquaponic Systems

Aquaponics is a form of recirculating aquaculture that incorporates soilless plant production into the fish-water loop. Recirculating systems are designed to conserve water, maintain water quality, and reuse dissolved nutrients for crop growth [30]. The integration of biomass heating into such systems must therefore protect biological filtration, fish welfare, and plant nutrient uptake. A biomass heating unit should be connected to the aquaponic system through a closed heat-transfer loop rather than direct combustion contact. Hot water from a biomass boiler or biogas heater can pass through a heat exchanger, while aquaponic water remains physically separated. This arrangement reduces contamination risks and allows better control of fish-tank and nutrient-solution temperatures. Pumps, thermostats, valves, and temperature sensors are required to regulate heat flow and prevent overheating.

Fish Tank Heating Strategies

Fish tank heating is often the most critical thermal-management priority because fish metabolism, feeding behavior, growth rate, dissolved oxygen demand, and immune function are temperature-dependent. Warm-water fish such as tilapia require relatively warm water, while cooler-water species such as trout require lower temperatures and higher dissolved oxygen levels [1]. Temperature management must therefore be species-specific. Biomass-based fish tank heating can be achieved using external heat exchangers, submerged heating coils, jacketed tanks, or hot-water circulation pipes placed outside the fish culture chamber. External plate or shell-and-tube heat exchangers are safer

because they isolate aquaponic water from combustion systems. Direct heating devices inside fish tanks should be avoided where they may create hot spots, electrical hazards, or water-quality contamination. Heating should be gradual and controlled because rapid temperature changes can stress fish and disturb microbial processes.

Nutrient Solution and Root-Zone Heating

Nutrient solution and root-zone heating can improve crop performance in aquaponics, especially during cold periods. Root-zone temperature affects nutrient uptake, root respiration, microbial activity, and plant-water relations. Low root temperatures can reduce nutrient absorption and slow vegetative growth even when air temperature is suitable [4, 1]. Biomass heat can be supplied to plant beds through hydronic pipes, heated nutrient reservoirs, under-bench heating, or root-zone heating loops. This strategy is useful for leafy vegetables and herbs because they respond strongly to root-zone conditions. For fruiting crops, root-zone heating may support flowering, fruit development, and nutrient uptake when greenhouse air temperatures fluctuate. Heat exchangers are necessary where biomass boilers or biogas heaters are used, as aquaponic nutrient solutions must remain free from ash, smoke, oils, and combustion residues.

Heat Distribution and Control Systems

Efficient heat distribution is essential for uniform temperature regulation across fish tanks, sump tanks, biofilters, hydroponic beds, and greenhouse air spaces. Hydronic systems are particularly suitable because hot water can be circulated through pipes, coils, radiators, floor loops, or heat exchangers. Greenhouse-heating reviews identify hot-water systems, air heaters, heat storage, and heat exchangers as important technologies for protected agriculture [27]. Control systems should include thermostats, water-temperature sensors, air-temperature sensors, flow meters, mixing valves, and automated pumps. Proper control prevents overheating, reduces biomass consumption, and protects fish and bacteria from sudden thermal shifts. Energy-efficient aquaponic facilities increasingly depend on coordinated control of heating, ventilation, shading, and water temperature to maintain productivity while reducing energy demand [31].

System Sizing and Design Considerations

Sizing a biomass heating system requires estimation of total heat demand, including fish tank volume, water-flow rate, greenhouse area, heat losses, target temperature, outdoor climate, insulation level, and desired operating schedule. The design must consider peak heat demand during the coldest period rather than only average daily demand. Undersized systems may fail to protect fish and crops during cold nights, while oversized systems may increase capital cost, fuel use, and overheating risk. Feedstock characteristics also influence system design. Moisture content, calorific value, ash content, particle size, and fuel density affect combustion efficiency and heat output. Biomass boilers and burners should be matched to locally available fuels such as wood chips, pellets, briquettes, rice husks, coffee husks, maize cobs, or sawdust. Thermal storage tanks can improve performance by storing excess heat and releasing it during periods of high demand. Biomass greenhouse systems may also benefit from integration with thermal energy storage to reduce fossil-fuel dependence and manage peak heat loads [32].

Safety and Operational Requirements

Safety is essential when integrating biomass heating into aquaponic production. Biomass combustion can produce carbon monoxide, particulate matter, nitrogen oxides, volatile organic compounds, smoke, and ash. Combustion units should therefore be installed in well-ventilated spaces with proper chimneys, flue-gas control, fire protection, and carbon monoxide monitoring. The U.S. Environmental Protection Agency notes that biomass combined heat and power systems require appropriate technology selection, emissions control, and operational management. Operational requirements include fuel drying, regular ash removal, burner cleaning, inspection of heat exchangers, pump maintenance, water-temperature monitoring, and emergency shutdown procedures. Combustion systems should remain physically separated from fish tanks and plant beds to avoid contamination. Operators also need training in safe fuel storage, fire prevention, equipment maintenance, and response to overheating or pump failure. A well-designed biomass heating system can support sustainable aquaponic production, but poor installation or weak maintenance can create serious risks to fish health, crop quality, worker safety, and environmental performance.

Effects of Biomass Heating on Crop Performance

Germination and Seedling Growth

Biomass heating can support germination and seedling establishment in aquaponic systems through the maintenance of suitable air, water, and root-zone temperatures. Seed germination is strongly influenced by temperature because enzymatic activity, water absorption, respiration, and early root emergence are temperature-dependent processes. In aquaponic nurseries, low temperature can delay germination, weaken seedling vigor, and extend the transplanting period, while excessive temperature may reduce emergence and increase seedling stress. Lettuce, one of the most common aquaponic crops, performs best under moderate temperatures, and high temperatures can reduce leaf growth and promote premature bolting. Biomass-derived heat can be used to warm nursery trays, seedling benches, greenhouse air, or nutrient solution through indirect heating systems. Stable seedling temperatures are particularly important in regions with cold nights or seasonal fluctuations because young plants have limited root systems and

lower tolerance to thermal stress. Root-zone temperature regulation can improve early nutrient absorption and biomass accumulation, especially in hydroponic and aquaponic systems where roots are continuously exposed to circulating nutrient solution [4, 33].

Vegetative Growth of Leafy Crops

Leafy vegetables such as lettuce, spinach, kale, pak choi, Swiss chard, and basil are widely cultivated in aquaponics because they have short production cycles, moderate nutrient demand, and high market value. Temperature regulation affects leaf expansion, chlorophyll formation, photosynthesis, transpiration, and biomass production. In cold conditions, vegetative growth slows because root activity, microbial nutrient conversion, and plant metabolic processes are reduced. In overly warm conditions, leafy crops may experience reduced quality, bitterness, bolting, and lower marketable yield. Biomass heating can improve leafy-crop production when it maintains root-zone and greenhouse temperatures within crop-specific ranges. Recent hydroponic lettuce studies show that root-zone temperature affects plant growth, nutrient uptake, and physiological quality [33]. Similarly, root-zone temperature regulation has been associated with improved water and nutrient absorption efficiency in lettuce production. These findings are relevant to aquaponics because the crop root system depends on circulating nutrient-rich water, and temperature instability in the nutrient solution can directly affect nutrient uptake and crop growth.

