Automated, technified and traditional aquaponic systems: a systematic review

Sistemas acuapónicos automatizados, tecnificados y tradicionales: revisión sistemática

Sistemas aquapônicos automatizados, técnicos e tradicionais: revisão sistemática

Sergio Alejandro Vaca Vargas[1]
Óscar Leonardo García Navarrete[2]
Mario Andrés Colorado Gómez[3]

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[1] Faculty of Engineering, Master student in Biosystems Engineering Program, Universidad Nacional de Colombia, Bogotá, Colombia.
E-mail: svacav@unal.edu
ORCID: https://orcid.org/0000-0003-2006-4813
CvLAC: https://scienti.minciencias.gov.co/cvlac/visualizador/generarCurriculoCv.do?cod_rh=0001549579

[2] Faculty of Engineering, Department of Civil and Agricultural Engineering, Universidad Nacional de Colombia, Bogotá, Colombia.
E-mail: olgarcian@unal.edu
ORCID: https://orcid.org/0000-0001-5075-460X
CvLAC: https://scienti.minciencias.gov.co/cvlac/visualizador/generarCurriculoCv.do?cod_rh=0000920045

[3] SENNOVA Centro de Biotecnología Agropecuaria, Servicio Nacional de Aprendizaje SENA, Mosquera, Colombia
E-mail: mcolorado@sena.edu.co
ORCID: https://orcid.org/0000-0002-0333-4896
CvLAC: https://scienti.minciencias.gov.co/cvlac/visualizador/generarCurriculoCv.do?cod_rh=0000892653

Summary

Introduction: This paper is product of the research: Automatización, modelamiento y evaluación de un sistema acuapónico NFT para cultivo de Carpa Roja (Cyprinus carpio) y Lechuga Crespa (Lactuca sativa), developed in the Universidad Nacional de Colombia in the year 2022. In this paper a systematic review is carried out in order to observe the research current state in automated, technified and traditional aquaculture systems, thus having a sight of the investigative orientation in this field. This review is based on scientific papers from four databases, taken in March of 2020, obtaining 1356 results, evaluated and filtered for further analysis.

Problem: Nowadays there are different research areas in aquaponics, from ones focused on the applied techniques in aquaculture and hydroponic sub-systems; through applied sciences such as modeling from both physical and chemical systems; arriving to the types of aquaponics, qualified from technification grades; concluding with fish and plant crop species and their interaction. Although there have been different reviews, they are no organized in research branches that simplify it in a graphical way.

Objective: In this paper a systematic review is carried out in order to observe the research current state in automated, technified and traditional aquaculture systems, thus having a sight of the investigative orientation in this field.

Methodology: Methodologically, a systematic literature review is implemented due to the large volume of scientific publications, being useful to integrate, evaluate and analyze available information on a given topic. The queried databases correspond to: IEEE Xplore, Scopus, Science Direct and Scielo, in March 2020.

Results: By means of an Ishikawa diagram, a research orientation graph was obtained, summarizing all the findings regarding the techniques that define a aquaponic systems, types of automated, technified and traditional systems, applied sciences and crop species statistics.

Conclusion: Of the publications reviewed, although only 6% corresponds to the area of electronics, it is observed that in other study fields monitoring units are already implemented on traditional aquaponic systems, this is why the figure given could vary depending on the type of tools that are already being used for water analysis, yields, flow control, recirculation in aquaponics, among others.

Originality: Through this research, there was found a picture of the current state of the automated, technified and traditional aquaponic systems.

Limitations: The review was limited to four databases that were queried in March 2020.

Abstract

Aquaponics are defined as hydroponic crops merged with recirculating aquaculture systems and bacteria, achieving a synergic relationship that takes fish wastewater and uses it in order to grow plants, then the last one in association with nitrifying bacteria are used as a natural filter that removes dissolved nitrogen, ammonia, among others, controlling the fish waste accumulation. Nowadays there are different research areas in aquaponics, from ones focused on the applied techniques in aquaculture and hydroponic sub-systems; through applied sciences such as modeling from both physical and chemical systems; arriving to the types of aquaponics, qualified from technification grades; concluding with fish and plant crop species and their interaction. In this paper a systematic review is carried out in order to observe the research current state in automated, technified and traditional aquaculture systems, thus having a sight of the investigative orientation in this field. This review is based on scientific papers from four databases, taken in March of 2020, obtaining 1356 results, evaluated and filtered for further analysis. From the review it was found that there is an exponential quantity growth in papers per year, moreover, it is noted that the paper fields of greatest concentration are aquaculture, agriculture, environment, water analysis, horticulture and electronics, the most worked species are lettuce (Lactuca sativa) in hydroponic NFT and tilapia (Oreochromis niloticus) in single recirculating aquaponic systems (SRAPS). With the obtained data it was built a diagram that consolidates current research branches in aquaponics.

Keywords: Aquaponics, review, systematic, automated, research.

Resumen

La acuaponía es definida como la integración de cultivos hidropónicos en conjunto con sistemas acuícolas recirculantes y bacterias, logrando así una relación sinérgica en donde las aguas residuales producidas por peces son utilizadas para el crecimiento de plantas, luego estas últimas en asociación con bacterias nitrificantes fungen como filtro natural para remover nitrógeno disuelto, fósforo, amonio, entre otros, controlando la acumulación de desechos de peces. En la actualidad existen diversas áreas de investigación en acuaponía, desde las enfocadas a las técnicas de cultivo en los sub-sistemas acuícola e hidropónico; pasando por las ciencias aplicadas de las cuales se derivan el modelamiento tanto en la parte física como química del sistema; llegando a los tipos de acuaponía calificados a partir del grado de tecnificación; finalizando con las especies cultivadas, tanto peces como plantas y los resultados de su interacción. En el presente artículo se genera una revisión sistemática con el fin de observar el estado actual de los sistemas acuapónicos automatizados, tecnificados y tradicionales y tener un panorama de la orientación investigativa en este campo. Esta revisión se basa en artículos científicos de cuatro bases de datos, tomados en Marzo de 2020, obteniendo 1356 resultados evaluados y filtrados para su posterior análisis. A partir de la revisión se encontró que hay un crecimiento exponencial en cantidad de artículos por año, por otra parte, se observa que las áreas con mayor concentración de publicaciones corresponden a acuacultura, agricultura, ambiente, análisis de aguas, horticultura y electrónica, las especies más trabajadas son lechuga (Lactuca sativa) en sistemas hidropónicos NFT y tilapia (Oreochromis niloticus) en sistemas de recirculación SRAPS. Con los resultados obtenidos se construyó un diagrama que consolida las ramas de investigación actuales en acuaponía.

Palabras clave: Acuaponía, investigación, automatización, revisión, sistemática.

Resumo

A aquaponia é definida como a integração de culturas hidropónicas juntamente com sistemas de aquicultura recirculantes e bactérias, conseguindo assim uma relação sinérgica onde as águas residuais produzidas pelos peixes são utilizadas para o crescimento das plantas, estas últimas em associação com as bactérias nitrificantes atuam como filtro natural para remover nitrogênio dissolvido, fósforo, amônio, entre outros, controlando o acúmulo de dejetos de peixes. Atualmente existem diversas áreas de pesquisa em aquaponia, desde aquelas voltadas para técnicas de cultivo nos subsistemas de aquicultura e hidroponia; passando pelas ciências aplicadas de onde deriva a modelação tanto na parte física como química do sistema; atingindo os tipos de aquaponia qualificados a partir do grau de tecnificação; terminando com as espécies cultivadas, peixes e plantas e os resultados de sua interação. Neste artigo, uma revisão sistemática é gerada para observar o estado atual dos sistemas aquapônicos automatizados, técnicos e tradicionais e ter uma visão geral da orientação da pesquisa neste campo. Esta revisão é baseada em artigos científicos de quatro bases de dados, tomadas em março de 2020, obtendo 1.356 resultados avaliados e filtrados para análise posterior. A partir da revisão, constatou-se que há um crescimento exponencial no número de artigos por ano, por outro lado, observa-se que as áreas com maior concentração de publicações correspondem a aquicultura, agricultura, meio ambiente, análise de água, horticultura e eletrônica, as espécies mais trabalhadas são a alface (Lactuca sativa) em sistemas hidropônicos NFT e a tilápia (Oreochromis niloticus) em sistemas de recirculação SRAPS. Com os resultados obtidos, foi construído um diagrama que consolida os atuais ramos de pesquisa em aquaponia.

Palavras-chave: Aquaponia, pesquisa, automação, revisão, sistemática.

1. Introduction

Aquaponic systems are defined as a merge of two main technologies: recirculating aquaculture systems (RAS) and hydroponics (soilless crop production), integrated in a closed loop [1]. Including optional sub systems such as mechanical and biological filtration, oxygenation, sedimentation and disinfection units [2]. Over time, these systems have been developed in order to offer an innovative and sustainable alternative for food production [3]; to achieve this it is needed to include features that are capable of solving one of its greatest challenges: regulate nutrient concentration and conversion of ammonium into nitrate through nitrification [4], while overcoming drawbacks in environmental sustainability and its performance to meet the bioeconomic demand [5].

Modern aquaponics began in 1975, when a hydroponic system of different plant species was placed in the effluent of catfish culture tanks, designed without a biofiltration stage and intended as a system with no recirculation [6]; Later, between 1977 and 1989, RAS fish production systems were combined with hydroponic systems, both without nutritional supplements; subsequently, the initial models were expanded to form the first totally closed or coupled aquaponic systems, including biofiltration, sedimentation and nitrification stages [1] .

