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Filters and media used in aquaponic system filtration: A systematic review

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ABSTRACT

This study presents a systematic review of a compilation of articles on different filters and media used in aquaponic systems, encompassing 89 indexed publications from the period 2008 to 2024. The research analyzed the efficiency of different types of filters, including mechanical, biological, and bacteriological, as well as the application of various filtration media, such as bio-balls, sand, and natural materials (*e.g.*, açaí seeds and biochar). The results indicated an increasing trend in publications on this topic, with the United States of America and Malaysia leading the research in this field. While American studies focus on parameters such as hydraulic loading rate, research in Malaysia emphasizes the use of sand as a filtering medium for solid and nutrient removal. The analyzed media range from simple substrates, such as gravel and expanded clay, to more advanced technologies, including hollow fiber membranes and biochar, demonstrating the diversity of approaches in optimizing filtration in aquaponics. This review highlights that the appropriate selection of filters and media plays a key role in the sustainability and efficiency of aquaponic systems, directly influencing water quality, waste removal, and environmental stability in production settings.

Keywords: Aquaponics; Filtration; Sustainability; Nutrient recycling; Filtration media.

Filtros e meios utilizados na filtração de sistemas aquapônicos: Uma revisão sistemática

RESUMO

Este estudo apresenta uma revisão sistemática sobre os filtros e mídias utilizados em sistemas aquapônicos abrangendo 89 publicações indexadas no período de 2008 a 2024. A pesquisa analisou a eficiência dos diferentes tipos de filtro, incluindo mecânico, biológico e bacteriológico, bem como a aplicação de diversas mídias filtrantes, como *bio balls*, areia e materiais naturais (por exemplo, sementes de açaí e biochar). Os resultados evidenciaram um crescimento das publicações sobre o tema, com Estados Unidos e Malásia liderando as pesquisas na área. Enquanto estudos estadunidenses se concentram em parâmetros como taxa de carga hidráulica, as investigações na Malásia destacam o uso de areia como meio filtrante para remoção de sólidos e nutrientes. As mídias analisadas variam desde substratos simples, como cascalho e argila expandida, até tecnologias mais avançadas, como membranas de fibra oca e biochar, evidenciando a diversidade de abordagens na otimização da filtração em aquaponia. Concluiu-se que a seleção adequada de filtros e mídias desempenha um papel essencial na sustentabilidade e eficiência dos sistemas aquapônicos, influenciando diretamente a qualidade da água, a remoção de resíduos e a estabilidade do ambiente produtivo.

Palavras-chave: Aquaponia; Filtração; Reciclagem de nutrientes; Mídias de filtração; Sustentabilidade.

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INTRODUCTION

Aquaponics is the integration of recirculating aquaculture systems (RAS) and hydroponic cultivation systems (soilless plant production), in which nutrients dissolved in the water originating from the cultivation of aquatic animals, especially fish, are used for plant growth (Amin et al., 2023; Tetreault et al., 2023). By combining RAS and hydroponics, aquaponics offers significant advantages over the isolated operation of each system (Teng et al., 2024). These advantages include nutrient recycling and reducing of effluent discharge (Prastowo et al., 2024), water recirculation, that leads to substantial water savings compared to conventional systems (Schmautz et al., 2021a), the simultaneous production of animal protein and vegetables, which diversifies output and increases the potential for economic return (Yep & Zheng, 2019), and a decreased need for chemical fertilizers (Yang & Kim, 2020a). Additionally, greater production efficiency per unit area allows for higher overall yields in limited spaces (Goddek et al., 2015).

The nutrients absorbed by plants in aquaponic systems originate from the feed provided to aquatic organisms. Once introduced into the system, the feed is consumed and subsequently excreted in the form of nutrient-rich compounds, primarily nitrogen. Uneaten feed residues and excretions from aquatic organisms become sources of nitrogenous compounds that may be potentially toxic, such as un-ionized ammonia (NH_3). When present in excess, this compound can accumulate in tissues, trigger metabolic disorders, increase body pH, and damage respiratory structures, such as the gills of fish and shrimp, resulting in stress and physiological impairment (Hamid et al., 2024). Furthermore, exposure to high concentrations of ammonia reduces appetite, redirects energy utilization, and decreases growth rates (Dawood et al., 2023). For safe growth, it is recommended to maintain ammonia levels at or below 0.05 mg/L (Deviona et al., 2020).

Moreover, it has been reported that nitrogenous compounds, particularly ammonia excreted in aquaponic systems, may serve as a direct nitrogen source for plants. However, excessive concentrations can negatively affect water quality and hinder plant development (Endut et al., 2016).

The bacteria present in the system, especially in the filters, promote microbial nitrification by converting ammonium (NH_4^+-N) into plant-assimilable compounds such as nitrate (NO_3^--N), while also making other essential nutrients available, including phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and micronutrients, such as iron (Fe), manganese (Mn), and zinc (Zn). This process occurs mainly through bacterial activity in the filters and rhizosphere zones, involving both nitrification, which converts ammonium into assimilable nitrate, and the mineralization of organic matter, which releases phosphorus, potassium, calcium, magnesium, and micronutrients. In addition, solubilizing bacteria contribute to the release of micronutrients such as iron, manganese, and zinc, thereby increasing their availability to plants (Eck et al., 2019; Lam et al., 2015; Lobanov et al., 2021; Prastowo et al., 2024; Wongkiew et al., 2017). Once mobilized, these nutrients pass through the hydroponic beds, in which they are absorbed by plants and used for growth, while simultaneously contributing to water purification and creating a mutually beneficial ecosystem for both aquatic organisms and plants (Prastowo et al., 2024; Wongkiew et al., 2017; Yep & Zheng, 2019).

Aquaponics can be implemented using different cultivation configurations, with the most notable being deep water culture (DWC), in which plants are placed on floating rafts with their roots fully submerged; the nutrient film technique (NFT), characterized by a thin film of nutrient-rich water that continuously flows over the roots; and the media bed (MB), which employs solid substrates such as gravel or expanded clay to support the plants and simultaneously function as both biological and mechanical filters (Goddek et al., 2015; Somerville et al., 2014).

