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Equipment and Intelligent Control System in Aquaponics: A Review

YAOGUANG WEI, WENSHU LI, DONG AN, DAOLIANG LI, YISHA JIAO, AND QIONG WEI
College of Information and Electrical Engineering, China Agricultural University, Beijing 100083, China

Corresponding author: Daoliang Li (dliangl@cau.edu.cn)

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ABSTRACT Traditional planting and aquaculture has the problem of large consumption of water resources and land resources, and the water environmental pollution is also a difficult problem facing human beings. Population growth and food safety issues have promoted the concept of aquaponics——a recycling ecological planting and breeding mode. It combines hydroponics and recirculating aquaculture technology to realize water resources and nutrient recycling, low pollution and high productivity and efficiency. In this paper, hydroponics as the main vegetable cultivation method in aquaponics and the main equipment of water treatment in recirculating aquaculture are introduced, and the traditional equipment and its development prospects are analyzed. The greenhouse environments, water quality and nutrient circulation involved in intelligent monitoring and control of aquaponic systems are systematically analyzed and summarized. This paper summarizes the current development of technology and methods in aquaponics and provides prospects for future development trends. With the development of technology, in the future, the aquaponics system will become more intelligent, intensive, accurate and efficient.

INDEX TERMS Aquaponics, efficient utilization of water, intelligent controlling, nutrient cycle, precision monitoring.

I. INTRODUCTION

Aquaponics is a new technology in modern agricultural production that combines aquaculture with hydroponics. Thus, vegetable planting no longer requires fertilization, and fish cultures do not need water changes as frequently. This change allows fish, cultivated crops and microorganisms to form mutually beneficial symbiosis and harmonious coexistence of ecological balance relationships. It is a working mode of sustainable healthy food production [1]. In the face of soil pollution, drought and climate change, aquaponic systems have attracted increasing attention due to their resource savings, high efficiency and low consumption, and they have become the trend and direction of modern agricultural development [2].

As one of the important contributors of aquaculture production in the world, China has the largest aquaculture industry. Moreover its aquaculture production exceeded 50 million tons, accounting for more than 60% of the world's aquaculture production in 2018. However, at the same time as the rapid industrial development, some problems occurred in different areas, such as the unreasonable distribution of aquaculture, serious pollution from aquaculture in some areas and a low degree of scale and organization. The traditional methods of aquaculture in China are still characterized by high density, high baiting rates and high water exchange rates [4]. It is estimated that 52-95% of nitrogen, 85% of phosphorus and 60% of feed put into aquaculture will eventually be converted into particulate matter, dissolved chemicals or gases. Ultimately, different feeding residues and animal excretions will appear in the water due to different feeding types and techniques [5]. In the aquaculture process, with the continuous accumulation of fish excrement and bait, wastes will be converted into ammonia-nitrogen, nitrite, hydrogen sulfide and other components. These harmful substances have immediate effects

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and accumulation effects, and these effects can reach levels that will inhibit the respiration, feeding, and growth of fish, and even endanger the ability of fish to survive. High density and intensive farming methods will not only cause serious losses to the economic benefits of aquaculture but also cause negative impacts on the environment, resulting in the eutrophication of the water body and a waste of water resources [6]–[8].

Since the 1990s, sustainable development strategies have become a global trend, and a circular economy is the general trend of sustainable development and the best mode of economic development. The traditional fish culture mode not only consumes many natural resources and introduces pollution to the environment but also has certain problems, such as the difficulties related to water treatment and the inefficiency of aquaculture. Grass carp farming in paddy fields in China started as early as 1100 years ago, and this type of farming provides an example of realizing the resource utilization of aquaculture wastes through the nutritional relationship between rice and grass carp. Grass carp feed on weeds, which reduces the nutritional competition between weeds and rice, and fish feces also play a role in fertilizing rice. Chinese traditional mixed cultures of grass carp and silver carp have the same function, i.e., grass carp feed on grass, and grass carp bait and feces are used to fertilize water and feed silver carp. After the mechanization of pond fish farming was completed in the 1970s, China began to explore ''assembled'' industrialized fish farming. European industrialized fish farming also realized the ''unified'' fish farming model. Then, the concept of aquaponics was proposed; however, most attempts to integrate aquaculture and hydroponics had limited success until the 1980s. [9]. Aquaponics has become an innovative exploration of the aquaculture industry in recent years.