Despite having started in 1975, it was not until 2010 that this field began to take on greater relevance [5]; in the search for solutions to contribute to productivity, reduce waste and renew production processes, research in aquaponics began to diversify in order to contribute to reduce sustainability problems at different levels, urban/rural, small/large scale, developed/developing countries [3]. This is reflected in the number of scientific publications on hydroponics, aquaculture and aquaponics (Figure 1). The blue line (aquaponics) shows an exponential growth trend that starts in 2004 and has its inflection point from 2010 onward.

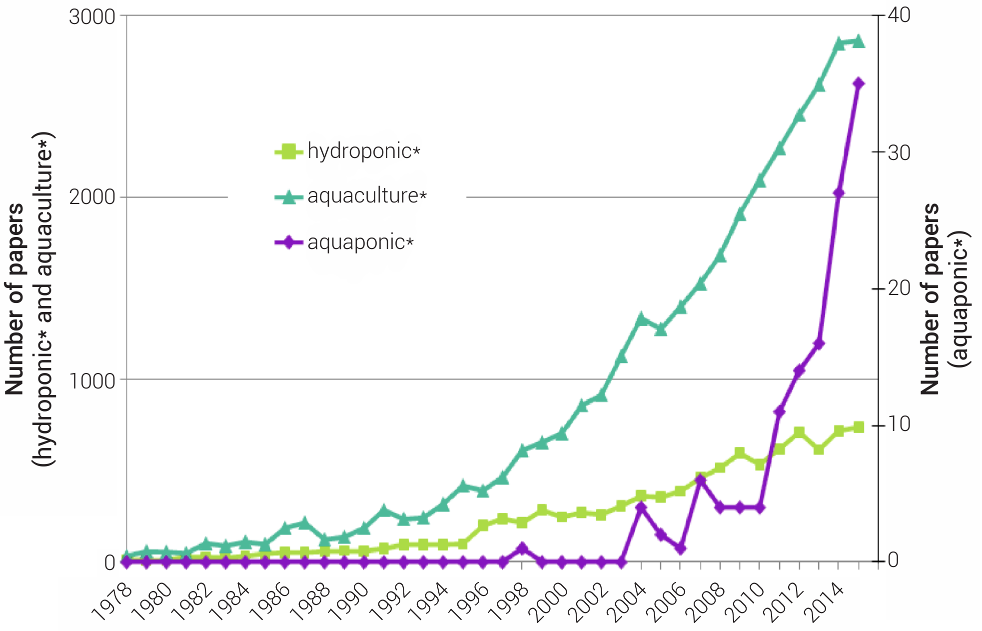

Figure 1. Number of publications in hydroponics, aquaculture and aquaponics (from 1978 to 2015).

Source: [1]

Currently, aquaponic systems are based on the use of fish waste and non-consumed food, in order to decompose ammonium and nitrogen contained in the water through microorganisms [2]. Nitrifying bacteria are in charge of carrying out the previously mentioned transformation in such a way that plant crops can absorb and use them for their growth [7]. Plants carry out a nitrogen fixation process in which they produce nitrogen bonding to organic compounds [8]. Once water has passed through this medium it can be used again through a circulation system, thus closing the nitrogen cycle through assimilation and absorption and consequently forming a water recycling effect that improves nutrient utilization.

In order to meet the needs at the critical points of aquaponic systems, it is necessary to consider not only each of its sub-systems but also the influence of the environment, cycle of water resources and nutrients; therefore, to obtain optimal growth of both fish and plants, it is essential to understand mass and energy balances [9] and nutritional and chemical exchanges that occur in the environment.

Considering the aforementioned, research fields have been introduced in aquaponics, from the study of techniques in the hydroponic sub-system (plant crop), that include: nutrient film technique (NFT) [10], substrate media bed [11], floating root (sponge and raft) [12]; passing through the evaluation and efficiency of recirculating aquaponic systems (RAS) [13] and double recirculating aquaponic systems (DRAPS) [14]; reaching water and waste management [8,14] along with studies in micro and macro nutrients [15] and the effects of bacteria in the decomposition process [16]; Following with modeling in each of the sub-systems, whether physical and chemical interactions between fish, plants and bacteria [17], water and hydraulic systems [18], bioclimatic [19] and climatology [20]; ending with the implementation of measuring instruments, actuators and controllers to monitor and/or optimize the aquaponics system in some of its critical points [21].

The great variety of research lines is reflected in the growth of scientific papers; thus, the objective of the following systematic review is to gather available information on aquaponics and to generate an overview of its current status and its development at different technological levels.

The systematic review on aquaponics was generated from the scheme proposed by Khan and Petticrew [22,23], where initially a research question related to the topic is generated. Based on the question, a general objective is produced in order to stablish the review scope. Subsequently, a delimitation of the search framework is made where the topics to be included are defined, obtaining a series of search keys that were then fed into the IEEE Xplore, Scopus, Scielo and Science Direct databases in March 2020.

Then, the inclusion/exclusion criteria are specified, serving as an initial filter to take advantage of the useful data and discard all those documents that are not relevant for the review. In addition, a second filter is performed with a quality evaluation based on Mori's guide [24] adapted from the Mixed Methods Appraisal Tool (MMAT).

Finally, a synthesis is made in order to statistically analyze the information obtained, emphasizing the current research areas and the most worked species worldwide.

2. MATERIALS AND METHODS

Methodologically, a systematic literature review is implemented due to the large volume of scientific publications, being useful to integrate, evaluate and analyze available information on a given topic [23].

This review is based on the methodologies generated by Khan [22] and MMAT, following the structure described below.

2.1 Review boundary

Initially, a research question is defined in order to guide the search. Based on the question, a general objective is established as a basis for the scope of the review.

For the present review, the guiding question is: What is the current status of Automated, Technified and Traditional Aquaponic Systems and towards where are they oriented? The main objective is to gather the available information on aquaponics and to generate current status on its development at different technological levels.

The queried databases correspond to: IEEE Xplore, Scopus, Science Direct and Scielo, in March 2020.

2.1.1 Search framework

Subsequently, the search framework is outlined, defining the topics to be included and the scope of the review; there are different tools for defining the topics, one of which is the Ishikawa diagram (Figure 2).

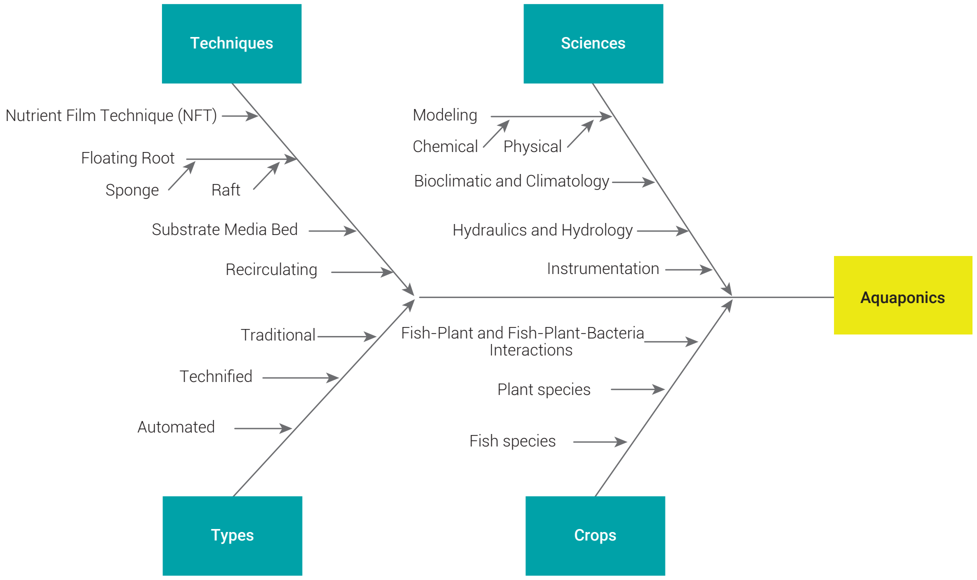

Figure 2. Ishikawa diagram for systematic review in aquaponics.
Source: Own elaboration

Initially aquaponic techniques are taken into account (using as a basis the type of hydroponic system that it is attached to, i.e., the structural configuration), in this case they include: Nutrient Film Technique (NFT), Substrate Media Bed, Floating Root and Recirculating.

From its structural configuration arises the inclusion of sciences in aquaponics, in this section are seen applied concepts such as Modeling (related to the physical and chemical interactions between fish and plants, in addition to the hydraulic and climatological system) and Instrumentation (understood as all those sensors and actuators that can be applied to aquaponics).

Then the types of aquaponics are taken into account, the first block derived from the application of Modeling and Instrumentation (together with controllers), resulting in an Automated system; on the other hand, systems that only have Instrumentation are observed, measuring variables but without applying control techniques or also called Technified; finally there are the production systems based on ancestral knowledge and practices, which have been developed through many generations, treated in this review as Traditional systems.

Finally, the crops in aquaponics are established, determined by the species of fish and plants that have been cultivated in this type of systems, as well as the interactions between these and the nitrifying bacteria.