According to Wongkiew et al. (2018), aquaponic systems are essentially composed of three main components: a tank for aquatic animals, a filtration system, and a hydroponic growing bed. Among these components, the filtration system is considered the key element of aquaponics (Boaventura et al., 2018; Lennard & Goddek, 2019; Timmons et al., 2018). The filtration system commonly used by various researchers typically consists of a mechanical filter or sedimentation unit and a biological filter. However, additional filtration units, such as ultraviolet filters, can also be incorporated into the system.

According to Teng et al. (2024), the mechanical filter or sedimentation unit, typically placed after the aquatic organism tanks and before the biofiltration stage, removes suspended solids such as uneaten feed and feces. This prevents root clogging and the formation of anoxic zones, which can lead to the production of toxic compounds such as hydrogen sulfide and methane (Thorarinsdottir, 2015). In most cases, this type of filter is designed without internal filter media, but some researchers have used sand, gravel, and filter mats to aid in the physical removal of solids. This stage is essential to prevent excess particulate matter from impairing the performance of the biofilter and reducing nitrification efficiency. The biological filter, in turn, is usually filled with various types of media, and among the most used are bio-balls, ceramic rings, and K1 (Kaldness). It is responsible for the oxidation of ammonia (NH_3) and nitrite (NO_2^-), both of which are toxic to fish and shrimp, into nitrate (NO_3^-), a form that is readily assimilated by plants (Prastowo et al., 2024; Wongkiew et al., 2017). The integrated operation of these filtration stages ensures the maintenance of safe levels of nitrogenous compounds, reduces stress on the fish and shrimp, enhances nutrient uptake by the plants, and consequently improves the productive performance of the cultured organisms.

This interdependence between mechanical and biological filters has guided the search for technological alternatives aimed at increasing the efficiency of recirculating systems. Espinal and Matulić (2019) reported that in Europe and the United States of America, researchers have attempted to adapt domestic wastewater treatment technologies to improve water reuse in recirculating systems. Among these technologies, notable examples include activated sludge processes, submerged and down-flow biofilters, as well as various mechanical filtration systems. Improving filtration systems has been a priority to enhance aquaponic efficiency, resulting in the classification and documentation of biofilters, as well as the development of guidelines for farmers and system designers (Drennan II et al., 2006; Gutierrez-Wing & Malone, 2006). Some of the most used models include moving bed bioreactors (MBBR) (Rusten et al., 2006), fluidized sand filter bioreactors (Summerfelt, 2006), and fixed-bed bioreactors (Emparanza, 2009).

Regarding filter composition, Somerville et al. (2014) proposed a filtration model for small-scale NFT systems consisting of a set of two filters: a mechanical filter for solid removal, and a biological filter containing expanded clay as a substrate for the colonization of nitrifying bacteria. However, in more complex aquaponic systems, filtration media with higher capacity are used, such as sintered glass, ceramic, K1 plastic media, and bio-balls. Although these materials are effective, they can significantly increase implementation costs.

Considering this, several studies have investigated alternative and lower-cost materials, aiming to maintain filtration efficiency without compromising the economic viability of aquaponic systems. Zhang et al. (2020) evaluated the performance of lignocellulosic materials (corn straw, wheat straw, and sawdust) combined with ceramsite in aquaponic filtration systems, demonstrating their feasibility for nutrient recovery from fish sludge. Khiari et al. (2020) analyzed the use of biochar in effluent filtration, highlighting its potential as a renewable and low-cost biomass. Gao et al. (2022) investigated sludge removal using sponges in aerated biological filters, emphasizing their effectiveness in maintaining water quality. Other studies have also explored strategies to enhance the nitrification process in biological filters. Zou et al. (2016) tested the addition of nitrifying agents to accelerate bacterial colonization and optimize the conversion of nitrogen compounds. Sirakov (2019) evaluated the impact of light intensity (both natural and artificial) on nitrogen and phosphorus compounds in water, as well as its influence on plant productivity. Meanwhile, Setiadi et al. (2019) analyzed three types of filters—settling, semi-anaerobic, and aerobic—and observed that implementing an efficient filtration system resulted in a higher survival and growth rate of catfish, increased plant biomass, and improved water quality.

Given this context, the present systematic review aimed to characterize studies on filters and media used in aquaponic systems from 2008 to 2024, compiling information on the employed techniques, materials used, and the efficiency of different filtration configurations across various countries. In addition to consolidating existing knowledge in the field, this study also sought to compile information on the current state of research in this area and provide a foundation for future advancements in optimizing filtration in aquaponic systems.

MATERIALS AND METHODS

A literature review was conducted on scientific articles from 2008 to 2024, indexed in any language, that examined aspects related to the science of filtration systems in aquaponics. Based on this premise, a literature search was performed in the Institute for Scientific Information (ISI) Scopus database. The search was conducted using the following term (in the title) related to the topic: “Aquaponic”, and ‘filter’ or ‘filtration’* (all fields). Through the search in the ISI database, 175 documents were found (Fig. 1). The studies were then selected based on exclusion criteria adapted from Moher et al. (2009). For the first exclusion criterion, the following types of documents were excluded: conference papers, book chapters, review articles, theses, dissertations, and technical reports, with the last three not being indexed.

Regarding the type of source, conference proceedings, book series/collections, and books were excluded. In terms of publication stage, articles that were still in press were also excluded. Secondly, articles were excluded if the full document was not available online (12 documents). Thirdly, articles were excluded if, after reading the full text, they did not mention the use of filter(s) as a separate compartment within the aquaponic system (33 documents). Consequently, systems that used only the hydroponic grow bed as a filtration medium were excluded. For each included article, information was extracted regarding:

- Year of publication;
- Country where the experiment was conducted;
- Study objective;
- Type of water used;
- Cultivation system;
- System structural configuration;
- Number of filters;
- Types of filters;
- Filter media used.

The extracted data were organized into a spreadsheet to facilitate comparative analysis.