Fruiting Crop Yield and Quality

Fruiting crops such as tomato, cucumber, pepper, eggplant, and strawberry require more stable thermal conditions than many leafy vegetables because flowering, pollen viability, fruit set, fruit enlargement, and quality formation are highly temperature-sensitive [34]. Low temperatures can delay flowering and fruit development, while excessive temperatures may cause flower abortion, poor pollination, fruit cracking, uneven ripening, and reduced market quality. Greenhouse tomato research has shown that fruit yield and quality are directly influenced by microclimate conditions, including air temperature, humidity, and vapor pressure deficit. Biomass heating can support fruiting crops in aquaponic greenhouses through warm-water pipes, root-zone heating, air heaters, or thermal storage systems [35]. Night-time heating is particularly important because low nights temperatures can reduce fruit set and slow assimilate transport. Tomato studies indicate that night temperature can strongly affect fruit number, fruit weight, and fruit quality during fruit set. In biomass-heated aquaponics, controlled heat supply can therefore improve yield stability, especially in seasons or regions where low night temperatures limit reproductive development.

Nutrient Uptake and Water Use Efficiency

Temperature affects nutrient uptake and water use efficiency through its influence on root membrane activity, transpiration, dissolved oxygen, microbial mineralization, and nitrification. In aquaponics, nutrient availability depends not only on fish waste production but also on microbial conversion and plant absorption. Poor thermal control can reduce nitrification and slow nutrient uptake, causing nutrient imbalance or accumulation in the recirculating water [1, 6]. Root-zone heating can improve nutrient uptake where cold water limits root activity. Moccio *et al.* [33] reported that root-zone temperature influenced lettuce growth and nutrient uptake under hydroponic conditions. Recent work on lettuce root-zone regulation also found that suitable root-zone temperature improved nutrient solution consumption and absorption efficiency. In aquaponic systems, biomass heating may therefore improve nutrient-use efficiency when heat is applied through indirect water heating, hydronic root-zone loops, or warmed nutrient reservoirs. Excessive heating should be avoided because warm water holds less dissolved oxygen, which may impair root respiration and fish welfare.

Crop Health, Pest Pressure, and Disease Incidence

Temperature regulation influences crop health, pest development, and disease pressure in protected cultivation. Cold and humid greenhouse conditions can favor fungal diseases, while excessive heat can weaken plants and increase susceptibility to pathogens [14]. Temperature and relative humidity also affect insect pest activity, reproduction, dispersal, and interactions with biological control agents. Greenhouse climate research indicates that temperature and humidity influence both pest behavior and biological control performance. Biomass heating can reduce disease risk when it lowers excessive humidity, prevents condensation, and maintains crop surfaces and root zones within suitable temperature ranges [17]. However, poorly controlled heating may create warm and humid microclimates that favor pathogens or increase pest reproduction. Recent plant-health reviews emphasize that temperature changes can alter pathogen development, host susceptibility, and disease severity. Therefore, biomass heating should be integrated with ventilation, humidity control, air circulation, and regular crop monitoring to support crop health rather than merely increase temperature [17].

Crop-Specific Responses to Temperature Regulation

Crop responses to biomass heating depend on species, cultivar, growth stage, and production environment. Lettuce and other leafy greens often benefit from moderate root-zone temperatures but may lose quality under excessive heat. Lettuce is commonly described as a cool-season crop, and high water temperatures can negatively affect taste and quality. Basil and other herbs generally tolerate warmer conditions than lettuce, while fruiting crops such as

tomato and cucumber require stable day and night temperatures for flowering and fruit development. Aquaponic systems must also consider compatibility between crop temperature requirements and fish temperature requirements [23]. Warm-water fish such as tilapia may require water temperatures that are higher than the optimum range for some cool-season leafy vegetables. This creates a biological compromise in which heating must support fish welfare, nitrification, and crop growth simultaneously [1, 2]. Biomass heating is most effective when combined with species selection, crop scheduling, thermal zoning, and separate root-zone or greenhouse-air heating strategies. Such integration allows aquaponic producers to match heat supply to the specific thermal needs of different crops while maintaining overall system stability.

Effects of Biomass Heating on Fish and Microbial Performance

Fish Growth Rate and Feed Conversion Ratio

Biomass heating can improve fish growth performance in aquaponic systems when it maintains water temperature within the optimal physiological range of the cultured species. Fish are ectothermic organisms, meaning that their metabolic rate, appetite, digestion, swimming activity, and feed utilization are strongly controlled by water temperature [36]. Warm-water species such as Nile tilapia generally show improved growth and feed conversion under suitable warm conditions, whereas low temperatures reduce feeding activity, digestion, and growth efficiency [37, 38]. In aquaponics, the effect of biomass heating on fish growth is indirect. Biomass heat does not enhance growth through a unique biological mechanism; rather, it prevents cold stress and stabilizes water temperature. Azaza *et al.* [38] reported that juvenile Nile tilapia showed better growth and feed utilization at moderate warm temperatures than at lower or excessively high temperatures. Similarly, Abd El-Hack *et al.* [37] noted that low temperatures reduce tilapia growth and feed efficiency. These findings suggest that biomass heating can reduce seasonal growth depression, shorten production cycles, and improve feed conversion where cold conditions limit aquaponic fish production.

Fish Welfare and Stress Reduction

Fish welfare depends strongly on stable environmental conditions, especially temperature, dissolved oxygen, pH, ammonia, and nitrite. Temperature instability can cause physiological stress, reduce feeding, alter behavior, impair osmoregulation, and increase vulnerability to poor water quality [36, 1]. In aquaponic systems, welfare concerns are particularly important because fish health directly affects nutrient generation, microbial activity, and crop productivity. Biomass heating can reduce thermal stress during cold nights, rainy seasons, winter periods, or high-altitude production. Stable heating is especially useful for warm-water species such as tilapia, catfish, and carp. However, heating must be carefully controlled because high water temperature lowers dissolved oxygen solubility while increasing fish oxygen demand [39, 1] Therefore, biomass heating should be combined with aeration, dissolved oxygen monitoring, thermostatic control, and gradual temperature adjustment.