2.1.2 Search keys

The search keys were generated for each of the sections, that is to say, the concepts for the search were the blocks contained in the Ishikawa diagram form Figure 2, which are shown below by section:

- Techniques: (Aquaponic OR Aquaponics) AND ("Nutrient film technique" OR NFT OR Substrate OR "Substrate bed" OR Soil OR "Floating root" OR Recirculation)
- Sciences: (Aquaponic OR Aquaponics) AND (Modeling OR Model OR "Mathematical model" OR Instrumentation OR Instrument OR Device OR Sensor OR Actuator OR Electronic OR Electronical)
- Aquaponic AND (Model OR "Mathematical model" OR Instrumentation OR Instrument OR Device OR Sensor OR Actuator OR Electronic) *Modified to Science Direct.
- Types: (Aquaponic OR Aquaponics) AND (Automated OR Automation OR Autonomous OR Automatic OR Control OR Smart OR Monitoring OR Technified OR Technical OR Traditional OR Rustic)
- Aquaponic AND (Automated OR Automation OR Control OR Smart OR Monitoring OR Technified OR Traditional OR Rustic) * Modified to Science Direct.

Generated search keys are used in each one of the previously stablished databases.

2.1.3 Inclusion/Exclusion criteria

The results obtained are submitted to a review regarding the title and abstract taking into account the following inclusion/exclusion criteria (Table 1).

Table 1. Inclusion/Exclusion criteria.

Inclusion	Exclusion
• Papers explicitly specifying the type of technique implemented, including, but not limited to NFT, Substrate media bed, Floating root, Recirculating. • Systematic reviews • Comparative analyses between aquaponics and other crop techniques • Papers in English language	• Narrative papers • Studies exclusively about hydroponics or aquaculture • Papers without DOI or ISBN • Papers of legislative scope • Studies of social or economic impact

Source: Own elaboration

2.2 Quality assessment

By applying the Mixed Methods Assessment Tool (MMAT), an evaluation is generated and applied to the scientific papers that have passed the inclusion/exclusion filter, thus the papers are rated according to the following scheme:

- Is the objective clear?
- Do the data obtained allow the objective to be met?
- Are the collected data complete?
- Are the measurements appropriate (sample size)?
- Is the sampling strategy relevant to solve the objective?
- Are the experimental conditions sufficiently explicit to be replicated?
- Is the results interpretation sufficiently supported by the data?

The evaluated papers receive a score from 0 to 7 according to the above criteria, 0 representing a low-quality paper and 7 a representative paper for the review. Those with a score lower than 4 are automatically excluded.

2.3 Data analysis

With the papers that have passed each of the filters, a quantitative analysis is performed to quantify the number of publications per year in total and for each of the databases. Additionally, the study fields of the journals are evaluated in order to obtain the most representative ones at the moment.

On the other hand, the species currently worked on and the research lines that are not registered in the initial Ishikawa diagram are synthesized, modifying it to represent the research orientation in aquaponics systems.

3. RESULTS

3.1 Preliminary results

The initial search using each of the keys in the four databases returned a total of 1356 documents, that were submitted to each of the filtering stages (Figure 3), finally obtaining 204 publications, all used in the systematic review.

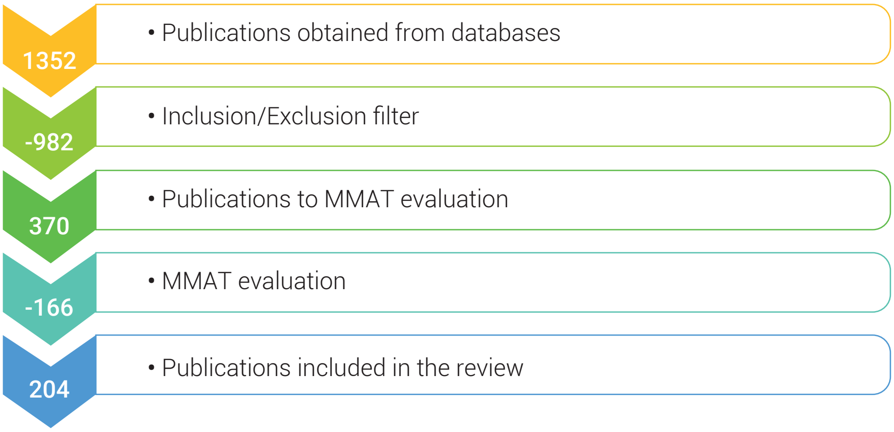

Figure 3. Number of publications at each review stage.
Source: Own elaboration

3.2 Bibliometric analysis

Taking into account the publications included, a trend line is generated (Figure 4), showing a growth similar to the one reported by [1].

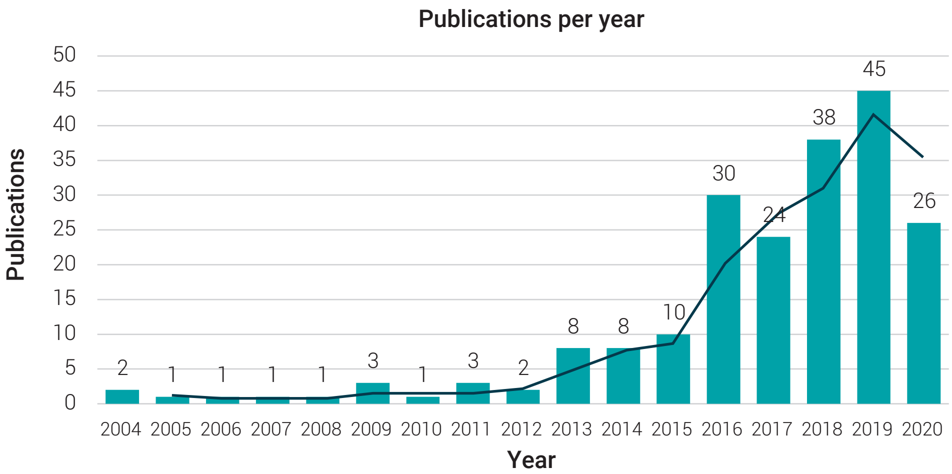

Figure 4. Number of publications per year.
Source: Own elaboration

As can be seen in Figure 4, the number of publications in aquaponics was not considerable in the databases until 2012, after this point a sustained growth begins, evidencing the interest of researchers to deepen and develop different branches of aquaponics.

The publications obtained are organized according to the study fields (Figure 5).

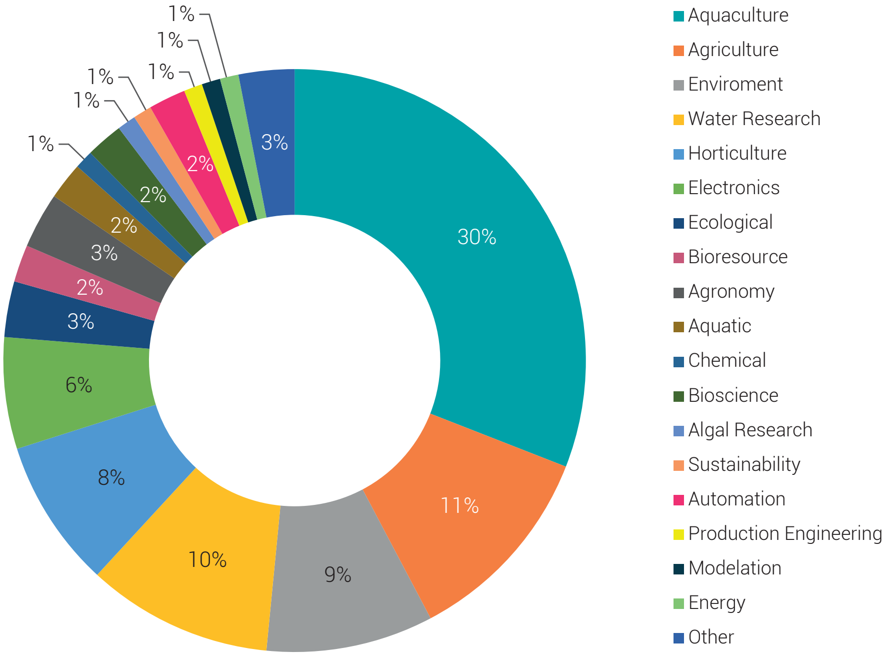

Figure 5. Publications by field.
Source: Own elaboration

The main publication fields are aquaculture, agriculture, environment, water analysis, horticulture and electronics.

3.3 Publication findings

From the publications it was found that 161 (78.92%) correspond to experimental papers, 16 (7.84%) to descriptive papers, 13 (6.37%) to papers with emphasis on simulation, 12 (5.88%) to reviews and the remaining 2 (0.98%) to book chapters.

On the other hand, it was possible to identify the publications scope (Figure 6), highlighting that 99 of these correspond to evaluative procedures in which the following are measured: crop yields of both fish and plants, variations in water loads, dissolved oxygen, light and their effects on crop growth and nutrient cycling.

Of the selected publications, 18 are comparative studies, comparing: two or more types of plants to analyze nitrogen transformation in water, different hydroponic systems analyzing their performance, including comparative analysis between substrates in the case of the substrate bed technique, ending with different fish species in order to analyze their effluents and potassium, phosphorus and nitrogen loads.