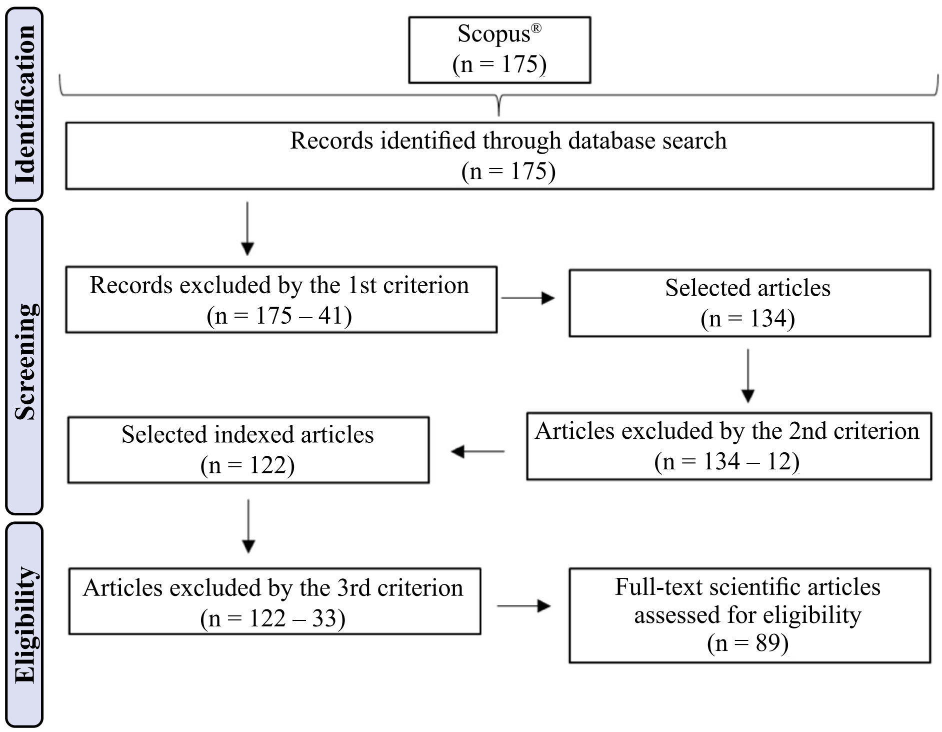


Figure 1. Flowchart describing the document search protocol considered in the systematic review.

RESULTS

Historical perspective of publications on aquaponics

The analysis of the 89 reviewed articles revealed an exponential increase in the number of publications on filtration in aquaponic systems from 2008 to 2024 (Fig. 2). The data indicated that the use of filters in studies is diverse, with growing interest in the efficiency of solid and nutrient removal in aquaponic systems. An upward trend was observed starting in 2015, with a significant rise in publications after 2020, reaching a peak of 15 publications by September 2024.

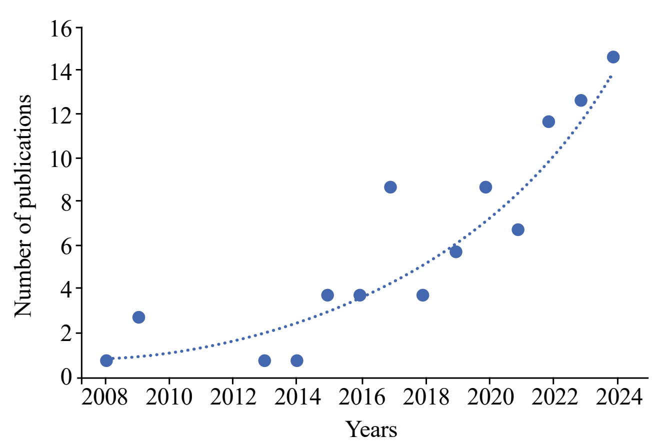
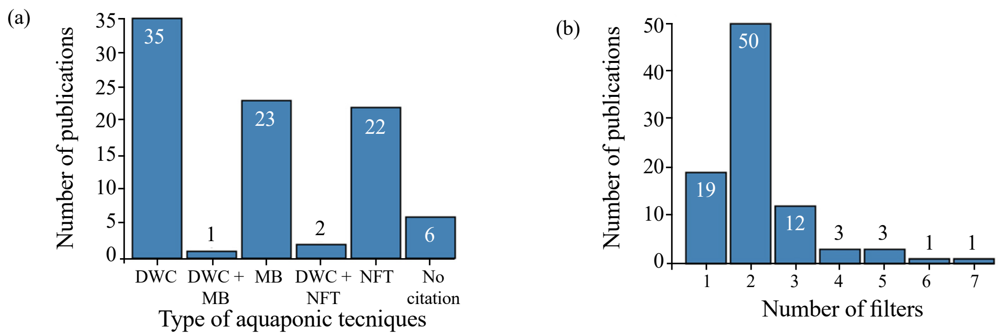


Figure 2. Number of publications per year on aquaponics citing the use of filter(s) published between 2008 and 2024 (n = 89 publications).

Cultivation systems, structural configuration, and filtration methods

The predominant cultivation systems in the reviewed studies were DWC (n = 35), MB (n = 23), and NFT (n = 22), respectively (Fig. 3a).



DWC: deep water culture; MB: media bed; NFT: nutrient film technique; NI: not informed.

Figure 3. Number of publications per (a) aquaponic techniques used in the studies and (b) quantity of filters used in the published studies (n = 89 publications).

Regarding system configuration, coupled models were predominant (n = 78), followed by decoupled systems (n = 5) and hybrid systems that combine both approaches (n = 6).

The analysis revealed that most studies employed two filters, followed by those using only one filter. Additional filters (three or more) were less common (Fig. 3b). The most common filtration types were mechanical + biological combinations (n = 42), while systems using only biological filtration (n = 07) or only mechanical filtration (n = 5) were less frequently reported. Advanced systems, such as biofilm reactors and ultraviolet (UV) filters, were also documented (Table 1).

The most used materials were bio-balls (n = 16), sand (n = 14), and K1 (n = 11), which were mainly employed in the biological filter, whereas gravel (n = 7) was used in the mechanical filter, highlighting the relevance of these materials for filtration efficiency. In addition, natural materials such as coconut fiber and açaí seeds were also reported, reflecting a growing trend toward sustainability in aquaponic systems (Table 2).

Table 1. Combinations of filters used in the studies (n = 89 publications).