Disease Resistance and Survival Rate

Temperature affects fish disease resistance because immune response, pathogen development, and host–pathogen interactions are temperature-dependent. Extreme or fluctuating temperatures can weaken fish immunity, increase oxidative stress, and raise the probability of disease outbreaks [36]. Heat stress and cold stress may both reduce survival when fish are exposed to temperatures outside their tolerance range. Biomass heating can improve survival indirectly when it keeps water temperature within the preferred range for the cultured species. Stable temperature supports feeding, growth, immune competence, and recovery from handling stress. In tilapia, suboptimal temperature exposure has been associated with chronic stress, impaired feed conversion, reduced growth, and compromised immune responses [40]. Nevertheless, poorly designed biomass heating systems can create risks such as overheating, carbon monoxide leakage, ash contamination, smoke exposure, or heat-exchanger failure. Safe application requires indirect heat transfer through closed-loop hydronic systems, proper ventilation, and continuous temperature monitoring.

Species-Specific Temperature Responses

Fish species differ widely in their thermal requirements, and biomass heating systems should therefore be designed according to species-specific needs. Warm-water species such as Nile tilapia generally require warmer water than cool-water species such as trout. Tilapia is widely used in aquaponics because it tolerates variable water quality and grows well in warm conditions, but its performance declines at low temperatures [1, 37]. Trout, in contrast, requires cooler water and higher dissolved oxygen, making it less suitable for warm aquaponic greenhouses unless cooling and oxygenation systems are available. Species selection also affects crop compatibility. Warm-water fish may require temperatures that exceed the optimum range for some cool-season leafy vegetables, while cool-water fish may require temperatures below the preferred range for many tropical crops. Aquaponic design therefore requires a compromise temperature range that supports fish growth, crop productivity, and microbial nitrification simultaneously [1, 2]. Biomass heating is most useful when paired with suitable species selection, thermal zoning, and careful system design.

Nitrification Efficiency and Microbial Stability

Nitrifying microorganisms are essential in aquaponics because they convert ammonia excreted by fish into nitrite and then nitrate, which plants can absorb. This process is mainly carried out by ammonia-oxidizing and nitrite-oxidizing microorganisms. Temperature affects nitrification through its influence on microbial growth, enzyme activity, oxygen demand, and biofilm performance [6]. Biomass heating can support microbial stability by preventing biofilter temperatures from falling below the range required for effective nitrification. Low temperatures slow ammonia and nitrite oxidation, which can lead to toxic ammonia or nitrite accumulation in fish tanks. Zhu and Chen [6] showed that temperature influences nitrification rates in fixed-film biofilters, although the response depends on dissolved oxygen limitation, total ammonia nitrogen limitation, and mass-transfer conditions. Kinyage and Pedersen [41] also reported that temperature affects ammonium and nitrite removal in recirculating aquaculture biofilters. Excessive heating can also destabilize microbial performance. Warm water holds less dissolved oxygen, and nitrifying bacteria require oxygen to oxidize ammonia and nitrite. High temperatures may therefore reduce nitrification efficiency indirectly through oxygen limitation. Effective biomass-heated aquaponics should monitor temperature, dissolved oxygen, pH, alkalinity, ammonia, nitrite, and nitrate together rather than managing temperature alone.

Water Quality Implications

Water quality in aquaponics is closely linked to temperature. Warmer water increases fish metabolism and waste production but reduces dissolved oxygen solubility. Colder water slows fish metabolism, plant nutrient uptake, and microbial nitrification. These effects influence ammonia, nitrite, nitrate, dissolved oxygen, pH, alkalinity, and overall system stability [1, 6]. Biomass heating can improve water quality when it maintains stable thermal conditions for fish and biofilters. Stable temperatures support predictable feeding, steady ammonia production, efficient nitrification, and continuous nutrient supply to crops. Poorly controlled heating, however, may cause oxygen depletion, ammonia accumulation, thermal shock, or contamination if combustion residues enter the aquaponic water loop. Safe system operation therefore requires indirect heat exchange, emergency aeration, thermostatic control, temperature alarms, proper boiler ventilation, and regular inspection of pipes, pumps, and heat exchangers. Overall, biomass heating can benefit fish and microbial performance when it is used as a controlled thermal-regulation strategy. Its effectiveness depends on correct system sizing, species-specific temperature targets, biofilter protection, adequate aeration, safe heat transfer, and continuous water-quality monitoring.

Environmental Sustainability Assessment

Carbon Footprint of Biomass Heating

The carbon footprint of biomass heating in aquaponic systems depends on feedstock source, production method, transport distance, moisture content, combustion efficiency, and the fossil fuel being displaced. Biomass is often described as renewable because its carbon originates from recently grown organic matter rather than geological fossil carbon; however, biomass heating is not automatically carbon neutral. Life-cycle emissions may arise from harvesting, drying, processing, pelletizing, transport, combustion, ash handling, and equipment operation [42, 21]. In aquaponic production, biomass heating can reduce carbon footprint when it replaces diesel, coal, liquefied petroleum gas, or grid electricity generated from fossil fuels. The benefit is strongest when residues such as rice husks, sawdust, maize cobs, coffee husks, or sugarcane bagasse are used locally with efficient combustion systems. A life-cycle assessment of biomass-fueled combined heat and power reported lower carbon dioxide equivalent emissions for wheat straw heat than coal heat under the assumptions used in the study, although wood pellets showed higher emissions than wheat straw because of processing and supply-chain factors [43]. These findings show that feedstock choice and supply-chain design strongly influence the sustainability of biomass heating.

Greenhouse Gas Emissions

Greenhouse gas emissions from biomass heating include carbon dioxide, methane, nitrous oxide, and indirect emissions from feedstock logistics. Carbon dioxide released during combustion is biogenic, but methane and nitrous oxide have high global warming potential and may increase the climate impact of poorly managed systems. Incomplete combustion can also increase carbon monoxide and organic carbon emissions, indicating low combustion efficiency and potential climate and health concerns [12]. Greenhouse gas performance depends on whether biomass is sourced from true residues, dedicated energy crops, or harvested forest biomass. Residues that would otherwise decompose or be openly burned may offer greater climate benefits than biomass obtained through land-use conversion or unsustainable forest extraction. Cherubini and Strømman [42] emphasized that bioenergy systems require life-cycle assessment because land use, reference systems, supply chains, and conversion technology determine whether greenhouse gas savings occur. For aquaponics, sustainable biomass heating should prioritize locally available residues, efficient boilers, low-moisture fuels, and short transport distances.

Waste Valorization and Circular Economy Benefits

Biomass heating can strengthen the circular economy potential of aquaponics through the conversion of agricultural and agro-industrial residues into useful thermal energy. Aquaponics already promotes circularity through fish-waste

nutrient recovery and water reuse, while biomass heating can extend this logic to energy supply. Crop residues, wood-processing wastes, animal manure, food-processing residues, and pruning waste can be transformed into heat rather than discarded, openly burned, or left to decay [20, 21]. This waste-to-energy approach is particularly relevant in agricultural regions where residues are abundant but poorly utilized. Biomass heating can reduce waste accumulation, provide local energy, support rural livelihoods, and decrease dependence on imported fossil fuels. In integrated farm systems, manure and wet organic wastes may also be converted into biogas for heating, while solid residues may be pelletized, briquetted, or gasified. These pathways support resource efficiency, provided that biomass removal does not reduce soil fertility, livestock bedding availability, or other beneficial residue uses.