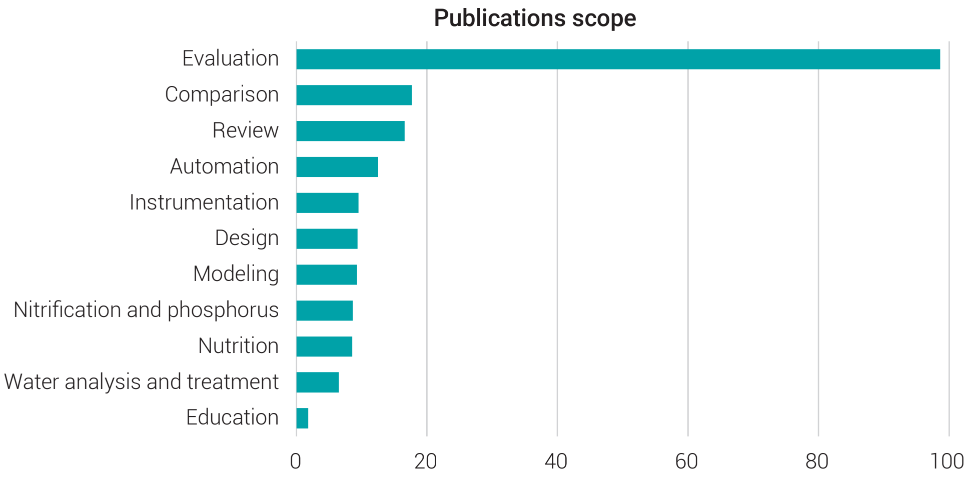

Figure 6. Publication scope of the publications selected for the review.
Source: Own elaboration

There are 17 publications referring to reviews (including book chapters and descriptive papers), including general data searches on aquaponics literature, as well as topics such as industrial aquaponics, water management in recirculating systems, nitrification systems and their evolution over time, and the introduction of fish and plant polyculture, ending with the transformation of traditional aquaponics towards technification and automation.

In addition, there are 13 publications on automation and 10 on instrumentation, focusing mainly on the implementation of measurement, notification and control systems, either in situ or through *Internet of Things* (IoT); in the publications, these systems cover the measurement of critical variables of the aquaponic system: pH, dissolved oxygen, conductivity, turbidity, temperature, ammonium and nitrate.

Finally, other research approaches are included such as system design (where new technologies are implemented to increase filtration, nitrification and recirculation system efficiency), modeling (where mathematical tools are used to generate mass balances and predictions in nutrient systems, nitrification, phosphorus cycling, hydrological, fish and plant yields), nutrition (including feeding cycles for fish and supplements for plants), water treatment (understanding it as the adequacy of system water effluents in order to reduce environmental impacts), concluding with systems for educational purposes (producing teaching systems around aquaponics and the multi-trophic integration of species in the same system).

3.4 Hydroponic systems, NFT, floating root and substrate media bed

Currently, hydroponic systems that complement aquaponics are divided into three main groups:

- Nutrient film technique (NFT) (Figure 7), bases its operation on pipe systems (commonly PVC) that allow different plant species to be adapted so that their roots can be in contact with a water flow, which can be constant or intermittent depending on the applied control technique [25].

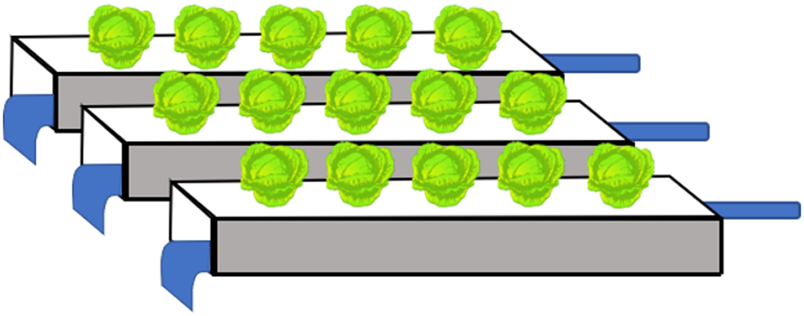

Figure 7. Nutrient Film Technique NFT.

Source: Own elaboration

Floating root, also known as floating raft [26], provides a platform where plants are placed to be grown (Figure 8), normally the platform is located over the water coming from aquaponics in separate tanks or it can be directly over the fish crop [27].

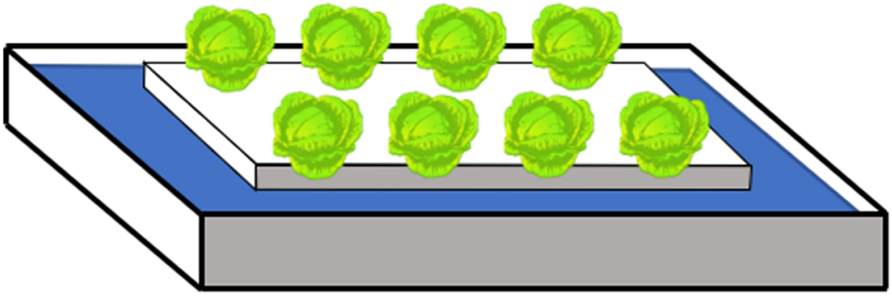

Figure 8. Floating root hydroponic system (raft).
Source: Own elaboration

Substrate media bed, handling a certain volume of substrate, ensuring an anchorage by the roots (Figure 9), also acting as a culture medium for nitrifying microorganisms, the substrate can be synthetic, organic and inorganic according to crop requirements [28].

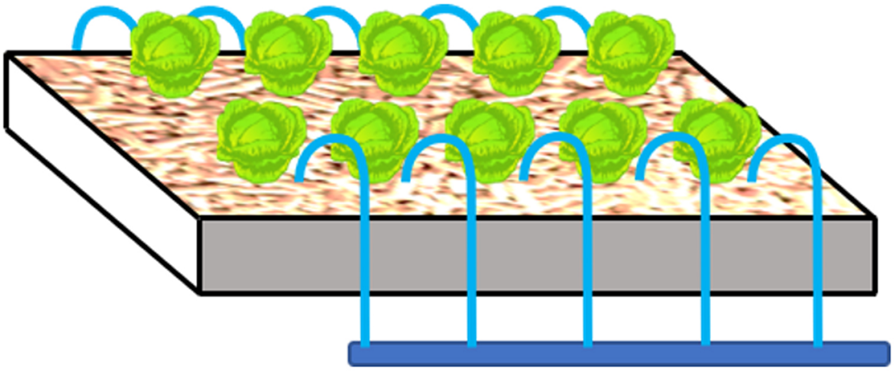

Figure 9. Hydroponic system with substrate media bed.
Source: Own elaboration

From the review publications it was found that 140 of these explicitly report the type of hydroponic system, distributed as illustrated in Figure 10, where it is shown that NFT systems are currently the most used, followed by substrate media bed and floating root.

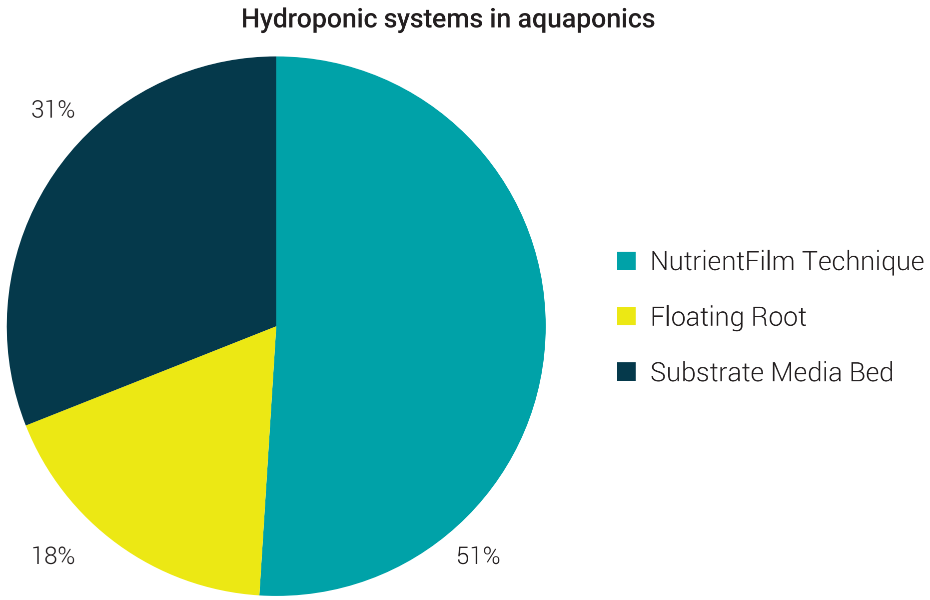

Figure 10. Hydroponic systems in aquaponics.
Source: Own elaboration

The hydroponic system choice is based on the advantages conferred by each component and its impact on the aquaponic system life cycle, thus the hydroponic system selection impacts whole aquaponics design; with a substrate media bed system as reported by [28], a simple biofiltration system is possible since the implemented substrate provides sufficient surface area for bacterial growth and in turn generates mechanical filtration; on the other hand, if a NFT system as designed in [29] is implemented, the channels or pipes do not allow sufficient adhesion for bacterial growth, which is why a complete biofiltration stage is necessary.

Differences such as those mentioned above are stated by [10], carrying out comparative analyses between NFT, floating root and substrate bed, in which the daily water consumption stands out, being much higher in floating root and substrate bed systems, while much higher nitrate removal values are obtained due to the flooded area of their roots, which allows a better assimilation of nitrate.

Currently, multiple hydroponic systems have begun to be implemented, [12] evaluated a set of subunits that alternate the use of floating root systems in conjunction with substrate media beds, allowing oxygenation through aerators at the tank base where the ponds are located, while in series substrate media beds allow biofiltration and at the same time crop other plant species, making optimal use of the space and improving system biomass yields.

3.4.1 Substrate types

The different substrates implemented in the hydroponic system have been extensively evaluated, measuring the performance of different physicochemical parameters. Table 2 shows the effectiveness of some substrates in increasing or reducing pH, NO2, NO3 and NH3 with respect to fish effluent water.

Table 2. NO2, NO3 and NH3 conversion in different substrate types.