Filter combinations	N
2 Mechanical (Clarifier), 4 Mechanical (Rectangular Tanks) & Degasser	1
2 Mechanical (Drum & Radial Flow Settler), 2 Biological (BFO & Anaerobic Digester) + Ultraviolet	3
Biological	7
Biological (DHS), Physical & Biological (moving bed bioreactors—MBBR)	1
Biological (Upflow & Downflow)	1
Biological + Cascade Aeration Tank	1
Bio-mechanical	4
Bio-mechanical + Biological	1
Denitrifier, Bio-mechanical & Wool Filter	1
Fibrous Filter + Biological	1
Vertical Filter, Biological (Horizontal Sand Filter) + Biological (Sump)	1
Vertical Filter, Biological (Sump) + Bio-mechanical	1
Membrane Photobioreactor	1
Mechanical	4
Mechanical (Clarifier) + Biological	6
Mechanical (Clarifier) + Biological (Upflow & Downflow)	1
Mechanical (Clarifier) + Biological (Mineralization Tank)	1
Mechanical (Clarifier) + Mechanical (Separator)	1
Mechanical (Clarifier), Biological & Solid Subsystem	1
Mechanical (Clarifier), Biological, Degasification Tank + pH Correction Tower	1

Continued...

Continuation

Filter combinations	N
Mechanical (Clarifier), Mechanical (Drum Filter) + Biological (MBBR)	1
Mechanical (Lamella Settler) + Biological (Rotating Arm Drip Filter)	1
Mechanical (Lamella Settler), Mechanical (Separator) + Vertical Wetland Zone	1
Mechanical (Vertical Settler) + Biological (MBBR)	1
Mechanical (Settler)	1
Mechanical (Settler) + Biological	10
Mechanical (Settler) + Biological (Upflow & Downflow)	1
Mechanical (Settler) + Biological (MBBR)	1
Mechanical (Settler), Biological (MBBR) + Sponge Filter	1
Mechanical (Settler), Biological, Sequential batch reactor (SBR) + Anaerobic Fermenter	1
Mechanical (Settler), Bio-mechanical + Biological	1
Mechanical (Suction) + Biological	1
Mechanical (Drum) + Biological	1
Mechanical (Drum), Biological (MBBR) + Reactor (UASB)	1
Mechanical (Drum), Screw Press + Mechanical (Settler)	1
Mechanical + Biological	18
Mechanical + Bio-mechanical	3
Mechanical, Biological + Biological (MBBR)	1
Mechanical, Biological + Ultraviolet	1
Mechanical, Degasser, Biological + Denitrifier	1
Sludge Tank	2

N: number of articles cited for each filter combination.

Table 2. Types of materials and use frequency in the analyzed studies (n = 89 publications).

Material	N	Filter type	Material	N	Filter Type
Activated carbon	1	M	Layered fiberglass	1	M
Bioactive corals	3	B	Marine shells	1	M
Bio-balls	16	B	Mesh net	1	B
Bio-barrels	1	B	Microspheres	1	M
Biocarriers	1	MB	Microwave pyrolysis biochar	1	B
Biochips	2	B	Non-woven fabric	1	B
Biofilm supports	1	B	Not specified	12	B
Biofilter media	1	B	Nylon mesh	1	M
Bio rings	1	B	Nylon net	2	B
Cationic polyacrylamide flocculant	1	B	Orchard net	2	B
Ceramic rings	5	B	Oyster shells	1	B
Ceramsite	1	B	Pad blocks	1	B
Cloth bag	1	B	Plastic bottle caps	1	
Coarse aggregates	1	B	Plastic mesh rings	1	B

Continued...

Continuation

Material	N	Filter type	Material	N	Filter Type
Coarse filter (EHEIM FIX)	1	B	Plastic tubes	1	B
Coconut husk	1	M	Plexiglass sheets	1	B
Coconut peat	1	B	Polyester fibers	1	B
Corn straw	1	B	Polyethylene biocarriers	1	B
Corrugated plastic hose pieces	2	MB	Polyethylene fabric	1	M
Crushed coral	1	M	Polyethylene liner	1	M
Cubic sponge supports	1	B	Polyethylene particles	1	M
Cylindrical plastic biofilter media	1	B	Polyvinylidene (PVD) hollow fiber membrane	1	M
ECO Pond Chip	1	B	Polyvinylidene fluoride (PVDF) hollow fiber membrane	1	M
Euterpe oleracea seeds	2	B	PPI 20 sponge	1	M
Expanded clay	2	B	Pumice stone	1	B
Extruded polystyrene foam	1	B	Polyvinyl chloride (PVC)	1	B
Fabric bag	1	B	Rolled pebble	1	M
Filling material	1	B	Sand	14	B
Filter bag	1	M	Sand gravel	1	B
Filter cotton	1	M	Sawdust	1	B
Filter mats	2	M	Shade cloth	1	B
Fine mesh	3	M	Sieve	1	B
Fine mesh sieve	1	M	Spheres	1	B
Gravel	7	M	Sponge	1	M
Handmade bio-balls	1	B	Stainless steel sieve (150 µm)	1	M
Hollow fiber membrane	1	B	Ultraviolet radiation lamps	3	M
Japanese filter mats	1	B	Wheat straw	1	B
K1 (Kaldness)	11	M	Wire mesh	1	B
K3	1	M	Wool	2	B
Lava grains	1	B	Zeolite	1	B

N: number of articles cited for each material; M: mechanical; B: biological; MB: mechanical and biological.

Geographical distribution of publications on aquaponics

Studies on filtration in aquaponics were recorded in 20 different countries (Table 3), with the United States of America leading in the number of publications (n = 14), followed by Malaysia (n = 11), Germany (n = 6), China (n = 6), Greece (n = 6), Mexico (n = 6), Brazil (n = 5), and Egypt (n = 5). Each country demonstrated specific research focuses. The United States of America stands out due to its high volume of studies, driven by its well-established research infrastructure and technological innovation. While Germany focuses on the development of decoupled systems and advanced filtration techniques, Brazil explores the use of natural substrates as a filtering medium, seeking sustainable and cost-effective alternatives.