As a sustainable, circular, efficient and intensive low-carbon production mode in the future, the aquaponics system has realized the transformation from waste to nutrients and has effectively solved the problem of environmental pollution [10]. The principle of constructing an aquaponic system is that waste and unfinished bait discharged from farmed fish can be used to decompose ammonia-nitrogen in water into nitrite by microorganisms. The nitrifying bacteria decompose it into nitrates so that they can be absorbed as nutrients by the cultivated crops to be used for growth; thus, the aquaculture water environment has been effectively improved. After the water that has ammonia-nitrogen is purified, it can be used as new aquaculture water again through the circulation system, which saves water resources and makes the exchange efficiency of water less than 2% per day. The water use efficiency has been improved, and a water resource cycle has been formed. Finally, an ecological model of aquaponics and a virtuous cycle are formed [11]. Aquatic plants bind nitrogen to organic compounds through nitrogen fixation, thus connecting the beginning and end points of nitrogen metabolism in closed aquaculture by assimilation and absorption by plants. Finally, the nitrogen cycle of fish and vegetables can be formed, resulting in the ecological effect of nutrient recycling, which simultaneously saves on costs related to water purification and enhances the harvest of pollution-free green fish and vegetable products [12]. At the same time, with the growing world population and energy costs, the reduction of natural resources such as water and the demand for food contribute to the continuous development of aquaponics systems [13].

With the continuous development of the system and the increase of growing objects, the approach of artificial management alone cannot meet the needs of the current system. By means of intelligent algorithm and considering the influence of the environment and other aspects comprehensively, the cycle of water resources and nutrients in the aquaponics system is ensured to be in an optimal range. Therefore, in order to make fish and vegetables grow healthier, it is very important to monitor and control the aquaponics system. The premise is that the intelligent monitoring and controlling of the system can only be achieved only by first provisioning the equipment with integration, automation and the addition of intelligence concepts. First, this paper introduces the two aspects of facility vegetable cultivation and recirculating aquaculture. Then, we summarize the main vegetable cultivation methods - hydroponics, recirculating aquaculture equipment and the recent developments. Finally, this paper summarizes and analyses the three main aspects of the impact system, including the technology of the intelligent monitoring and controlling of the greenhouse environment, the water quality and the nutrient solution. The shortcomings and challenges of the current development and a prospect for future development are proposed in the last section. The overall framework of the paper is shown in Fig. 1.

Currently, aquaponic systems have mature planting technology and culture equipment in vegetable cultivation and recirculating aquaculture. In the future, the combination of aquaponic systems with greenhouses will be a developing trend. With the continuous development of modern equipment technology and information technology, the equipment needed for planting and breeding will gradually transition away from manual control, and improvements are being made in terms of automation, intelligence and high efficiency. Intelligent automatic control of the greenhouse environment, water treatment process and nutrient circulation process in aquaponic systems has become the main direction of development of aquaponic systems through the use of intelligent algorithms and optimization model control.

II. HYDROPONICS

Hydroponics, proposed by W.E. Gericke of the University of California in 1930 [3], is one of the most commonly used vegetable cultivation methods in aquaponic systems. Hydroponics refers to a technique in which plants are grown in a nutrient solution without a rooting medium, and the plant roots are suspended in either a static, continuously aerated nutrient solution or a continuous flow or mist of nutrient solution [14]. Strictly speaking, hydroponics is a way to solve the problem of plant growth and nutrition, in addition to systems