Susbstrate	Ammonium	Nitrite	Nitrate	pH	Ref.
Coconut shell fiber	High reduction	No change	Low increase	Low reduction	[30]
Palm fiber	High reduction	Low reduction	Low reduction	No change	[31]
Periwinkle fiber	High reduction	Low reduction	Low increase	Low increase	[31]
Gravel	Medium reduction	Low reduction	Low reduction	Low reduction	[31]
MIX (Palm, periwinkle, gravel)	High reduction	Low reduction	Medium reduction	Low increase	[31]
Sand	High reduction	Low reduction	No change	Low reduction	[30]
Flexible polyurethane foam	High reduction	Medium reduction	Low reduction	Does not report	[32]
Crushed rock	Medium reduction	Medium reduction	Low increase	Does not report	[32]

The transformation of compounds in a substrate bed varies according to the cultivated species, plant physiological state and nitrifying bacteria, [33] generated a study in which it was proved that proteins and amino acids released during germination are converted into ammonium; additionally, the solutes generated by seeds can stimulate the growth of nitrogen-fixing organisms, increasing ammonium levels at the beginning of the crop. Thanks to aeration effects it is possible to convert ammonium to nitrite and then to nitrate to be consumed by the plants, in more advanced stages the effluent measurements in the substrate bed show lower amounts of nitrates, nitrites and ammonium.

According to evaluated publications, a table was generated with plant species implemented in aquaponics systems (Figure 11):

Figure 11. Plant species in aquaponics.

Source: Own elaboration

In most studies, lettuce (*Lactuca sativa*) is implemented, followed by tomato (*Lycopersicum esculentum*), water spinach (*Ipomea aquatica*) and Pak choi (*Brassica chinensis*).

Furthermore, the use of two or more plant species is observed either to generate comparative analyses or to complement the hydroponic plant crop process using multiple techniques (Figure 12).

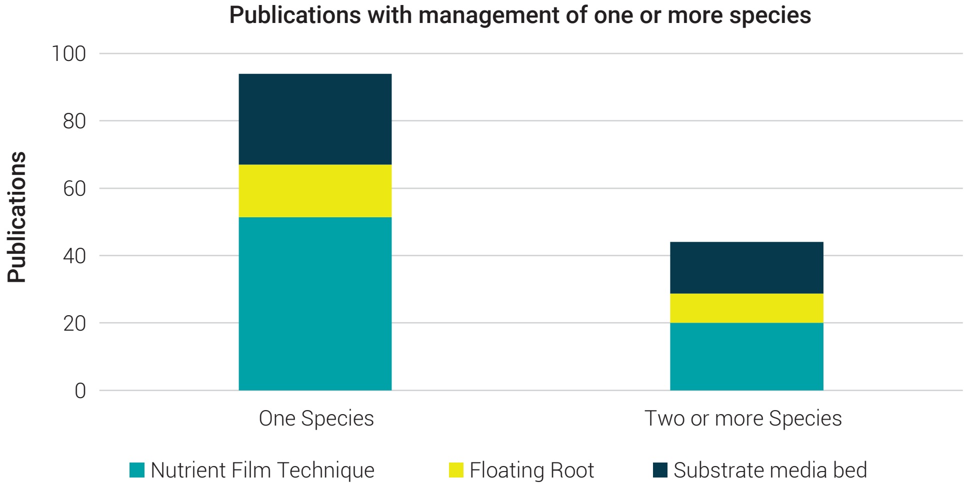

Figure 12. Distribution of publications implementing one or more species in aquaponics.
Source: Own elaboration

3.5 Recirculating systems

Water flow in aquaculture systems is a variable that directly affects the concentrations of waste produced by fish, in addition to oxygen saturation, turbidity, pH, alkalinity and temperature [34]. In aquaponics, flow has an influence on contact time achieved by microorganisms or nitrifying bacteria and plant roots, playing a fundamental role in the utilization and transformation of nutrients.

Studies conducted by [35] show that the variation of water load affects not only energy costs, but also fish and plant yields, as well as the removal of nutrients like phosphorus, nitrates, potassium and the balance of dissolved oxygen at optimal levels for the system. These studies found that at a constant rate of 1.5 l/min, carp (*Cyprinus carpio*) and spinach (*Beta vulgaris*) crops showed better growth and weight gain, respectively; Moreover, [36] found similar water flow rates, reporting that at 1.6 l/min, African catfish (*Clarias glariepinus*) and water spinach (*Ipomoea aquatica*) crops gave better performance than at lower flows, as demonstrated in [26], stating that the lower the flow rates, the less capacity the plants have to assimilate nitrogen, phosphorus and potassium.

It is important to highlight the water cycling times, taking into account continuous and intermittent flow cycles, as proven by [35] in a comparative study, using continuous recirculation times of 11, 13 and 24 hours, taking water samples in the effluents of Tilapia (*Oreochromis niloticus*) (inlet to the hydroponic system) and Lettuce (*Lactuca sativa*) (throughout the hydroponic system), measuring temperature, dissolved oxygen, conductivity, pH, nitrates, nitrites and ammonium, including plant growth. It was found that it is possible to obtain similar nutrient assimilation in periods of 11 and 13 hours regardless of whether they are performed during the day or night, in contrast, the study by [37] shows that intermittent cycles of 10min on and 50min off in carp (*Cyprinus carpio*) and mint (*Mentha arvensis*) crops can maintain temperature and dissolved oxygen balance in water, at the cost of suffering interruptions in the nitrification process and therefore low crop yields.

Currently, there are two general classifications of recirculating systems:

- Simple recirculating aquaponic systems (SRAPS), wastewater from fish production flows through a mechanical filter and then into the hydroponic system [38], water is cleaned by plants and bacteria living in the root zone (or in some cases in separate sub-systems) and then recirculated to the fish tank (Figure 13).

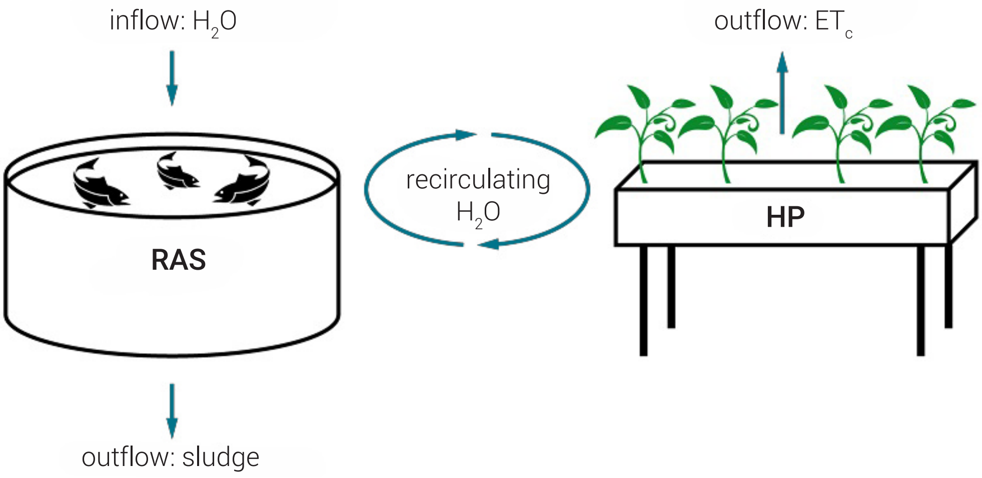

Figure 13. SRAPS System.
Source: [39]

- Dual recirculating aquaponics systems (DRAPS), also known as decoupled RAS systems, wastewater from fish and plant production is kept in different cycles (Figure 14), allowing independent operation, adjusting individual parameters in each system [34].

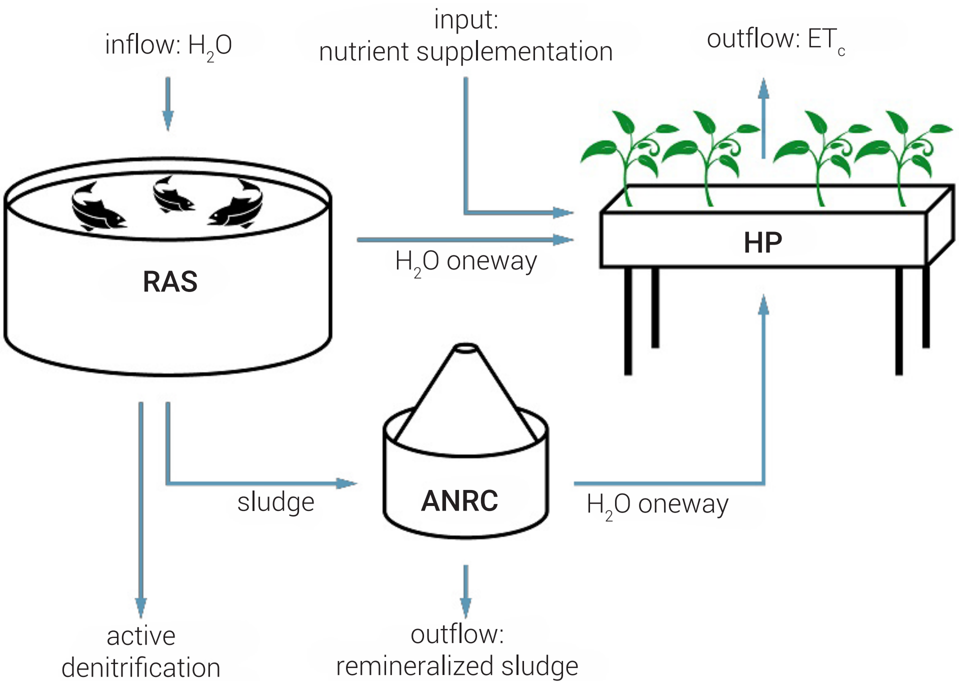

Figure 14. DRAPS System.
Source: [39]

Table 3 shows a summary taken from [38] where advantages and disadvantages of each recirculation technique are evaluated:

Table 3. Advantages and disadvantages of SRAPS and DRAPS systems.