Air Pollution and Particulate Emissions

Air pollution is one of the major environmental concerns associated with biomass heating. Combustion of solid biomass can emit particulate matter, carbon monoxide, nitrogen oxides, volatile organic compounds, polycyclic aromatic hydrocarbons, and other trace pollutants. The level of pollution depends on feedstock quality, moisture content, combustion temperature, air supply, burner design, chimney performance, and emission-control technology [12, 14]. Particulate emissions are especially important because fine particles can affect respiratory and cardiovascular health. Small-scale biomass combustion is widely recognized as a significant source of particulate matter when equipment is inefficient or fuel is wet. Szyszlak-Bargłowicz et al. [44] reported that biomass combustion can contribute substantially to winter particulate matter emissions in urban settings. Therefore, aquaponic biomass heating should use efficient combustion chambers, dry fuel, adequate air control, chimneys, cyclones, filters, or electrostatic precipitators where appropriate. Poorly designed biomass heaters may undermine the environmental benefits of aquaponics if air-quality impacts are ignored.

Ash Management and By-Product Utilization

Biomass combustion generates ash containing minerals such as potassium, calcium, magnesium, phosphorus, silica, and trace elements. The quantity and composition of ash depend on feedstock type, combustion temperature, soil contamination, harvesting method, and furnace design. Agricultural residues such as rice husks and straw may produce higher ash contents than clean wood fuels, and high-ash feedstocks can cause slagging, fouling, corrosion, and maintenance problems [45]. Ash may be reused in agriculture, construction materials, soil amendment, or land reclamation, but only after proper chemical assessment. Heavy metals, chlorides, sulphates, unburned carbon, pH, salinity, and contaminant levels must be evaluated before land application. IEA Bioenergy [46] notes that biomass ash management practices vary among countries and that ash recycling requires attention to nutrient value and contaminant risks. In aquaponics, ash should not be added directly into fish tanks or hydroponic beds because high alkalinity, salts, metals, or suspended solids may harm fish, roots, and biofilters. Safer utilization should occur outside the aquaponic water loop after laboratory testing and regulatory approval.

Life Cycle Assessment Approaches

Life cycle assessment is essential for evaluating the true environmental performance of biomass-heated aquaponics. A complete assessment should include feedstock production or collection, transport, drying, pre-treatment, combustion or gasification, heat distribution, equipment operation, emissions, ash management, and avoided fossil-fuel use. The functional unit may be expressed as one kilogram of crop produced, one kilogram of fish produced, one megajoule of useful heat, or one combined unit of fish and crop output. Life-cycle assessment should also compare biomass heating with alternative heating systems, including electric heating, diesel heating, liquefied petroleum gas, natural gas, solar thermal, heat pumps, or hybrid systems. Cherubini and Strømman [42] emphasized that bioenergy LCA outcomes are highly sensitive to system boundaries, allocation methods, land-use assumptions, and reference scenarios. In aquaponics, LCA should account for the water–energy–nutrient linkages unique to integrated fish and crop production. This allows researchers to determine whether biomass heating actually reduces environmental burdens or merely shifts them from energy use to air emissions, land use, or logistics.

Water-Energy-Food Nexus Perspective

The water-energy-food nexus provides a useful framework for assessing biomass-heated aquaponics because the system combines water reuse, food production, nutrient recycling, and renewable energy. Aquaponics can reduce freshwater demand through recirculation, produce fish and vegetables in controlled environments, and recover nutrients from fish waste [1, 2]. Biomass heating adds an energy dimension by using agricultural residues or organic wastes to stabilize system temperatures. A nexus perspective shows that sustainability depends on balancing benefits and trade-offs. Biomass heating may improve year-round food production and reduce fossil-energy dependence, but it may also increase air emissions, ash handling needs, labor demand, and feedstock competition. Sustainable implementation therefore requires integrated planning across water quality, energy supply, crop productivity, fish welfare, biomass sourcing, and environmental regulation. Biomass-heated aquaponics is most promising where local residues are abundant, clean combustion technologies is available, and heating demand is matched to system scale. Biomass-heated aquaponics contributes to circular economy goals but also presents environmental trade-offs (Figure 4).