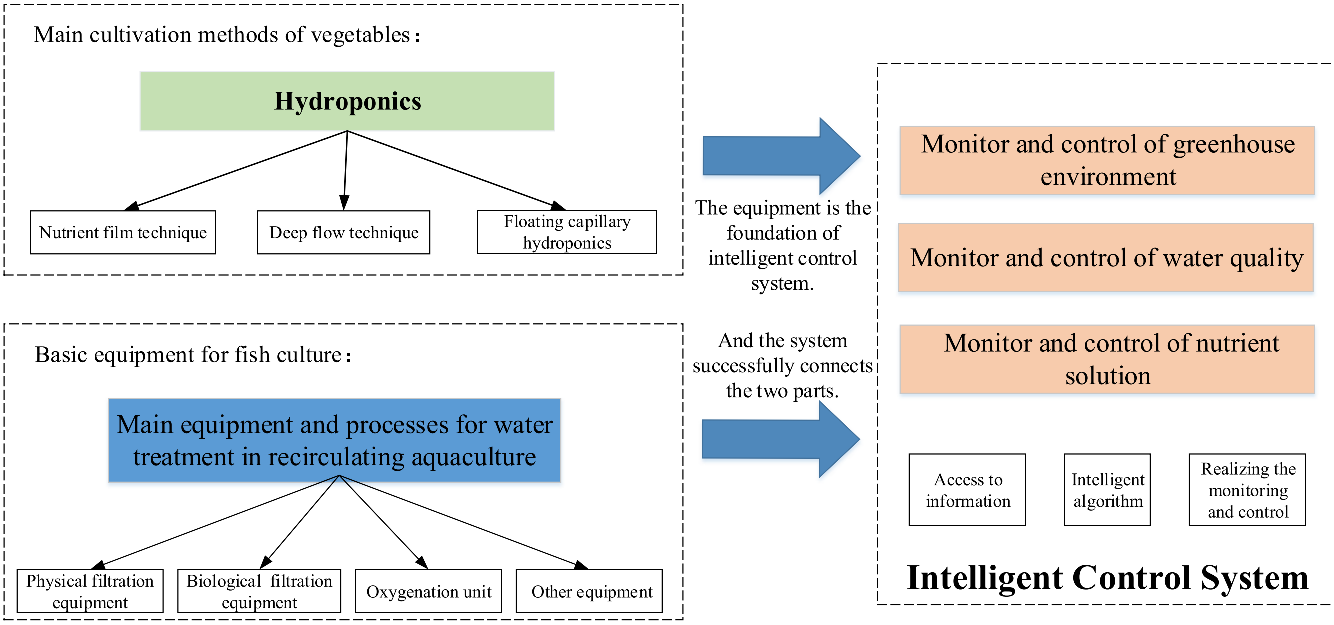

FIGURE 1. Overall framework of the full text.

that exclusively use a nutrient solution and air [15]. Compared with traditional methods, hydroponics uses only 10% of the water resources and enables growers to achieve complete control of nutrient transport [16]. Compared with soil agriculture, hydroponic systems can save 5-20 times the water consumption and reduce land requirements for crops by 75% or more [16], [17]. The production of hydroponic systems can be ten times greater than that of conventional agriculture production [18], and the system allows for the more accurate control of vegetable nutrition [19]. In hydroponics, plant roots directly contact nutrient solutions, absorb nutrients needed in the process of growth, and avoid many unfavorable factors in the process of soil cultivation. It has the advantages of providing a balanced supply of nutrients, easy regulation, and protecting crops from soil-borne diseases [20]. According to the depth of the nutrient liquid layer, it can be divided into three types: NFT (nutrient film technique), DFT (deep flow technique) and FCH (floating capillary hydroponics).

A. NUTRIENT FILM TECHNIQUE (NFT)

The NFT provides the possibility for the precise control of the root environment [21]. Its basic principle is to make the shallow nutrient liquid layer flow from the higher end to the lower end of the planting trough through gravity. The nutrient solution continuously circulates through the vegetable root system, causing the root of the crop to directly contact the nutrient liquid in the planting trough [22]. This technique allows for the provision of adequate ventilation, water and nutrition. Depending on the size of the crop and channel, the inlet flow rate varies from 1 to 3 liters per minute [19]. An intermittent or continuous liquid supply is usually used to solve the contradiction between root water absorption and oxygen absorption. Intermittent flow technology can also save pump wear and reduce power consumption by up to 84% [23].