	SRAPS	DRAPS
Advantages	- Complete documentation of lettuce and tilapia combined production - Suitable for small spaces, small producers, hobby and education.	- Separation of fish and plant yields, allowing production under optimal conditions (pH, nutrients, water quality independent in each system). - Optimized measures in plant cycles do not affect fish cycle. - Allows for large-scale intensive crop cultivation

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	SRAPS	**DRAPS**
Disadvantages	- Low conditions for pH, nutrient requirements and overall water quality of the integrated species (fish, plants and bacteria). - Low production in hydroponic sub-system - Lack of research for long term behaviors	- Does not have an optimized construction for the ratio of plants to fish effluent. - Lack of research

Source: [38]

It was found that 159 (92%) of the studies evaluated in the review implemented RAS/SRAPS systems while only 14 (8%) corresponded to decoupled DRAPS/RAS, although it is important to emphasize that most of the studies with single recirculation systems correspond to publications more than 5 years old, while those with double recirculation are all from 2015, showing that this technology is on the rise.

[40] in their research on decoupled systems generates a comparative analysis over 5 months with a RAS and a DRAPS system with four fish tanks (*Oreochromis niloticus*) and three NFT pipes with tomato (*Solanum lycopersicum*), finding that there is a better performance in DRAPS systems (producing 8.2 kg of tomato) due to the independent regulation of pH and the dynamic adaptation of nutrients by making use of supplements; In addition, it shows evidence from other research with decoupled systems in which they obtained yields of 8.89 kg of tomato compared to 6.1 kg produced in hydroponics.

3.5.1 Aquatic species in aquaponics

Taking into account aquatic species reported in the reviewed publications, Figure 15 was constructed:

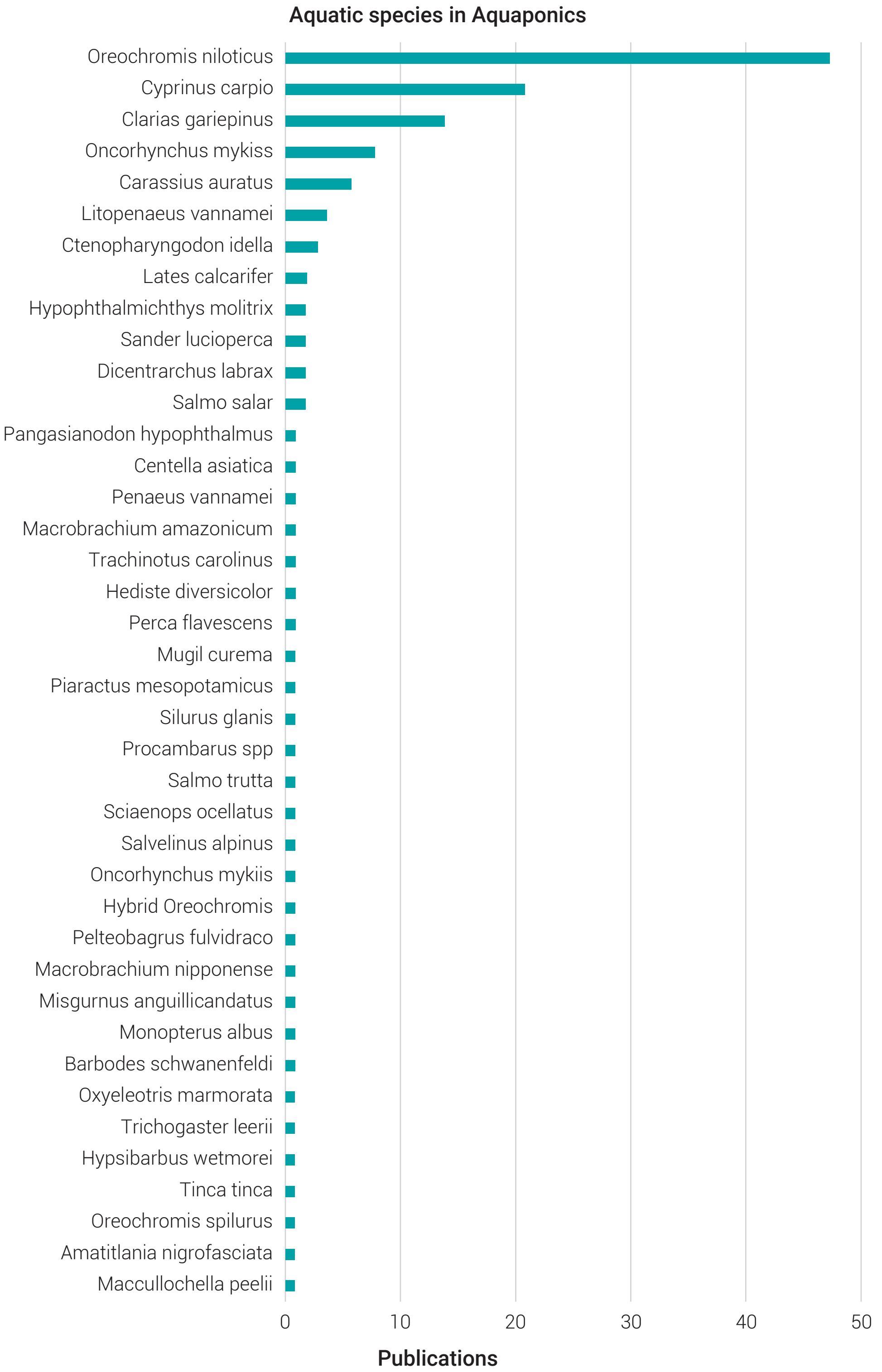

Figure 15. Aquatic species in aquaponics.

Source: Own elaboration

Tilapia (*Oreochromis niloticus*), carp (*Cyprinus carpio*), African catfish (*Clarias gariepinus*) and rainbow trout (*Oncorhynchus mykiss*) are among the species most commonly used in aquaponics, as well as freshwater and saltwater crustaceans such as white-legged shrimp (*Litopenaeus vannamei*) and ornamental species such as goldfish (*Carassius auratus*).

It is important to highlight the increasing significance of the study of multi-trophic interactions generated in aquaculture crops. [41] presents an analysis of the carbon balance of integrated multitrophic aquaculture (IMTA) systems in earthen ponds planted with freshwater Amazon River prawn (*Macrobrachium amazonicum*) and Nile tilapia (*Oreochromis niloticus*), where they established a carbon sequestration within the ponds from the input water that was similar to 1 ton per ha and the atmosphere similar to 0.1-0.3 tons per ha. The accumulated carbon in the sediment was about 3.5 tons per ha. Thus, they concluded that integrated aquaculture in stagnant earthen ponds traps large amounts of carbon from the nutrient-rich source water and the atmosphere.

Likewise, [42] studied the production performance of genetically improved farmed tilapia (GIFT, *Oreochromis niloticus*) and freshwater shrimp (*Macrobrachium rosenbergii*) in periphyton-based systems in farmers' ponds in Mymensingh, Bangladesh. This combination also gave the highest economic return. Therefore, a stocking ratio of 75% fish plus 25% shrimp with a total density of 20 000 ha was shown to be the best choice in stocking ratio in terms of fish production and economics for a periphyton-based polyculture system.

3.6 Yield and water use

Considering the number of aquatic species and plants, there is a great variety of combinations for aquaponics systems, and for this reason, variations can be found regarding optimal performance conditions [43].

Generally, in aquaponics, performance depends on the capacity of each one of the systems to produce, transform and consume nutrients [44], including adjustment of variables such as pH, dissolved oxygen and temperature. [26] in their review on aquaponics systems found a range of values that are useful for the fish-plant-bacteria multitrophic system (Table 4); maintaining these values in each of the stages of the aquaponic system it is possible to produce optimum yields.

Table 4. Aquaponics system parameters.

Parameter	Fishes	Plants	Bacteria
pH	6-8	6-7	5,5-7
Disolved Oxigen (mg/l)	3-9	3-5	4-7
Temperature (°C)	15-30	17-25	15-25
Electroconductivity(uS/cm)	100-2000	-	-
Light intensity (PPFD)	-	600-900	-

Source: Adapted from [21,26]

Table 5 shows the most commonly used species combinations together with the type of hydroponic system, reported yields and fish-plant ratios recommended by authors.

Table 5. Ratios plant per fish kg and yields in aquaponic systems.