Table 3. List of countries that have published studies on aquaponics and reported the use of filters, which were included in the present review according to the established criteria (n = 89 publications).

Country	N	Country	N	Country	N	Country	N
Belgium	2	Germany	6	Japan	1	Slovenia	1
Brazil	5	Greece	6	Kenya	2	Spain	2
Canada	1	Hungary	1	Malaysia	11	Switzerland	4
China	6	India	2	Mexico	6	Taiwan	3
Egypt	5	Indonesia	3	Saudi Arabia	2	Thailand	1
France	1	Israel	1	South Korea	1	United States of America	14

N: number of articles cited for each country.

Water type and animal and plant species used in the articles

Freshwater dominated the reviewed aquaponic systems, representing 81 studies (91%), whereas both brackish and saltwater were reported in only four cases each (4.5%) (Table 4). The crop most frequently cultivated was *Lactuca sativa* (n = 32), which has consistently been identified as a model species due to its rapid physiological response, short production cycle, and high market value. Other widely reported species included *Ocimum basilicum* (n = 15) and *Solanum lycopersicum* (n = 12), confirming their commercial importance and adaptability to aquaponic conditions. *Ipomoea aquatica* (n = 10) was particularly relevant in Asian studies, since in Asian countries it is traditionally cultivated in integrated systems owing to its tolerance to nutrient variability and ease of harvest.

In contrast, experiments with brackish water were limited and involved only moderately salt-tolerant species, such as *O. basilicum* and *Crithmum maritimum*. Saltwater systems were even scarcer and were primarily restricted to halophytes (*Batis maritima*, *Sesuvium portulacastrum*, *Salsola komarovii*, and *Sarcocornia ambigua*), reflecting experimental efforts to explore the reuse of effluents from marine aquaculture (Table 4). The analysis of the Table 5 shows that aquaponic systems remain predominantly associated with freshwater species, with tilapia (*Oreochromis* spp.) being the most frequently reported (n = 41).

Table 4. Plant species used in the articles and their correlations with water type (n = 89 publications).

Plant species	Water type			Plant species	Water type		
	Freshwater	Brackish	Saltwater		Freshwater	Brackish	Saltwater
Allium ascalonicum	1	0	0	*Mentha spicata*	3	1	0
Allium schoenoprasum	1	0	0	*Melissa officinalis*	1	0	0
Apium graveolens	1	0	0	*Mentha canadensis*	1	0	0
Artemisia annua	1	0	0	*Mentha piperita*	1	0	0
Amaranthus dubius	1	0	0	Microgreens	1	0	0
Atriplex hortensis	1	0	1	*Nasturtium officinale*	1	0	0
Beta vulgaris	1	0	0	*Ocimum basilicum*	15	1	0
Brassica oleracea	2	0	0	*Origanum vulgare*	1	0	0
Brassica juncea	4	0	0	*Petroselinum crispum*	3	0	0
Brassica chinensis	1	0	0	*Persicaria odorata*	1	0	0
Brassica rapa	3	0	0	*Portulaca oleracea*	1	0	0
Batis maritima	2	0	2	*Perilla frutescens*	1	0	0
Capsicum annuum	1	0	0	*Plantago coronopus*	1	0	1
Chlorella vulgaris	1	0	0	*Psophocarpus tetragonolobus*	1	0	0
Corchorus olitorius	1	0	0	*Rumex acetosa*	1	0	0
Coriandrum sativum	2	0	0	*Solanum lycopersicum*	12	1	0
Crithmum maritimum	1	1	0	*Solanum melongena*	2	0	0
Cucumis sativus	7	0	0	*Samambaia azolla*	1	0	0
Cucurbita pepo	1	0	0	*Spinacia oleracea*	1	0	0
Eruca sativa	1	0	0	*Salvia officinalis*	1	0	0
Euterpe oleracea	3	0	0	*Salvia hispanica*	1	0	0
Ipomoea aquatica	10	0	0	*Salsola komarovii*	1	0	1
Kalanchoe blossfeldiana	1	0	0	*Sarcocornia ambigua*	1	0	1
Lavandula angustifolia	1	0	0	*Sesuvium portulacastrum*	2	0	2
Lactuca sativa	32	0	0	*Tagetes erecta*	1	0	0
Lycopersicon esculentum	2	0	0	Leafy vegetables	2	0	0

Table 5. Aquatic animal species used in the articles and their correlations with water type (n = 89 publications).

Aquatic animal species	Water type		
	Freshwater	Brackish	Saltwater
Acipenser ruthenus	1	0	0
Acipenser sp.	1	0	0
Aspatharia chaiziana	1	0	0
Carassius auratus	5	0	0
Catfish	1	0	0
Cherax quadricarinatus	1	0	0
Clarias gariepinus	12	0	0
Colossoma macropomum	3	0	0
Cyprinus carpio	6	0	0
Hybrid lemon fin barb	2	0	0
Lates calcarifer	1	0	0
Litopenaeus vannamei	3	2	2
Liza ramada	1	0	0
Macrobrachium rosenbergii	2	0	0
Micropterus pallidus	1	0	0
Micropterus salmoides	1	0	0
Mugil cephalus	1	0	0
Oncorhynchus mykiss	2	0	0
Oreochromis spp.	41	1	0
Oreochromis mossambicus	1	0	0
Oxyeleotris marmorata	2	0	0
Pangasianodon hypophthalmus	2	0	0
Perca flavescens	1	0	0
Perca fluviatilis	1	0	0
Sciaenops ocellatus	0	0	1
Sparus aurata	0	1	0
Xiphophorus sp.	0	0	1

DISCUSSION

The findings demonstrated that the evolution of knowledge on filtration in aquaponic systems has been strongly influenced by the growing environmental awareness and the pursuit of more sustainable and efficient production methods (Goddek et al., 2015; Kloas et al., 2015). The increase in publications after 2015 coincides with the introduction of decoupled systems, which represented a milestone by enabling the separation of aquaculture and hydroponic flows. This innovation expanded nutrient control and allowed for specific conditions in each compartment (Monsees et al., 2017; Suhl et al., 2018).