As early as 1974, there was an attempt to combine the NFT with vegetable cultivation, and the results were encouraging [21]. After that, the technology continued to mature and develop [23]–[26] and was applied to the aquaponics system [27]–[30]. Compared with other techniques, the NFT can achieve the best results in hydroponic vegetable cultivation [31]. Hydroponic NFT systems can purify water to a certain extent [32], [33], require less water and are one of the most often used and best understood hydroponic growing systems [34]. The advantages of the system are its low costs, and it is easy to automate production management. The reduced volume of nutrient solution required and the absence of substrate result in significant savings in water and fertilizers [19]. The development of the NFT system removes the necessity for the determination of water requirements and provides an opportunity for more precise control of plant nutrition [35]. The disadvantages include the strict technical requirements, poor durability and stability, and high operating costs. Root uptake of the nutrient solution is affected by system failure or power failure [36]. The hydroponic NFT system is suitable for short-term and multichannel crops [37].

Experiments show that the hydroponic system using NFT technology can improve crop yield to a certain extent. Castillo-Castellanos *et al.* [38] proposed the design and implementation of an NFT-type aquaponics system that did not include a sump pump. The experimental results showed that the yield of lettuce and cucumber planted under this system was high. Kloas *et al.* [39] used two independent recirculating units: a recirculating aquaculture system (RAS) for fish and a plant hydroponics unit based on NFT to form an aquaponics system of tomato and fish production in a greenhouse with almost no emissions (ASTAF-PRO). This study proved that the ASTAF-PRO system did not reduce fish and vegetable production, and it improved sustainability and productivity while reducing environmental emissions.

B. DEEP FLOW TECHNIQUE (DFT)

Deep flow hydroponics is the first successful hydroponic technology used in commercial plant production, and this method uses a deeper layer of nutrient liquid that is circulated continuously through the vegetable roots. This method ensures the continuous supply of water and nutrients to crops and the continuous supply of fresh oxygen to roots [15], [40]. In 1976, it was independently developed by researchers at the University of Arizona and the University of Pisa in Italy and is now widely used in the United States, Japan and Canada [41]. The DFT system consists of PVC (polyvinyl chloride) trays with a length of 4 m, a width of 0.15 m and a depth of 0.20 m and is regulated by flowmeters and electric pumps at a speed of 60 L min−1 [42]. Compared with the NFT system, the DFT system has a deeper nutrient solution layer, so it is more difficult to dramatically change the parameters in the nutrient solution. The system provides a stable growth environment for roots and does not need pumps to provide the nutrient solution for plants. Usually, this method is suitable for single harvest crops [37]. It has strong circular and continuous tillage performance and can improve the yield and quality of vegetables to a certain extent.

Now, the technological development of using deep flow hydroponics to grow vegetables is becoming increasingly mature [43]–[45]. Its application in aquaponic systems has also achieved good results. Mustikasari *et al.* [46] studied the physical growth of three types of plants based on aquaponics technology, and the experimental results showed that the development of the deep flow system was more useful for aquaponic systems than hydroponics. Vermeulen and Kamstra [47] compared the aquaponics system with the typical Dutch rockwool system and found that the use of deep flow hydroponics could provide better nutrition for plants and reuse nitrate. Compared with traditional hydroponic systems, it is more advantageous to use in aquaponic systems. Walters and Currey [37] planted basil cultivars in two hydroponic production systems using an NFT and deep flow hydroponics technology. After three weeks of cultivation, the fresh weight of plants grown in the DFT systems was 2.6 g greater than that of plants grown in the NFT systems.