Hydroponic system	Aquatic species	Plant species	Water flow	Water consumption (%)	Ratio (Plant per fish kg)	Aquaculture production (kg/m³)	Plant production (kg/m²)	Ref
Floating root	*Oncorhynchus mykiss*	*Lactuca sativa*	Continuous 180 l/h	NR	10,3	9,5	0,45	[28]
Floating root	*Cyprinus carpio*	*Lactuca sativa*	Continuous (each 12h) 120 l/h	1,37	4,8	6,88	3,88	[43]
Floating root	*Cyprinus carpio*	*Cichorium intybus*	Continuous (each 12h) 120 l/h	1,37	3,6	6,88	0,91	[43]
Floating root	*Cyprinus carpio*	*Beta vulgaris*	Continuous (each 12h) 120 l/h	1,37	4	6,88	5,33	[43]

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Hydroponic system	Aquatic species	Plant species	Water flow	Water consumption (%)	Ratio (Plant per fish kg)	Aquaculture production (kg/m³)	Plant production (kg/m²)	Ref
Floating root	*Monopterus albus*	*Nasturtium officinale*	Continuous (each 24h) 180 l/h	14	5,3	53,57	15	[45]
Floating root	*Oreochromis niloticus*	*Lactuca sativa*	Continuous (each 24 h)	3,6	3,6	30	2,4	[46]
Floating root	*Oreochromis niloticus*	*Ocimum basilicum*	Continuous (each 24 h)	3,6	2,8	30	1,3	[46]
NFT	*Salmo trutta*	*Ocimum basilicum*	DNR	DNR	30	1,58	3,56	[47]
NFT	*Oreochromis niloticus*	*Origanum majorana*	DNR	DNR	12	4,31	3,7	[51]
NFT	*Oreochromis niloticus*	*Ocimum basilicum*	DNR	DNR	12	4,31	5,2	[51]
NFT	*Oreochromis mossambicus*	*Oenanthe javanica*	Continuous (each 24h) 50 l/h	DNR	3	35,56	2,38	[52]
NFT	*Carasssius auratus*	*Myriophyllum Spicatum*	Continuous (each 24h) 50 l/h	DNR	24	4,49	7,04	[52]
Substrate media bed	*Oreochromis niloticus*	*Amaranthus hybridus*	Intermitent (each 1,5 h) 300 l/h	DNR	0,76	5,62	2,58	[48]
Substrate media bed	*Oncorhynchus mykiss*	*Lactuca sativa*	Continuous 180l/h	DNR	10,3	9,5	0,45	[28]
Substrate media bed	*Carassius auratus*	*Ocimum basilicum*	DNR	DNR	0,15	5,36	DNR	[49]
Substrate media bed	*Oreochromis mossambicus*	*Oenanthe javanica*	Continuous (each 24h) 50 l/h	DNR	3	35,56	2,65	[52]
Substrate media bed	*Carasssius auratus*	*Myriophyllum Spicatum*	Continuous (each 24h) 50 l/h	DNR	24	4,49	7,87	[52]
Substrate media bed	*Macrobrachium amazonicum*	*Lactuca sativa*	DNR	DNR	1,6	4,68	3,8	[50]

Source: Adapted from [28,41,43,44,45,46,47,48,49,50]

Water flow is generally continuous, although flow rate varies depending on the specific dimensions of each system [48], as feed consumption and waste production may change depending on these.

Depending on the sizing of the aquaponic system, different plant-fish ratios are chosen [52], as in many cases aquaponics systems arise from projects that seek to take advantage of already established aquaculture systems, this is why the hydroponic sub-system sometimes does not follow the recommendations to implement the appropriate number of plants per kilogram of fish. It is important to keep in mind that when handling different crop cycles, a single planting of aquaculture species can represent a different number of plant harvests. [51] reported that for basil crops, 3 harvests were generated throughout the tilapia cycle.

Another factor that generates differences between fish and plant productions is planting density, [50] in their evaluation of the use of different shrimp densities, found that there is a correlation between this with respect to mass gain and lettuce nutrition, due to the low concentrations of nutrients in the aquaculture tank effluent; to compensate this, authors propose the use of supplements at low densities.

Water consumption, although in many of the publications it is not measured, plays a fundamental role since in aquaponics good quality water is required and effluents are produced with nutrient discharges that affect environmental degradation; according to [26], water exchange is an effective method to maintain good water quality in aquaponic farms, the exchange rate can vary from 250% to 10% of water per day; water losses are caused by wastewater runoff, evaporation, evapotranspiration, fish splashing during feeding, among others [53].

To maximize performance in aquaponic systems, a constant flow of waste must be produced on a daily basis [35]. As recommended in most publications, recirculation is suggested in the range of 0.8 l/min to 8 l/min, making 2.3 to 18 cycles in the fish tank, giving the possibility to maximize performance in terms of fish growth, plant growth and nutrient removal.

3.7 Instrumentation and Automation in Aquaponics

The design and management of aquaponic systems turns out to be a complex challenge when it comes to achieving high yield and quality crops. Thanks to the introduction of technological tools, there is a possibility to elaborate process control with accessibility and connectivity parameters.

Since approximately 3 years ago, research on sensors, actuators, controllers and Internet of Things (IoT) systems has increased [54], the main characteristic of this research orientation is to monitor and control parameters at critical points of the system (Figure 16), for example, the implementation of different techniques to detect pH levels, either with colorimetric meters, digital sensors with LCD screens or analog sensors with data transmission.

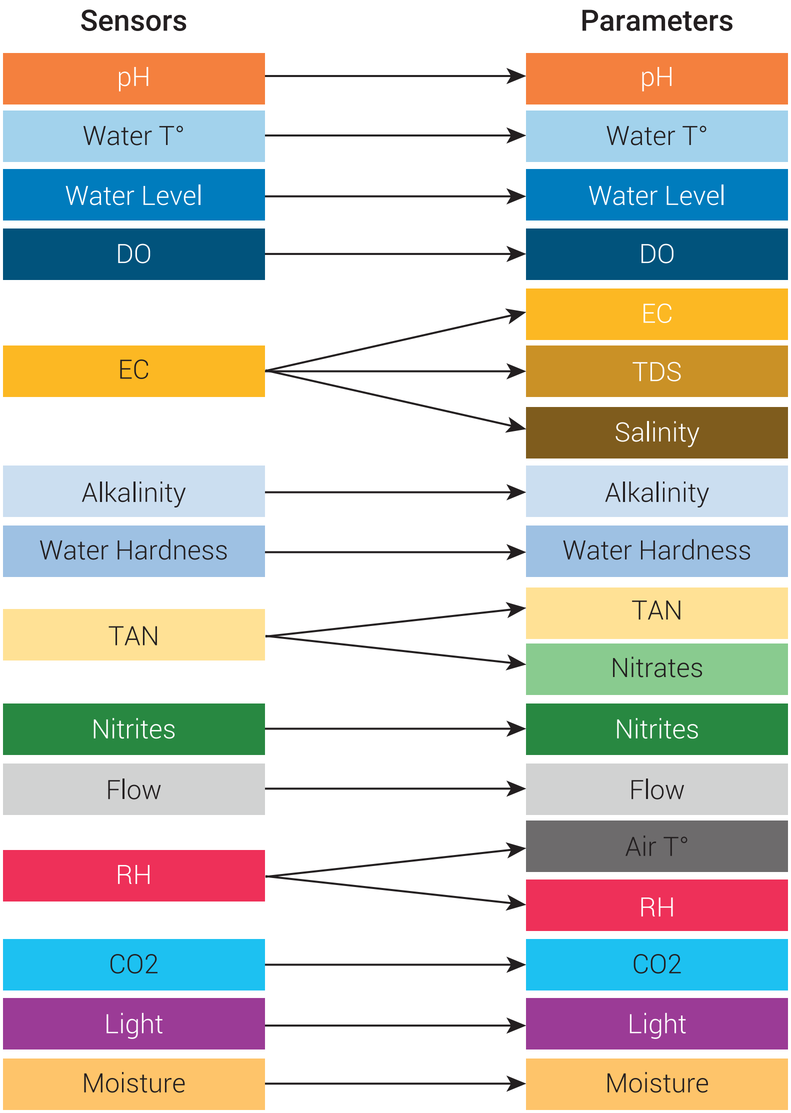

Figure 16. List of sensors and parameters found in literature.
Source: [21]

[21] made a table in which the types of sensors implemented in aquaponics and their functions in each sub-system can be seen (Figure 16).

Currently there are four key points that apply to the fish, plant and bacterial sub-systems (Figure 17), in association with systems modeling, understanding each of their parts, nutrient exchange and the requirements for balanced growth among species, it is possible to approach automation and control:

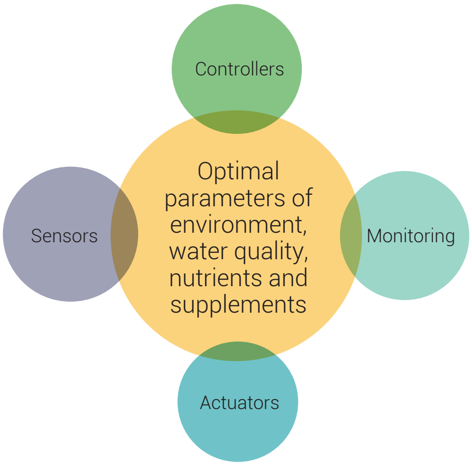

Figure 17. Tools to maintain optimal levels of environment, water quality, nutrients and supplements.
Source: Own elaboration

Considered as the most important matrix in the aquaponics process, water is one of the most important factors in the production of quality food. To ensure standards that meet the food industry requirements, it is necessary to maintain appropriate levels of nutrients, pH, temperature, dissolved oxygen, salinity, electrical conductivity and turbidity.

Works such as [55], implement water level sensors to monitor fish tanks and issue alerts in case it is necessary to open or close valves to perform recirculation tasks; DS18B20 submersible temperature sensors with capability to measure up to 125°C, coated with stainless steel that through programming read and send data to controllers such as Arduino comparing with references or set points, sending signals to water heaters to increase or decrease the temperature; pH probes in charge of measuring hydrogen ions to determine water acidity or alkalinity, alerting the user about the environmental quality of fish and plants.

There is a great relationship between temperature and dissolved oxygen, as the water warms up it tends to retain less oxygen, on the other hand, as the fish feed it can be reduced, arising the need to compensate by oxygenation methods such as water drops or aerators. Although DO is a very important variable it is little reported in research due to the high cost of sensors, in the case of [56] the use of Atlas DO probes distributed in nodes (communicating different stations) with TCP/IP connection to a Raspberry Pi controller which reads and interprets the signal to control aerators as required is presented.