The adoption of decoupled systems reflects the need for greater efficiency in water and nutrient management. While coupled systems present limitations in adjusting nutrient concentrations, decoupled configurations provide higher precision in maintaining optimal conditions for both aquatic organisms and plants. They also facilitate the removal and management of solid and organic waste, preventing its accumulation in the hydroponic unit (Eck et al., 2019; Goddek & Keesman, 2020; Karimanzira et al., 2016; Kloas et al., 2015). This characteristic underscores their relevance as an alternative for enhancing productivity while reducing environmental impacts.

Cultivation systems, structural configuration, and filtration methods

According to Somerville et al. (2014), aquaponic filtration systems may integrate different types of filters: mechanical (such as clarifiers and sedimentation units), biological (such as moving bed and trickling filters), and bacteriological (*e.g.*, ultraviolet filters). Among these, the biofilter plays a central role, as it is in which nitrification occurs—a process essential to reducing ammonia toxicity and ensuring water quality (Boaventura et al., 2018; Timmons et al., 2018).

The analysis of the studies revealed that the combination of mechanical and biological filtration is the most recurrent configuration, recorded in 43 publications, as reported by Armenta-Bojórquez et al. (2021), Castillo-Castellanos et al. (2016), and Pérez-Urrestarazu et al. (2019). This predominance confirms that integrated systems provide greater stability and efficiency in maintaining water quality. Although exclusively biological (n = 8) or solely mechanical filters (n = 5) were also used, as observed by Kim et al. (2023), Mulay and Reddy (2021), and Wongkiew et al. (2017), such simplified arrangements appear to be associated with specific purposes or experimental contexts of lesser complexity.

In more sophisticated systems, additional technologies have been incorporated, including MBBR and sponge filters (Shaw et al., 2023), as well as the combination of mechanical filters, drum filters, and moving bed reactors (Xu et al., 2023). Other approaches have explored advanced technologies such as membrane photobioreactors (Ji et al., 2022) and ultraviolet filters (Elumalai et al., 2017), primarily for microbial control and water purification.

The literature also highlights a wide variety of methods, ranging from traditional, low-cost solutions, such as sand filters (Endut et al., 2009) and trickle filters (Graber & Junge, 2009), to complex multi-layer systems that integrate drum, biological, ultraviolet, mechanical, and anaerobic digesters (Schmautz et al., 2021a; 2021b). The use of drum filters combined with press filters, as reported by Khiari et al. (2020), illustrates practices aimed at treating large volumes of water. The increasing adoption of advanced technologies such as MBBR and ultraviolet reflects a clear trend toward more efficient and sophisticated filtration systems.

Structurally, the introduction of decoupled aquaponic systems proposed by Kloas et al. (2015) is noteworthy. In this model, known as the double recirculating aquaponic system (DRAPS), two independent circuits are employed: a RAS for aquatic organisms, and a hydroponic unit for plants. The flows are connected unidirectionally through a one-way valve, allowing water transfer from the RAS to the hydroponic reservoir. This design enables optimization of pH and nutrient composition independently, preventing negative interactions and increasing the productivity of both compartments. In contrast, in coupled systems (single recirculating aquaponic systems—SRAPS), the hydroponic unit integrates into the filtration process, contributing to nutrient removal from aquaculture effluent and reducing the need for conventional biofiltration (Kloas et al., 2015).

This structural difference has direct implications for species selection. In SRAPS, more robust species such as *Carassius auratus* and *Xiphophorus* sp. predominate, as they can tolerate water quality fluctuations. In DRAPS, the presence of independent filtration units, including lamella clarifiers and complete biofilters in the RAS, allows for stricter water quality control, enabling the culture of more demanding, high-value species, including brackish and marine fish such as *Sparus aurata*, *Litopenaeus vannamei*, and *Sciaenops ocellatus* (Kloas et al., 2015; Su et al., 2020; Zhang et al., 2020).

Regarding filter media, a wide diversity of substrates is observed. Among artificial options, bio-balls (18%) and K1 carriers (12.4%) stand out, recognized for their high surface area that supports the colonization of nitrifying bacteria (Boxman et al., 2017; Hamid et al., 2024; Lam et al., 2014). Traditional materials such as sand and gravel also remain relevant, providing effective removal of suspended solids (Bartelme et al., 2019; Endut et al., 2009; Helmy et al., 2023).

More recently, innovative and sustainable materials have been tested, such as biochips, corals—employed as both filtering media and natural pH regulators (Lam et al., 2014; 2015)—, hollow fiber membranes for ultrafiltration, and zeolite, particularly effective in ammonia removal. Simultaneously, the use of natural and organic materials, including coconut husk, sawdust, straw, and açaí seeds (*Euterpe oleracea*), reflects the pursuit of environmentally friendly, low-cost solutions. Recent studies confirm their effectiveness in both biofiltration and solids removal, while also demonstrating additional benefits such as seed germination (Boxman et al., 2017; Nascimento et al., 2023; Natividade et al., 2024; Zhang et al., 2020).

The use of microwave-pyrolyzed biochar suggests the exploration of advanced and sustainable water treatment technologies, providing porous surfaces for bacterial biofilm growth and facilitating ammonia-to-nitrate conversion for plant nutrition (Su et al., 2020). The diversity of filtration materials reported across aquaponics literature underscores the need to adapt systems to the specific requirements of each aquatic environment. At the same time, the adoption of natural and organic substrates highlights an increasing concern with sustainability.

Geographical distribution of publications on aquaponics

In studies conducted in the United States of America (n = 14), all experiments employed coupled systems, predominantly based on the DWC cultivation technique (n = 12). Key research topics included hydraulic loading rates and their effects on water quality and plant growth (Boxman et al., 2017; Yang & Kim, 2020b). Boxman et al. (2017) observed that, in addition to the use of K1 media in biofilters, coconut fiber applied as a plant support significantly contributed to the denitrification process.

Other American studies, such as Dorick et al. (2023), investigated biofilm formation and reported that the presence of *Aeromonas hydrophila* compromised water quality prior to filtration, but the installation of biofilters substantially reduced this occurrence, thereby improving water quality parameters. In a complementary study, Dusci et al. (2022) evaluated three filtration methods (mechanical, mineralization tank, and biofilter) and found a limited impact on suspended solids removal, with the greatest reduction attributed to the activity of *Macrobrachium rosenbergii* shrimp ($p \leq 0.01$). Elumalai et al. (2017) proposed an integrated system combining mechanical, biological, and ultraviolet filters, in which the use of bio-balls, bio-barrels, and filter pads enhanced bacterial colonization and the conversion of nitrogenous compounds, demonstrating the effectiveness of hybrid systems.