C. FLOATING CAPILLARY HYDROPONICS (FCH)

FCH technology uses a piece of foam plastic with nonwoven cloth in a deeper nutrient liquid layer and makes the roots grow on the wet nonwoven cloth while recycling the nutrient solution [48]. Since 1990, new soil-less cultivation techniques, such as FCH, have been gradually developed on the basis of the advantages of soil-less cultivation facilities worldwide [49]. Its advantages include low cost, less investment, convenient management, energy savings, and practical and wide applicability of the system [50]. This method effectively overcomes the shortcomings of the NFT and solves the contradiction between supplying liquid and supplying oxygen in other hydroponic methods by the root-splitting method [51]. The rhizosphere environment is stable, and the oxygen supply is sufficient. In this system, the change in the liquid temperature is small, so its applicability is wider.

The FCH system consists of a cultivation bed, liquid storage tank, control system, liquid supply and circulation system [52]. The nutrient circulation system adopts an intermittent liquid supply circulation mode, but the interval time is longer than that of the NFT system. The running time of the pump is one quarter of that of the NFT system, thus saving energy consumption. Ye and Li [53] showed that FCH technology could greatly improve the root environment of crops and easily realized the automatic control of the soil environment.

As a promising technology, hydroponics has many advantages over traditional vegetable cultivation. It can break through the limitations of the traditional soil planting mode and make full use of planting space, so it has a high multiple cropping rate. In the planting process, there is no need to replace the nutrient solution. Through the growth of vegetables, it can purify the water quality circulating between planting and breeding to a certain extent. Hydroponics has the characteristics of water savings, fertilizer savings and impermeability. The summary of three hydroponics technologies is shown in Table 1; among the three hydroponics technologies, the NFT technology achieves the best results and more easily achieves automatic control. With the development of advanced control devices and the introduction of control algorithms, the nutrient composition of the nutrient solution can be accurately controlled to ensure the provision of more adequate, balanced and timely nutrition for vegetables. This method reduces the cost of traditional vegetable cultivation and provides quality and yield assurance for vegetables. To achieve better vegetable planting results, it is necessary to monitor and control the vegetable planting environment and nutrient solution intelligently. Not only can the greenhouse vegetables be planted in an optimal growth environment but the nutrient solution can also be reasonably regulated to provide the best nutrient elements. Currently, the introduction of intelligent greenhouse systems makes it easier to control all aspects.

III. EQUIPMENT IN RECIRCULATING AQUACULTURE SYSTEMS OF AQUAPONICS

Recirculating aquaculture is a water-saving, efficient, environmentally friendly production and aquaculture mode; through a series of water treatment processes, RASs provide opportunities to reduce water usage, improve waste management and nutrient recycling [67]. Compared with the traditional outdoor aquaculture method, recirculating aquaculture system can recycle 90-99% of the water and greatly increase

TABLE 1. Summary of three hydroponics technologies.

Different systems	Main growing objects	The depth of nutrient solution(cm)	Slope	pH and EC	Flow rate	Recirculation frequency	Advantage	Disadvantage	References
Nutrient film technique (NFT)	Leafy greens, principally lettuce and tomato.	0.1-0.3	2-3%	EC:2–3 dS m^{-1} pH:6.0-6.5	1 liters per minute	With high frequency recirculation of the nutrient solution, in a 15 minute interval.	1. The system has some flexibility; 2. High yield and quality; 3. Minimal use of materials; 4. High level of automation.	1. It cannot withstand unexpected power loss; 2. Temperature fluctuations of the nutrient solution are not easily controlled in summer; 3. Need higher level of management expertise.	[54] [55] [56] [57] [58] [59] [60]
Deep flow technique (DFT)	Leafy vegetables, principally lettuce.	5 - 20	zero slope	EC:0.8-1.2 mS/cm pH:6.0-6.5	60 liters per minute	With a smaller recirculation interval, approximately 4 or 6 hours. Water in the DFT system is updated every 72 hours.	1. The system can keep temperature more stable; 2. It is resistant to unexpected power failure.	1. The environment is relatively closed, and diseases are liable to spread; 2. Facilities investment is relatively high.	[42] [58] [61] [62] [63]
Floating capillary hydroponics (FCH)	Tomato, eggplant, pepper, melon, balsam pear, cucumber	3 - 6	—	EC:1.8-2.2 mS/cm pH:5.5-6.5	Nutrient solution provided at each feeding port: 5 - 6 liters per minute.	Circulation mode of 5 min supply/15-20 min shutdown.	1. Provide a more stable environment for roots; 2. Little change of nutrient solution temperature; 3. More oxygen content in the solution.	1. Poor reusability of the device; 2. Higher operating costs.	[49] [52] [64] [65] [66]