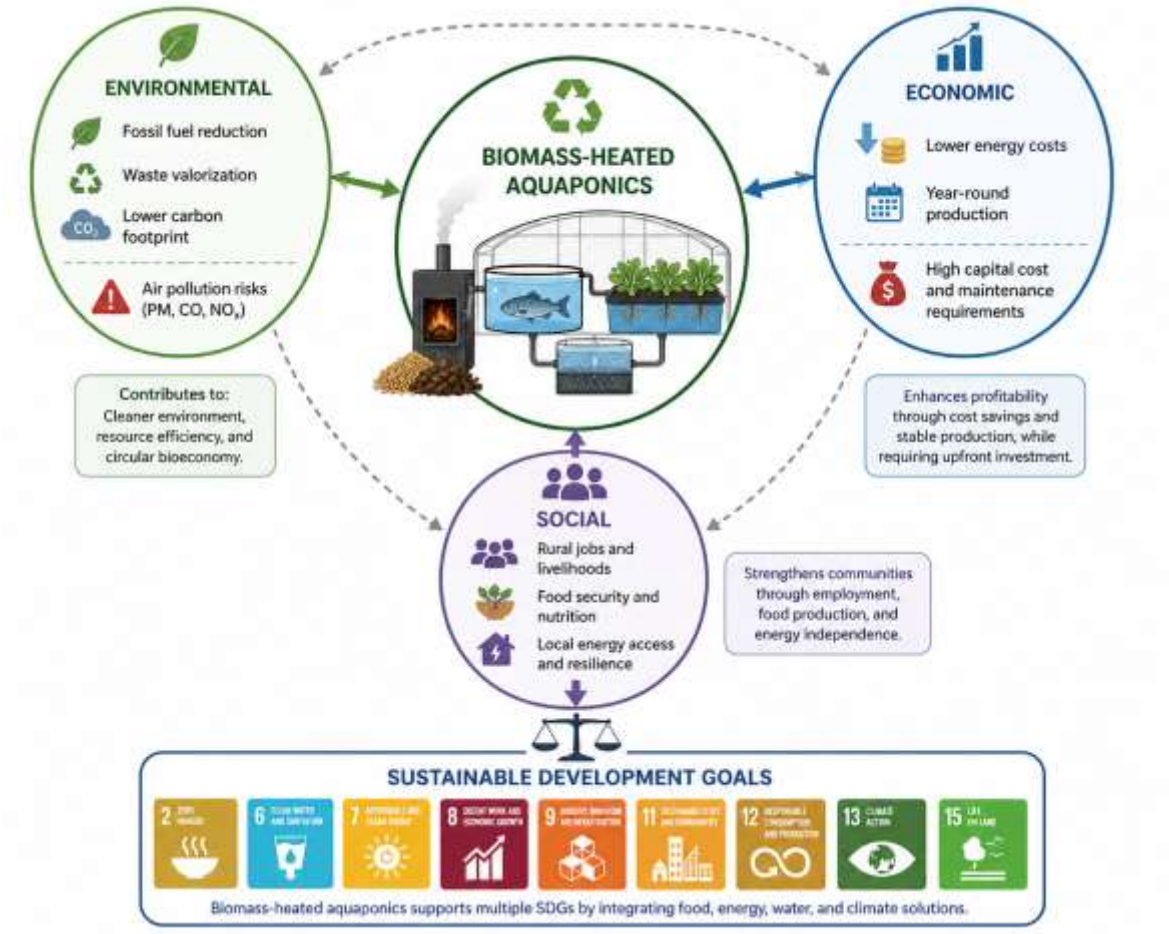

Figure 4: Sustainability Framework for Biomass-Heated Aquaponics

Techno-Economic Assessment

Capital Investment Requirements

Capital investment for biomass heating in aquaponic systems depends on system scale, technology type, level of automation, and integration complexity. Typical components include biomass boilers or burners, fuel storage units, feedstock handling systems, heat exchangers, pumps, piping networks, thermal storage tanks, control systems, and installation infrastructure. Compared with conventional electric or fossil-fuel heaters, biomass systems often require higher upfront investment due to additional equipment such as fuel feeders, combustion chambers, ash-handling units, and emission-control devices [27]. Capital cost also varies with feedstock type. Pellet-based systems tend to have higher equipment costs due to automated feeding and combustion control, while simple briquette or residue-based systems may be less expensive but require more manual operation. For aquaponics, system design must also account for indirect heating requirements, including heat exchangers that isolate fish water from combustion processes. High initial costs remain a key barrier to adoption, particularly for small-scale producers in developing regions [2].

Operating and Maintenance Costs

Operating costs of biomass heating systems include fuel procurement, transport, storage, labor, maintenance, and system monitoring. Biomass fuels such as crop residues, wood chips, or briquettes may be cheaper than fossil fuels, especially when sourced locally. However, costs vary depending on feedstock availability, moisture content, processing requirements, and competing uses [21]. Maintenance costs are generally higher than those of electric heating systems because biomass combustion produces ash, soot, and residues that require regular cleaning. Components such as burners, heat exchangers, chimneys, and pumps require periodic inspection and servicing. Fuel preparation, including drying, grinding, or densification, may also add to operational costs. IEA Bioenergy [11] highlights that fuel quality and pre-treatment significantly influence system performance and maintenance requirements. Labor demand is another factor, particularly in systems that rely on manual feeding or ash removal.

Comparison with Electric, Solar, and Fossil Fuel Heating

Biomass heating systems differ from other heating technologies in terms of cost structure, reliability, emissions, and operational requirements. Electric heating offers precise temperature control, low maintenance, and ease of installation, but it can be expensive where electricity tariffs are high or supply is unreliable. Fossil-fuel systems such as diesel, natural gas, or liquefied petroleum gas provide high heat output and rapid response but are associated with fuel-price volatility and greenhouse gas emissions [27]. Solar heating systems provide clean and renewable energy but are intermittent and depend on solar radiation. Solar thermal systems can reduce heating demand but often require thermal storage or backup systems during cloudy periods or nighttime. Hybrid biomass-solar systems can improve reliability by combining continuous biomass energy with intermittent solar energy [28]. Biomass heating offers a balance between cost and sustainability when feedstock is locally available. It reduces dependence on fossil fuels and grid electricity but requires more complex operation and maintenance. Comparative performance therefore depends on local conditions, including climate, fuel availability, energy prices, and system scale.

Energy Efficiency and Fuel Consumption

Energy efficiency in biomass heating systems depends on combustion efficiency, heat-transfer design, fuel quality, and system insulation. High moisture content reduces combustion efficiency because energy is consumed in evaporating water rather than producing heat. Properly dried and densified biomass fuels such as pellets or briquettes generally provide more stable and efficient combustion than raw residues [11]. Fuel consumption depends on heat demand, which is influenced by greenhouse size, insulation level, water volume, target temperature, and climatic conditions. Heat losses through greenhouse structures, pipes, and tanks can significantly increase fuel requirements. Efficient system design should therefore include insulation, thermal storage, and heat recovery where possible. Biomass combined heat and power systems can further improve efficiency by utilizing both electricity and waste heat [47].

Profitability and Payback Period

The profitability of biomass heating in aquaponics depends on capital cost, operating cost, energy savings, crop yield improvement, fish growth performance, and market value of products. Biomass heating can improve profitability by enabling year-round production, stabilizing yields, and reducing losses associated with cold stress. It can also lower energy costs where biomass is cheaper than electricity or fossil fuels. Payback period is influenced by initial investment and annual savings from reduced energy expenditure. Systems with high capital cost but low operating cost may achieve reasonable payback over time, especially in commercial-scale operations. Zheng *et al.* [43], reported that biomass-based systems can provide economic benefits compared with fossil-fuel alternatives under certain conditions, although results depend on feedstock cost and system efficiency. However, profitability is sensitive to several uncertainties, including fuel price fluctuations, labor cost, maintenance requirements, and market prices for fish and crops. Economic feasibility therefore requires site-specific analysis rather than general assumptions.

Feasibility for Smallholder and Commercial Systems

Feasibility of biomass heating varies significantly between smallholder and commercial aquaponic systems. Smallholder systems may benefit from low-cost biomass fuels such as crop residues, but they often face constraints related to capital investment, technical knowledge, labor availability, and access to efficient heating equipment. Simple biomass stoves or small-scale boilers may be more appropriate for such systems, although they may have lower efficiency and higher emission levels. Commercial aquaponic systems are better positioned to adopt advanced biomass technologies such as automated boilers, pellet systems, gasifiers, or combined heat and power units. These systems can achieve higher efficiency, better temperature control, and improved integration with greenhouse operations. However, they require higher investment, skilled labor, and reliable fuel supply chains [2]. Feasibility also depends on local resource availability. Regions with abundant agricultural residues, forestry by-products, or livestock waste may find biomass heating more viable than regions with limited biomass supply.