Electroconductivity in aquaponics is related to water salinity; in the case of fish, it represents an important element since, depending on its values, water can be cleaner or polluted [21]. Stable electroconductivity values and in optimal ranges (between 100uS to 2000uS) allow fish to maintain osmotic balance; in the plant system, as reported by [57] in their measurements with EC/pH sensors of HANNA Instruments, high levels of electroconductivity in nutrient solutions for basil (*Ocimum basilicum L.*), cabbage (*Brassica oleracea L.*), chili (*Capsicumannuum L.*), and cherry tomato (*Solanum lycopersicum L.*) yield greener and taller leaves compared to fertilizers with low levels.

In industrial aquaponic systems, understanding water flow allows estimating the capacity of mechanical filtration and biofiltration, as well as determining the availability of nutrients for plants. To achieve the above, using mathematical computational models such as those stated by [58], [59] and [60], an algorithm is generated in which the best crop environment for certain species of fish and plants is established, then sensors and actuators are adapted in conjunction with a controller (Figure 18) that will be evaluating the model and making adjustments according to the levels measured by each sensor.

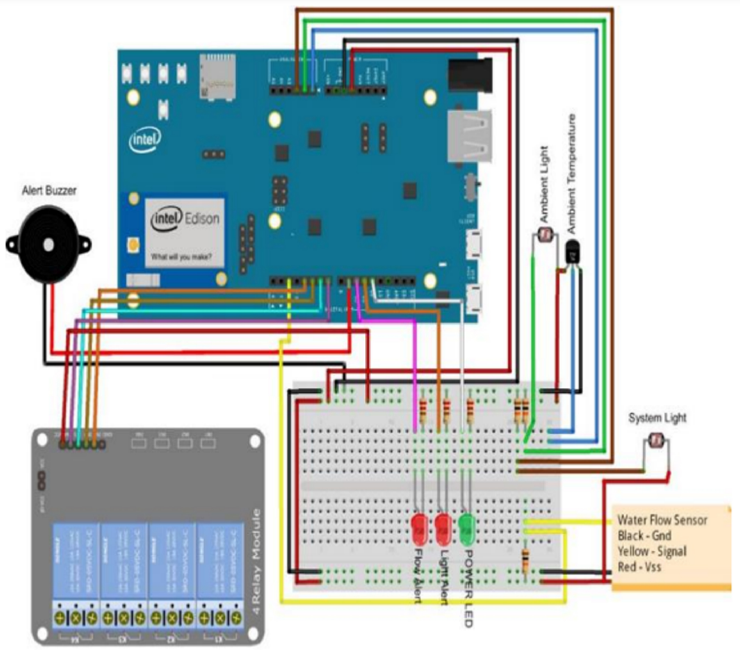

Figure 18. Electronic circuit to measure light, water flow and temperature in aquaponic systems.
Source: [58]

Although measurement and control are fundamental, data access is a critical factor to understand what is happening in the system, for this reason IoT technologies are gaining strength in aquaponics, [61] and [62] have implemented a data acquisition and control system in conjunction with web and mobile applications through the integration of web servers, receiving the information either by GSM, WiFi or wired networks and displaying it in applications that allow the user to know the system status at any time.

On the other hand, technological innovations not only depend on instrumentation, automation and control, the use of alternative energies in aquaponic systems that are commonly found in non-interconnected areas are equally important, studies such as [63] and [64] show the use of an automated aquaponics system powered by solar panels; Starting from a monitoring system of air and water temperature, relative humidity, light, pH, level sensors, dissolved oxygen, electroconductivity and turbidity, passing through conditioning circuits to input a microcontroller that through programming in LabVIEW analyzes and controls actuators such as water pumps, aeration, heaters, dispensers and fans, ending with an integration through GSM that sends data to mobile platforms.

4. DISCUSSION AND CONCLUSIONS

Based on the systematic review findings, taking into account the analysis of the papers' quality and their subsequent reading, adjustments were made (Figure 19) to the initial Ishikawa diagram in order to integrate it with the current research orientation, although some limitations were considered, such as the fact of adjusting the search to four databases and the use of English as the default language.

Currently, aquaponics systems have a great variety of study fields, as it could be observed throughout the review, new topics of interest arise in order to optimize yields, either in hydroponic or aquaculture systems, understanding each of its components and evaluating them comparatively in order to choose the components that best suit the environmental conditions.

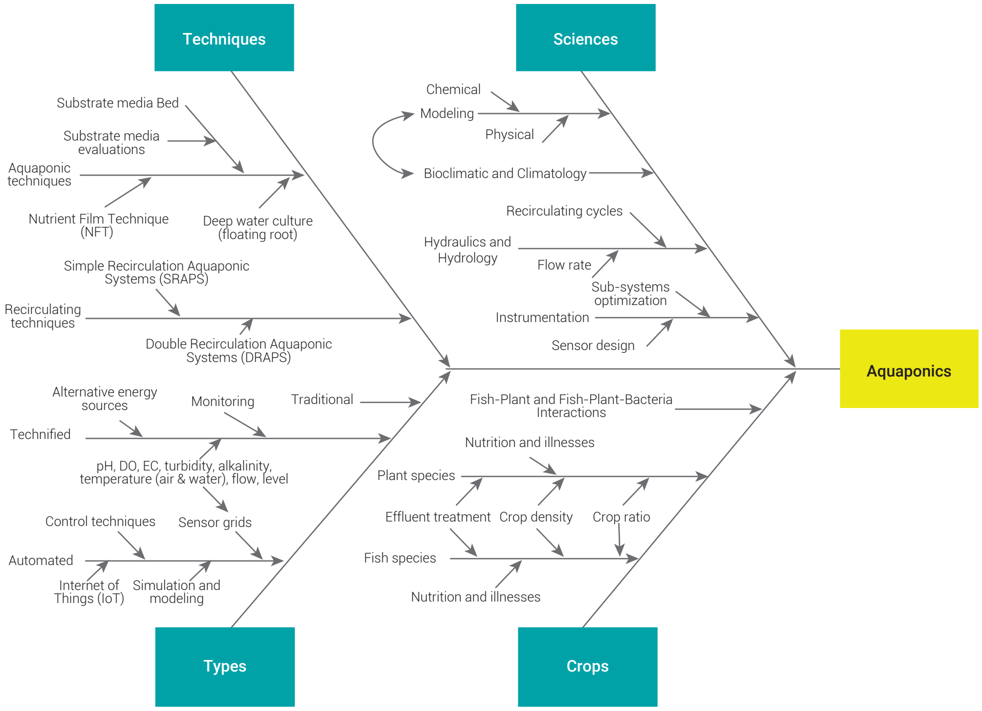

Figure 19. Updated Ishikawa diagram.
Source: Own elaboration

In addition, there are structural configurations in the hydroponic system that tend to be oriented towards nutrient film technique and substrate media bed, the first one due to its extensive research and the second one due to the possibility of adapting different types of substrates that are capable of hosting plant and bacterial species, adding the possibility of increasing the nitrification process and nutrient conversion, integration of different techniques is a possibility that has already begun to be implemented in industrial conditions.

Regarding recirculation techniques, there is already an established trend towards the use of SRAPS systems in small producers; on the other hand, recent studies have shown that double recirculation DRAPS systems are more efficient, although their costs can be high due to the technification level, which is why they are implemented to a greater extent by medium and large producers.

The most worked species correspond to tilapia and lettuce thanks to their pH and temperature tolerances, and their capacity to carry out the nitrogen and ammonium cycle. It is worth mentioning that the combination of other species more sensitive to changes in the environment has begun to be studied, since the application of sensors, actuators and controllers makes it possible to maintain more stable ranges in system's critical variables.

Derived from studied species is the ratio in aquaponics systems, this is why comparative evaluations are currently being generated between plant quantity per fish kilogram, in order to find proportions that are suitable for the generation, transformation and consumption of micro and macronutrients within the system.

On the other hand, and consistent with proportionality, there are also analyses of planting densities, since these directly affect the variation of pH and oxygen, nitrogen and ammonium consumption cycles. Normally aquaculture and hydroponic studies are done separately, but currently they have been integrated in order to obtain densities that are capable of meeting the nutritional demands between fish and plant species.

Finally, emphasis is placed on the instrumentation and automation systems, once the diagnostic analysis is done and the plant-fish-bacteria multitrophic system is understood, its nutrient flows, load capacities and environmental requirements, by means of computational tools the sub-systems are modeled and controllers capable of maintaining the most important variables in aquaponics at optimal levels are generated. Many of the studies focused on applied electronics are generated after understanding the above mentioned, that is why it is possible to identify the appropriate sensors to measure the most important variables, then controllers of different types are designed (either on/off, classical control, fuzzy logic) and finally actuators that are able to maintain systems in the desired range. Previously, automated systems focused on water replacement to control nutrients in aquaponics, but nowadays, thanks to technological advances, it is possible to focus the control on nutrient dosing, nitrogen, ammonium and phosphorus cycles.

Of the publications reviewed, although only 6% corresponds to the area of electronics, it is observed that in other study fields monitoring units are already implemented on traditional aquaponic systems, which is why the figure given could vary depending on the type of tools that are already being used for water analysis, yields, flow control, recirculation in aquaponics, among others.

Although there is currently an exponential growth in publications on aquaponics, in Colombia there is still a lack of studies to demonstrate its performance, capacity to meet the needs and reduce the use of soil and water in the agricultural sector, this is demonstrated in the number of papers found specifically for this region.

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