the density of aquaculture [68]. In the early 1970s, Bohl [69] carried out a preliminary aquaculture experiment using a circulating water system. Because aquaculture wastewater contains a large amount of N elements needed for vegetable growth, attempts have been made to use fish wastewater for plant nutrition through aquaponic systems [39]. Soil-less cultivation has been successfully combined with recirculating aquaculture [70]–[72] to realize the recycling of resources and proved that the two together could achieve greater economic benefits [73]–[76]. The results of the combination also proved that a closed recirculation system was the most suitable aquaculture system for integration with hydroponics [77]. Facing the problem of nutrient pollution in aquaculture, the recirculating system has been identified as one of the two main research fields in aquaculture because it can solve this problem [78]. It reduces the use of recycled water and greatly saves the amount of water used compared with the traditional method, so the utilization rate of water resources can reach 95%-99% [13]. The system can also maintain good breeding conditions by controlling some basic parameters, such as temperature and water quality. Therefore, it is widely used in aquaponic systems [79]. In aquaponic systems, the wastewater from aquaculture can be recycled, and water quality treatment is key [85].

The circulating water treatment system mainly realizes the functions of water purification, oxygen enrichment and sterilization and creates a suitable growth environment for aquatic animals. In the aquaponic system, the water treatment process and the main equipment used are shown in Fig. 2. The circulating water treatment system mainly includes one component to treat solid substances and another component to treat water-soluble wastes. According to the water treatment process, the water treatment equipment is divided into physical filtration equipment, biological filtration equipment, oxygen enrichment equipment, ultraviolet sterilization and disinfection equipment [82].

A. PHYSICAL FILTRATION EQUIPMENT

In the aquaculture process, because the unit water density of cultured fish is relatively high, there is a large amount of solid waste produced by the fish. For the consumption of feed per kilogram, the fish tend to create 0.25 kilograms of solids in the water [83]. The accumulation of fish excreta and bait will create a toxic environment for the growth of fish in a short time, which will eventually lead to the blockage of the system and disturb the flow rate of water, resulting in an instable system [84]. Therefore, physical filtration is needed to remove suspended solids (SS), feces and bait from the aquaculture water [82]. The removal of SS is one of the core links in the water treatment process of RAS, and its effective removal directly determines the quality of water and the stability of system operation [85]. In a particular system, the most appropriate device for the removal of solids depends mainly on the organic loading rate (i.e., the daily feed