Malaysia ranks second in the number of publications (n = 11), with a strong emphasis on optimizing plant nutrition and nutrient management to enhance fish and plant production in alignment with sustainable agriculture principles (Endut et al., 2016; Hamid et al., 2024). Among the studies conducted in the country, six employed sand filters as the primary filtration technology (Endut et al., 2009; Hamid et al., 2022). The efficiency of sand in removing solids and organic matter, combined with its low cost and feasibility as a cultivation medium, has been widely demonstrated. Endut et al. (2009) showed that moderate flow rates improved particle retention and water quality. Later, Lam et al.

(2015) highlighted that sand filters could remove up to 87% of nitrite and 60% of phosphorus. In comparison, Hamid et al. (2022) showed that lightweight expanded clay aggregate outperformed gravel, removing 92.47% of total ammonia nitrogen and 64.29% of phosphorus, suggesting its potential complementary use. Furthermore, Su et al. (2020) investigated the use of microwave-activated palm kernel shell biochar, whose high specific surface area (419 m^2/g) enhanced bacterial colonization, positioning it as a sustainable alternative to conventional sand filters.

In Germany (n = 6), research has primarily focused on high-technology decoupled aquaponic systems. Kloas et al. (2015) introduced the DRAPS, emphasizing its importance for sustainability and emission reduction. In this system, clarifiers and biofilters ensure efficient nutrient reuse while minimizing environmental impact. Subsequent studies refined this approach: Suhl et al. (2018) implemented suction filters and clarification units, resulting in improved solids removal and reduced need for additional fertilization. Monsees et al. (2017), when comparing coupled (1-loop) and decoupled (2-loop) systems, found that decoupled designs increased fruit production by 36% and allowed better control of pH and fertilization, reinforcing their efficiency in optimizing productivity.

In China (n = 6), studies have emphasized sustainability and nutrient recovery using low-cost materials such as biochar, lignocellulose, coconut husk, and phototrophic bacteria. These substrates promote biofilm formation and contribute to improved water quality. Zhang et al. (2020) demonstrated the efficiency of lignocellulosic media in nutrient mineralization. C. Zhu et al. (2024) showed that the combination of biochar and coconut husk improved nutrient retention and plant growth. Ji et al. (2022) analyzed algal-bacterial systems, reporting higher efficiency in nitrogen assimilation. Xu et al. (2023) demonstrated that hybrid hydroponic systems combined with waste fermentation enhanced nutrient conversion, while Xia et al. (2023) applied phototrophic bioconversion to recover nitrogen and phosphorus from fish sludge. Gao et al. (2022), in turn, employed moving bed biofilters enriched with humic acid, optimizing ammonia and nitrite removal. Research in Greece (n = 6) concentrated on improving mechanical and biological filtration through high-surface-area media, albeit at elevated costs. Aslanidou et al. (2023) tested combinations of mechanical and biological filters in both coupled and decoupled systems, employing ceramic rings and bio-balls that enhanced bacterial colonization. Tsoumalakou et al. (2022) showed that 10-cm fiberglass filters effectively retained solids, while biofilters with K1 media optimized nitrification. Ravani et al. (2024), working with vertical systems, found that mechanical filtration negatively affected phosphorus and potassium retention. Vlahos et al. (2019), however, highlighted the efficiency of bio-balls, ceramic rings, and lava grains in brackish systems, underscoring the importance of high surface area for supporting nitrification and halophyte cultivation.

In Mexico (n = 6), coupled systems predominated, including experiments with *Litopenaeus vannamei*. Most studies employed mechanical filters in combination with biofilters, though some relied solely on mechanical filtration (Silva et al., 2015). Limitations included the lack of information regarding filter media, which may have compromised system efficiency. Estrada-Perez et al. (2018) reported high nitrite levels due to immature biofilters, while Estrada-Perez et al. (2024) associated poor plant growth with solid accumulation on roots caused by inefficient clarifiers.

In Brazil (n = 5), an innovative approach highlighted the use of açaí seeds (*Euterpe oleracea*) as biofiltration substrates, promoting both water purification and the germination of tambaqui (*Colossoma macropomum*) seedlings. Studies reported high efficiency: Sterzelecki et al. (2022) observed 95.37% ammonia removal; Nascimento et al. (2023) reduced concentrations from 7.73 to 0.26 mg/L; and Natividade et al. (2024) found that lower hydraulic loading rates intensified denitrification and improved water oxygenation. These findings confirm the potential of organic substrates as sustainable alternatives for aquaponics.

In Egypt (n = 5), a country marked by water scarcity, research has prioritized the integration of integrated multi-trophic aquaculture (IMTA) systems to improve water efficiency and support sustainable production. All studies analyzed employed at least two filters (mechanical and biological). Helmy et al. (2023) demonstrated that magnetized water enhanced the growth of Nile tilapia and lettuce. Fawzy et al. (2024) tested organic residues, such as insect frass, as fertilizers in decoupled systems. Ali et al. (2024) evaluated the effect of protein skimmers on water quality and the performance of red tilapia and mint. Finally, Goda et al. (2024) reported the high efficiency of IMTA in feed conversion and nitrogen and phosphorus retention, reinforcing its relevance for the Egyptian context.

Water type and animal and plant species used in the articles

The review of the analyzed studies indicated that the integration of mechanical and biological filters represents the most recurrent configuration in aquaponic systems, regardless of operational scale or geographical context. Mechanical filters, typically represented by clarifiers or sedimentation units, play a key role in the removal of suspended solids, while biofilters—often using media such as bio-balls, K1 carriers, or ceramic rings—promote nitrification, thereby stabilizing water quality (Da Silva Alves et al., 2024; Estrada-Perez et al., 2024; Schmautz et al., 2021b). This configuration predominates in freshwater systems, which account for most of the reviewed publications, and is frequently complemented, particularly in large-scale or technologically advanced operations, by additional units such as drum filters, MBBR, ultraviolet treatment, or anaerobic reactors (Gao et al., 2022; Zhu et al., 2024).