Sensitivity Analysis

Sensitivity analysis is important in techno-economic assessment because it evaluates how changes in key variables affect system performance and feasibility. Key variables include biomass fuel price, moisture content, transport distance, system efficiency, capital cost, labor cost, and energy demand. Variations in these factors can significantly influence operating cost, profitability, and payback period. Life-cycle and economic studies emphasize that bioenergy systems are highly sensitive to assumptions related to feedstock supply, conversion efficiency, and market conditions [42]. In aquaponic systems, sensitivity analysis should also consider biological variables such as fish growth rate, crop yield, temperature requirements, and system productivity. Climatic factors such as seasonal temperature variation and heating demand should also be included. A comprehensive techno-economic evaluation therefore requires scenario analysis, cost-benefit analysis, and risk assessment. Such analysis helps identify optimal system configurations, suitable feedstocks, and economic thresholds for biomass-heated aquaponic production. The sustainability performance of biomass heating includes both opportunities and trade-offs (Table 4).

Table 4: Sustainability Benefits and Challenges of Biomass Heating

Dimension	Benefits	Challenges	Reference
Environmental	Renewable heat, waste valorization	Air pollution, ash disposal	[42]
Economic	Lower fuel cost, year-round production	High startup cost	[43]
Technical	Stable temperature control	Maintenance demand	[47]
Social	Rural jobs, food security	Skill gaps	[20]

Smart Control, Automation, and Future Innovations

IoT-Based Temperature Monitoring

Internet of Things (IoT) technologies are increasingly relevant to aquaponic temperature management because they enable real-time monitoring of water temperature, greenhouse air temperature, humidity, dissolved oxygen, pH, electrical conductivity, flow rate, and energy use. In biomass-heated aquaponics, continuous temperature monitoring is essential because fish, crops, and nitrifying microorganisms are highly sensitive to thermal fluctuations. Sensor networks connected to cloud platforms or local controllers can detect deviations from target conditions and trigger alarms or automatic responses before biological performance declines [48, 49]. IoT systems may include wireless temperature probes in fish tanks, root-zone sensors in hydroponic beds, ambient greenhouse sensors, fuel-storage sensors, and boiler-temperature sensors. Data can be transmitted through Wi-Fi, LoRaWAN, Zigbee, GSM, or other communication systems depending on farm scale and infrastructure. Real-time monitoring reduces manual inspection requirements and improves response speed during cold nights, fuel shortages, pump failure, or overheating events. In resource-constrained settings, low-cost microcontrollers and open-source platforms can provide affordable digital monitoring solutions for smallholder aquaponic systems.

AI-Driven Heating Optimization

Artificial intelligence (AI) can improve biomass heating performance through adaptive decision-making based on environmental data, biological responses, and energy demand. Unlike fixed thermostatic systems, AI models can learn patterns from historical data and optimize heating schedules according to fish growth targets, crop temperature requirements, weather forecasts, and fuel availability. Machine learning approaches such as artificial neural networks, reinforcement learning, fuzzy logic, and model predictive control are increasingly used in greenhouse climate management and energy systems [49, 50]. In aquaponic systems, AI can be used to minimize fuel consumption while maintaining acceptable thermal conditions. For example, heating intensity may be reduced during periods of solar gain or low biological demand and increased before predicted night-time temperature decline. AI systems can also detect anomalies such as rapid heat loss, blocked pipes, sensor malfunction, or unusual fuel consumption. However, successful implementation requires reliable sensor data, appropriate model training, and safeguards against algorithmic errors that could harm fish or crops.

Automated Biomass Feeding Systems

Automated biomass feeding systems improve the consistency, safety, and labor efficiency of biomass heating units. Manual feeding of briquettes, pellets, wood chips, or residues can create uneven combustion, variable heat output, and increased labor demand. Automated systems use augers, conveyors, hoppers, pneumatic feeders, rotary valves, or gravity-fed mechanisms to deliver fuel at controlled rates according to thermal demand. In pellet-based systems, automated feeding is already common because pellet size and density allow precise metering. Similar principles can be applied to briquettes or processed residues when fuel dimensions are standardized [49]. In aquaponics, automated fuel delivery is valuable because stable heating protects fish welfare, microbial nitrification, and crop growth. Integration with temperature sensors and control software allows fuel input to respond dynamically to greenhouse or water-temperature needs. Future systems may also include machine-vision fuel monitoring, blockage detection, and predictive maintenance alerts.

Digital Twins for Aquaponic Energy Management

A digital twin is a virtual representation of a physical system that receives real-time data from sensors and simulates system behavior under changing conditions. Digital twins are increasingly used in manufacturing, energy systems, water management, and smart agriculture because they support optimization, scenario testing, fault detection, and predictive planning [51, 52]. In biomass-heated aquaponics, a digital twin could integrate greenhouse climate data, fish-tank temperature, biofilter performance, crop growth indicators, biomass fuel use, weather forecasts, and equipment status into a single decision-support platform. This would allow operators to test different heating strategies without risking live production. For example, a digital twin could estimate the effect of lowering night-time temperature, switching fuel type, adding thermal storage, or changing crop species. It could also simulate emergency scenarios such as pump failure or fuel interruption and recommend corrective action. Although digital

twins remain an emerging concept in aquaponics, their potential is significant because aquaponic systems combine biological, hydraulic, thermal, and energy processes that are highly interconnected.

Predictive Thermal Control Models

Predictive thermal control models use current conditions and future forecasts to manage heating more efficiently than reactive on–off control systems. These models estimate future heat demand based on weather data, solar radiation, crop transpiration, greenhouse heat loss, fish metabolic heat demand, and thermal inertia of water tanks or storage systems. Model predictive control has been widely studied in greenhouse climate management because it can reduce energy use while maintaining crop conditions [53]. For aquaponics, predictive control is particularly valuable because water has high thermal mass and responds more slowly than air temperature. Fish tanks, sumps, and thermal storage tanks can therefore be heated strategically before expected cold periods rather than only after temperatures fall. Predictive control can also coordinate biomass boilers with solar heating, battery systems, or thermal storage units. This reduces fuel waste and temperature oscillation while improving system resilience. Future predictive models should integrate biological thresholds, such as minimum temperature for nitrification or species-specific fish stress limits, rather than relying only on engineering variables.

Advanced Biomass Reactors and Clean Combustion Technologies

The environmental performance of biomass heating depends heavily on combustion quality. Advanced biomass reactors are being developed to improve thermal efficiency, reduce emissions, and broaden feedstock flexibility. These include downdraft and fluidized-bed gasifiers, staged-combustion boilers, condensing biomass boilers, pyrolysis systems, pellet micro-CHP units, and reactors equipped with automated oxygen control [54]. Clean combustion technologies aim to reduce particulate matter, carbon monoxide, volatile organic compounds, and nitrogen oxide emissions through improved air staging, better fuel preparation, higher combustion temperatures, catalytic oxidation, ceramic filters, electrostatic precipitators, and advanced flue-gas cleaning systems. Such innovations are highly relevant to aquaponics because heating systems are often located close to greenhouses, workers, and sensitive biological systems. Future biomass-heated aquaponic systems are likely to combine clean combustion reactors, automated fuel handling, smart sensors, AI optimization, thermal storage, and renewable hybridization. These integrated technologies could make biomass heating more efficient, safer, and economically viable across both commercial and smallholder production systems.