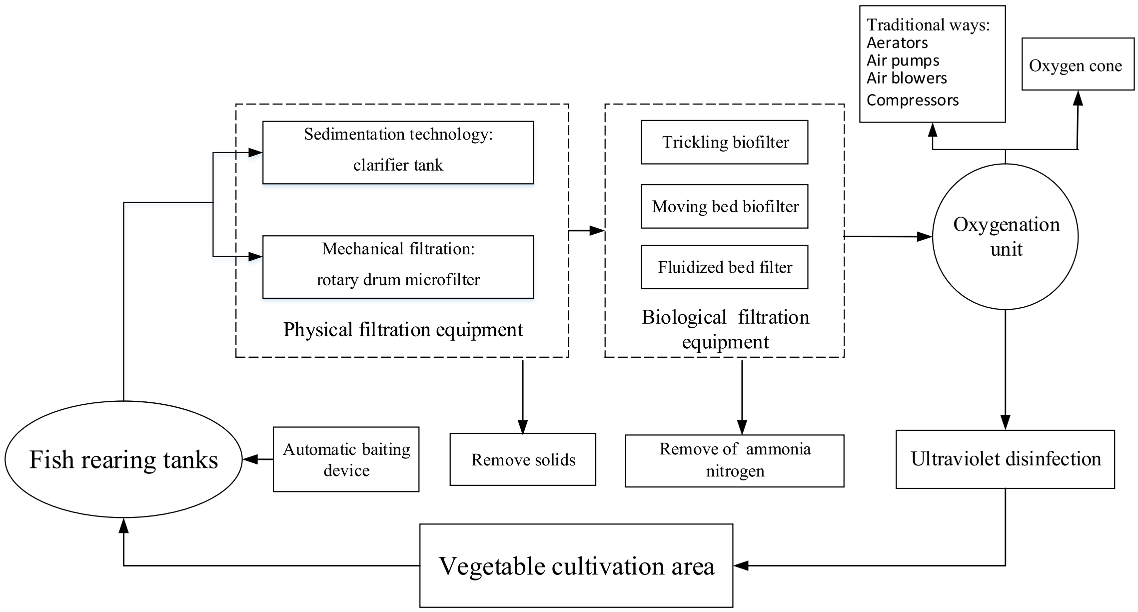

FIGURE 2. **Main equipment and flow chart of circulating aquaculture water treatment.**

volume and feces production) [86]. Physical filtration can be implemented in many ways, and the main technologies of removing solid particles in aquaponic RAS are sedimentation techniques and mechanical techniques [87].

Sedimentation technology mainly relies on gravity to solidify and remove solid waste particles, and clarifier tanks are often used in aquaponic systems [11], [88]–[90]. Clarifiers, also known as solid filters, serve as a simple unit for separating and removing precipitable solid fish waste and particulates from water. In an aquaponic system, the sedimentable solids in the water are passed through the clarifier and collected. There are currently two typical clarifiers: a conical design and a setting basin [91]. The commercial scale aquaponics system of UVI mainly relies on two cylindro-conical clarifiers to remove large settleable solids, and these clarifiers can remove approximately 50% of the total particulate solids produced in the system [11]. Savidov *et al.* [93] experimented that when removing solids, the water passing through the clarifier will pass through the sedimentation tank again. Dual filtration can achieve better results in removing solids. Pfeiffer *et al.* [94] evaluated the removal efficiency of suspended particulate matter by a cyclone separator in a tilapia RAS by screening suspended particulate matter. The results showed that the cyclone separator could remove more than 90% of the suspended particulate matter with diameters greater than 250 μm. Suhl *et al.* [95] reformed the sedimentation unit in double recirculating aquaponic systems (DRAPS) by implementing an innovative suction filter device, which improved the fertilizer saving rate and reduced the loss of nitrogen. Although sedimentation technology can only remove sedimentable and large suspended particulate matter from water, it has been widely used in the pretreatment step of suspended particulate matter in recirculating aquaculture production due to its low cost and low water loss [92].

Mechanical filtration achieves the purpose of separating solids from water by using some sort of material to screen the water. Its filtration methods include gravity (sedimentation, swirl separators/radial flow separators [96], [97]), screening (microscreen (drum) filter [96], [98]), sand filters, bead filters [99]) and other methods [13]. Drum screen filters are currently the most popular filter [87], and rotary drum microfilters are one of the main equipment types used for removing large particulate matter. It has the advantages of strong applicability, low energy consumption, less land occupation, and convenient use and maintenance. Solid particulate matter in water can be removed by solid-liquid separation, and the filter is the main working component. Samir Ahmad Ali developed a water-driven rotary drum microfilter and applied it to a tilapia RAS. The water wheel-driven method could not only achieve a better filtering effect but also save 18 kW of energy per day [80]. Al-Hafedh *et al.* [100] used a screened sedimentation tank and two up-flow cylindrical filters containing sand and plastic beads to remove solid particles. Karimanzira *et al.* [101] used drum filters to separate water from solids, and rotating microscreen filters captured solids by filtering water. Cronin *et al.* [102] used a new filtration method to provide mechanical filtration by changing the flow direction of water so that heavy solids could be precipitated at the bottom of a radial flow separator/settler (RFS). Kamauddin *et al.* [103] designed experiments to compare and analyze different water treatment technologies. The results showed that the plant growth rate and yield of the aquaponics system with mechanical filtration were the highest, and there was adequate quality of water.