In contrast, brackish and marine systems generally adopt more simplified filtration configurations, in which biofiltration plays a central role. These systems rely primarily on plastic or ceramic substrates associated with basic sedimentation units, reflecting the increasing importance of biological processes as salinity rises, while mechanical treatment is confined to preliminary stages (Armenta-Bojórquez et al., 2021; Chu & Brown, 2021; Pinheiro et al., 2017).

When considering the relationship between filter types and aquatic species, distinct patterns emerge. *Oreochromis* (tilapia)-based systems tend to employ the classical combination of mechanical and biological filters, often reinforced by advanced technologies in large-scale production (Helmy et al., 2023; Lobanov et al., 2021). In *Clarias* (African catfish) cultures, sand filters and sump-based biofilters are more frequently employed, providing greater efficiency in managing solids and high organic loads (Endut et al., 2009; Hamid et al., 2022). In the case of *Litopenaeus* (marine shrimp) cultivated in brackish environments, biofiltration with plastic media (bio-balls or K1) is prioritized, generally associated with simple sedimentation units and, in some cases, supplemented with zeolite to enhance ammonia control (Alarcón-Silvas et al., 2021; Armenta-Bojórquez et al., 2021). Other genera, such as *Cyprinus* (carp), *Carassius* (goldfish), and *Colossoma* (tambaqui), present more diverse configurations, though consistently based on the integration of sedimentation units with biofilters. Innovative solutions have also been reported, such as the experimental use of açaí seeds (*Euterpe oleracea*) as biofiltration substrates (Nascimento et al., 2023; Sterzelecki et al., 2022).

Similar trends are observed in the cultivation of plant species. *Lactuca* (lettuce) and *Ocimum* (basil) are the most frequently cultivated crops, requiring robust systems that combine clarifiers and biofilters, with large-scale arrangements often incorporating drum filters, MBBRs, or ultraviolet treatment (Aslanidou et al., 2023; Tsoumalakou et al., 2022). By contrast, *Ipomoea* (water spinach) performs well in simpler arrangements based on sand or gravel filters, without the need for complex biofiltration (Endut et al., 2016; Wang et al., 2016). Species of *Solanum* (tomato and eggplant) require more rigorously dimensioned mechanical and biological filters, with particular emphasis on the use of zeolite in brackish environments to enhance ammonia removal (Armenta-Bojórquez et al., 2021; Gebauer et al., 2022). Halophytes such as *Sarcocornia*, *Sesuvium*, *Crithmum*, and *Batis*, cultivated in saline water, rely predominantly on biofiltration, while mechanical treatment is restricted to preliminary stages (Boxman et al., 2017; Vlahos et al., 2019).

Overall, the results of this review suggested that the choice of filtration strategies depends less on water type *per se* and more on the interaction between the aquatic and plant species being cultivated, combined with the scale of production. In summary, tilapia–lettuce systems tend to employ classical combinations of mechanical and biological filters, catfish–water spinach systems are more often associated with sand filters and sump biofilters, whereas shrimp and halophyte systems exhibit greater dependence on biofiltration. These patterns underscore the importance of technical alignment between filter configuration and system biota, a factor central to ensuring the sustainability and long-term stability of aquaponics.

CONSIDERATIONS AND FUTURE PERSPECTIVES

The systematic review demonstrated that filtration systems and the media employed play a central role in maintaining balance and efficiency in aquaponic systems, directly influencing the removal of solids and nutrients—both essential for water quality and overall productivity. The appropriate selection of filters and substrates not only enhances system sustainability and performance but also contributes to mitigating environmental impacts.

Future perspectives include the development of more affordable and regionally adapted filtration technologies, particularly in contexts in which advanced materials are economically unfeasible. The use of alternative substrates such as biochar, coconut husk, and açaí seeds emerges as a promising strategy to make aquaponics economically viable and environmentally sustainable under diverse climatic and geographical conditions. At the same time, the integration of advanced technologies, such as membrane bioreactors and biofilm-based systems, may optimize nitrification and denitrification processes, thereby improving system efficiency and resilience.

Another significant advancement relates to the adoption of decoupled systems, which provide greater flexibility for specific adjustments in aquaculture and hydroponic units, enabling improvements in both water quality and nutrient availability. The expansion of aquaponics into saline environments and the development of filters tailored to different water types are also emerging areas of research, with strong potential to broaden the applicability of aquaponics in regions facing freshwater scarcity.

To consolidate aquaponics as a large-scale sustainable alternative, it is essential to expand cost-benefit studies and environmental assessments in both coupled and decoupled systems. Approaches such as life cycle analysis and the incorporation of circular economy principles may help reduce costs, optimize resource use, and reinforce long-term sustainability. Further research is also needed on the microbiological dynamics of biofilters, the influence of water quality on system performance, and the impact of different feeding regimes on both plant and aquatic organism productivity.

Additionally, the consolidation of aquaponics requires interdisciplinary research that addresses not only technical and environmental aspects but also economic viability and consumer acceptance. Studies on market perception and the development of value chains are fundamental to fostering large-scale adoption. In this sense, continued research will enable aquaponics to establish itself as a sustainable production model, capable of integrating environmental efficiency, food security, and technological innovation.

CONFLICT OF INTEREST

Nothing to declare.

DATA AVAILABILITY STATEMENT

The data will be available upon request.

AUTHORS' CONTRIBUTION

Conceptualization: Lima, R.S.; **Methodology:** Lima, R.S., Lima, J.S.; **Investigation:** Lima, R.S.; **Software:** Lima, R.S., Lima, J.S.; **Data curation:** Lima, R.S., Lima, J.S.; **Formal analysis:** Lima, R.S., Lima, J.S.; **Writing – original draft:** Lima, R.S., Lima, J.S.; **Writing – review & editing:** Lima, R.S., Lima, J.S.; **Supervision:** Lima, J.S., Pontes, C.S.; **Final approval:** Lima, R.S., Lima, J.S.

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