Challenges, Research Gaps, and Knowledge Limitations

Limited Experimental Studies on Biomass-Heated Aquaponics

One of the most significant limitations in the current literature is the small number of experimental studies that directly evaluate biomass-heated aquaponic systems under controlled and commercial conditions. Aquaponics has received growing scientific attention in areas such as nutrient cycling, water quality, system design, fish-plant integration, and economic feasibility; however, research specifically focused on biomass as a heating source remains limited [1, 4]. Most available evidence is derived indirectly from greenhouse heating, aquaculture thermal management, hydroponics, or general bioenergy studies rather than dedicated aquaponic trials. This evidence gap makes it difficult to quantify the actual effects of biomass heating on crop yield, fish growth, nitrification stability, fuel consumption, and profitability within integrated systems. Long-term studies across different climates, scales, and production models are still needed. Future research should prioritize replicated experiments comparing biomass heating with electric, solar, fossil-fuel, and hybrid heating systems under identical aquaponic conditions.

Feedstock Supply and Quality Variability

Reliable biomass heating depends on consistent fuel availability and stable feedstock quality. In practice, biomass supply is often seasonal, geographically uneven, and influenced by competing uses such as animal bedding, household fuel, composting, mushroom production, or industrial processing. Crop residues may be abundant after harvest but scarce during other periods, while transport distance can significantly affect cost and carbon footprint [21]. Feedstock quality also varies in moisture content, ash content, particle size, calorific value, and contaminant levels. Wet biomass reduces combustion efficiency and increases smoke emissions, whereas high-ash materials such as rice husks or straw may create slagging and maintenance problems. These challenges are particularly important in aquaponics because unstable fuel quality can lead to unstable heat output, exposing fish, plants, and nitrifying bacteria to harmful temperature fluctuations [11]. Standard protocols for feedstock grading, storage, drying, and pre-treatment are still insufficiently developed for small and medium aquaponic applications.

Emission Control and Environmental Regulations

Although biomass is renewable, combustion can generate particulate matter, carbon monoxide, nitrogen oxides, volatile organic compounds, and other pollutants. Poorly designed or poorly operated systems may create local air-quality problems that undermine the environmental benefits of aquaponics [12]. Emission control is therefore a major technical and regulatory challenge. Regulatory frameworks for biomass heating vary widely among countries. Some regions have strict standards for particulate emissions, appliance certification, chimney design, and fuel quality, while others have limited enforcement or no specific regulations for small-scale biomass systems. This

inconsistency creates uncertainty for investors and farmers. More research is needed on low-emission biomass systems suitable for protected agriculture and aquaponics, especially in developing regions where regulatory systems may be evolving.

High Initial Cost and Maintenance Requirements

Biomass heating systems often require higher capital investment than basic electric heaters or simple fossil-fuel burners. Costs may include boilers, burners, fuel storage, conveyors, augers, heat exchangers, pumps, piping networks, insulation, control systems, thermal storage units, and installation works [27]. Additional expenses may arise from emission-control equipment and safety systems. Maintenance is another barrier. Combustion systems require ash removal, cleaning of heat exchangers, inspection of flues, servicing of motors and pumps, and regular monitoring of combustion performance. Fuel preparation such as drying, grinding, pelletizing, or briquetting may also increase labor demand and cost. These burdens are especially challenging for smallholders or start-up aquaponic enterprises with limited technical capacity and capital reserves [2].

Lack of Standardized Design Models

There is no widely accepted standard design framework for integrating biomass heating into aquaponic systems. Existing systems are highly site-specific and vary according to climate, fish species, crop species, greenhouse structure, biomass type, tank volume, insulation level, and management objectives. As a result, many systems are designed through trial and error rather than using validated engineering models. The absence of standardized design tools affects technology transfer, investor confidence, and scalability. Important design questions often remain unresolved, including optimum boiler size, thermal storage capacity, heat-exchanger sizing, pipe layout, control logic, and backup energy requirements. Predictive design models that integrate biological thresholds with engineering heat-load calculations remain limited. Future work should develop validated design software and decision-support tools specifically for biomass-heated aquaponics.

Limited Crop- and Fish-Specific Performance Data

Crop and fish responses to thermal regulation are species-specific, yet most studies report general system outcomes rather than detailed species-level performance. Warm-water fish such as tilapia may respond positively to heating, whereas cool-water species such as trout may require different strategies. Similarly, lettuce, basil, tomato, cucumber, and pepper differ in their temperature preferences, nutrient uptake patterns, and sensitivity to root-zone temperature [1, 4]. This limitation restricts the ability to recommend optimal heating strategies for specific fish-crop combinations. More studies are needed on species-specific thermal thresholds, growth response curves, feed conversion, disease resistance, nutrient uptake, crop quality, and yield under biomass-heated conditions. Research should also consider genotype differences, growth stage, stocking density, and seasonal production schedules.

Policy, Financing, and Adoption Barriers

Even when biomass heating is technically feasible, adoption may be constrained by weak policy support, limited financing and low institutional capacity. Many agricultural and energy policies treat food production, waste management, and renewable energy as separate sectors, which can hinder integrated systems such as biomass-heated aquaponics. Lack of incentives, unclear permitting procedures, and absence of technical standards may discourage investment. Access to finance is another major challenge. Smallholders and emerging enterprises often struggle to secure loans for innovative technologies with high upfront cost and uncertain returns. Risk perception among lenders may be high when local demonstration projects are absent. Extension services and training programs are also limited in many regions, reducing awareness and technical confidence among potential adopters [20, 21]. Addressing these barriers requires coordinated policy frameworks, concessional financing, technical training, demonstration farms, carbon-smart agriculture incentives, and support for local biomass supply chains. Without institutional support, the transition from promising concept to widespread practice is likely to remain slow.

Future Perspectives and Research Roadmap

Biomass-Solar Hybrid Heating for Aquaponics

One of the most promising future directions for aquaponic temperature management is the integration of biomass and solar energy into hybrid heating systems. Solar thermal collectors can provide daytime heat when solar radiation is available, while biomass systems can supply backup heat during night-time periods, cloudy weather, and cold seasons. This combination reduces dependence on a single energy source and improves system reliability. Hybrid renewable systems are increasingly recognized as effective solutions for agricultural heating because they combine the low operating cost of solar energy with the dispatchable nature of biomass fuel [28]. In aquaponics, hybrid systems can be configured to heat fish tanks, root zones, greenhouse air, or thermal storage tanks. Smart control systems can prioritize solar heat when available and activate biomass heating only when temperatures fall below biological thresholds. Future research should compare biomass-only, solar-only, and hybrid systems under different climatic conditions to determine optimum configurations, cost-effectiveness, and environmental performance.

Decentralized Food-Energy Systems

Biomass-heated aquaponics aligns strongly with the concept of decentralized food–energy systems, in which food production and renewable energy generation occur close to the point of use. Decentralized systems can reduce dependence on centralized power grids, imported fuels, long-distance food transport, and vulnerable supply chains. This approach is particularly relevant in rural settlements, islands, peri-urban zones, refugee settlements, and regions with weak infrastructure. Aquaponics already offers localized production of fish and vegetables through water recirculation and nutrient reuse. When combined with locally available biomass resources such as crop residues, manure, sawdust, or agro-processing waste, the system can also generate its own thermal energy. Such integration can strengthen resilience to energy shocks, climate variability, and market disruption. Future research should evaluate the social, economic, and governance dimensions of decentralized biomass-heated aquaponics, including ownership models, cooperative fuel supply systems, and community-scale production hubs [20, 21].

Climate-Smart Urban and Peri-Urban Agriculture

Urbanization and climate change are increasing pressure on conventional food systems. Controlled-environment agriculture is therefore gaining importance in urban and peri-urban areas where land is scarce, food demand is rising, and transport costs are high. Aquaponics is particularly attractive in these settings because it can produce fish and vegetables intensively using limited land and water resources [2]. Biomass heating can support climate-smart urban agriculture where organic wastes from markets, households, food processors, landscaping activities, or municipal green waste are available for energy recovery. In peri-urban areas, crop residues and livestock waste may also provide feedstock for biomass or biogas heating. However, urban deployment requires strict emission control, safe waste handling, noise reduction, and compliance with environmental regulations. Future systems may integrate rooftop aquaponics, vertical farming, district heating links, and clean biomass micro-boilers with advanced filtration technologies.

Opportunities for Developing Countries

Developing countries present significant opportunities for biomass-heated aquaponics because many regions possess abundant agricultural residues, expanding urban food demand, and growing interest in climate-resilient agriculture. Crop residues such as maize stalks, rice husks, coffee husks, sugarcane bagasse, cassava peels, and groundnut shells are often underutilized or openly burned. These materials could provide low-cost heating fuel for aquaponic systems when appropriate technologies are available [21]. Biomass-heated aquaponics may also support nutrition, employment, youth entrepreneurship, and import substitution through local production of fish and vegetables. In regions where electricity supply is unreliable or expensive, locally sourced biomass can improve energy security. Nevertheless, adoption requires affordable equipment, training, access to finance, maintenance services, and locally adapted designs. Demonstration farms and public-private partnerships will be important for translating technical potential into practical adoption [20].

Pathways toward Net-Zero Aquaponic Production

The transition toward net-zero aquaponic production requires reduction of direct and indirect greenhouse gas emissions across the full production chain. Heating is often one of the largest energy burdens in controlled-environment aquaponics, making decarbonization of thermal energy a strategic priority. Biomass heating can contribute to net-zero pathways when sustainable residues replace fossil fuels, transport distances are minimized, combustion efficiency is high, and air emissions are controlled [42]. Additional pathways include solar integration, thermal storage, efficient insulation, low-energy pumps, smart climate control, waste-heat recovery, water recycling, and sustainable feed sourcing for fish. Carbon accounting should also include emissions from biomass processing, logistics, and equipment manufacture. Future research should develop standardized carbon-footprint models for aquaponic systems that compare alternative heating scenarios and identify the most cost-effective decarbonization pathways.

Proposed Research Framework for Future Studies

A structured research roadmap is needed to advance biomass-heated aquaponics from concept to scalable practice. Future studies should focus on six interconnected priorities:

a. Controlled Experimental Validation: Long-term replicated trials should compare biomass, solar, electric, fossil-fuel, and hybrid heating systems under identical aquaponic conditions. Performance indicators should include fish growth, crop yield, feed conversion ratio, nutrient uptake, nitrification efficiency, energy use, and profitability.

b. Species-Specific Thermal Optimization**:** Research should identify optimum temperature ranges for major fish-crop combinations under biomass-heated conditions. Separate evaluation is needed for warm-water fish, cool-water fish, leafy vegetables, herbs, and fruiting crops.

c. Engineering Design and Modeling**:** Validated design tools are needed for boiler sizing, heat-exchanger selection, thermal storage capacity, fuel consumption prediction, and greenhouse heat-load estimation. Digital twins and predictive control models should be incorporated into future design frameworks.
d. Environmental and Health Assessment**:** Future work should quantify greenhouse gas emissions, particulate matter, ash quality, life-cycle impacts, and occupational health risks associated with different biomass technologies.
e. Socio-Economic and Policy Research**:** Studies should examine adoption barriers, financing models, cooperative biomass supply chains, extension systems, and the role of policy incentives in accelerating uptake.
f. Regional Adaptation Pathways**:** Future research should develop region-specific models for tropical, temperate, arid, urban, and peri-urban contexts, recognizing that climate, feedstock availability, infrastructure, and market conditions differ substantially across locations.

This roadmap indicates that the future of biomass-heated aquaponics will depend on interdisciplinary collaboration among agricultural scientists, aquaculture specialists, engineers, economists, environmental scientists, and policymakers. Integrated research of this kind can help transform aquaponics into a low-carbon, climate-resilient, and commercially viable food production system.

CONCLUSION

Biomass-based heating systems present a viable and innovative option for addressing one of the most important constraints in aquaponic crop production: thermal instability. The evidence reviewed shows that well-managed biomass heating can maintain suitable temperatures for fish, plants, and nitrifying bacteria, thereby improving productivity, system resilience, and year-round operation. The use of agricultural residues, wood wastes, manure, and other organic resources also strengthens the circular economy value of aquaponics through waste-to-energy conversion and reduced reliance on fossil fuels. The sustainability and profitability of biomass-heated aquaponics are not automatic outcomes. Success depends on appropriate technology selection, clean combustion, reliable feedstock supply, efficient heat transfer, emission control, and robust management systems. High capital costs, maintenance needs, and limited technical knowledge remain important barriers, especially for smallholder producers. At the same time, advances in automation, artificial intelligence, hybrid renewable systems, and predictive control are expanding future opportunities. Further experimental research, standardized engineering models, supportive policies, and accessible financing mechanisms are required to accelerate adoption. With these conditions in place, biomass-heated aquaponics can contribute significantly to climate-smart agriculture, decentralized food-energy systems, and the transition toward net-zero food production.

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