B. BIOLOGICAL FILTRATION EQUIPMENT

Ammonia-nitrogen, as an important component of fish excretion, is mainly produced by the decomposition of fish bait, fish metabolites and organic matter. Ten percent of the protein in fish feed will be converted into ammonia in the system water [99]. The accumulation of ammonia can reach a level that is toxic to fish (0.05 mg L^{-1} [92]). The circulating water system mainly removes ammonia-nitrogen through the nitrification process, i.e., biological filtration [11]. The nitrification process can convert between 93% and 96% of the ammonia-nitrogen into nitrate through infiltration units [92]. The total surface area available for the growth of nitrifying bacteria largely determines the ammonia removal capacity of biofilters [105]. Fixed-membrane biofilters provide nitrifying bacteria with adherent substrates to form biofilms, providing them with a large surface area, appropriate temperature, acidity and alkalinity, and dissolved oxygen levels [104]. It is not only a common way to realize autotrophic nitrification but also the core water treatment unit of RAS [5]. Therefore, biofilm filtration is usually used to reduce the contents of ammonia-nitrogen and nitrite in water [106]. Different filter media and the environment have a great influence on the function of the biofilter [107]. The optimum filtration environment of the biofilter is as follows: the suitable temperature is between 77 and 86°F, the pH is between 7.0 and 9.0, and it should also have a biochemical oxygen demand (BOD) less than 20 mg/L, a saturated dissolved oxygen (DO) and a total alkalinity of 100 mg/L or more [11]. The size of the biofilters in aquaponic systems should be close to the recommended size of recirculating systems [86]. The commonly used biofilter equipment in aquaponic systems includes trickling biofilters [108], [109], moving bed biofilters [96], [97], [110], and fluidized bed filters [11], [109].

Trickling biofilters are the earliest biofilter method that were systematically studied and applied. This method has the advantages of a constant high oxygen content, effective removal of CO2, low operation cost, and simple operation and management. The main drawbacks include relatively low volumetric removal rates, easy blockages, short circuits and uneven distribution of nitrifying bacteria [105], [111]. Its main purpose is to provide nitrification and BOD removal [112]. The maximum ammonia removal rate is 0.43 g m-2 day-1, and it will increase linearly with the increase in the ammonia concentration [113]. The frequent contact between the carrier and water body in a moving bed biofilter, which is called a ''mobile biofilm'', can give full play to the advantages of the attached and suspended phase organisms [105]. Fluidized bed filters are essentially sand filters operating continuously in the expansion (backwashing) mode. Through continuous flow, carbon dioxide can be removed and DO can be provided with saturation greater than 90%, but a higher flow rate is needed to ensure the expansion of the filter bed and its full contact with the filter material [105].

Biofiltration is an indispensable stage in the water treatment of recirculating aquaculture, and the equipment and technology used in this stage have also been improved and have achieved good results in practical applications. The experimental station in Ginosar (Israel) can achieve a high nitrate removal rate in a relatively short residence time by equipping an aerobic trickling filter and two anaerobic fluidized bed columns on the aquaculture device [113]. Tyson *et al.* [99] used a perlite trickling biofilter in the aquaponics system. When the pH was 8.0, the maximum nitrogen removal was 80 g·m−3·d−1. When growing tilapia, Karimanzira *et al.* [101] modelled a biofilter as a trickling type and a moving bed type. Graber and Junge [112] constructed a special trickling filter using LECA as the filling medium and realized the full treatment of RAS wastewater. In addition to toxin transformation, some biofilters can be used as solid filters or degassing chambers to improve operation efficiency [114].

C. OXYGEN ENRICHMENT EQUIPMENT

In the aquaculture system, a large amount of oxygen is consumed in the process of fish culture with circulating water. The oxygen consumption rate of different species of fish ranges from 200-500 (mg O_2/kg/h) [81]. Generally, fish need approximately 4 to 5 mg/L of dissolved oxygen [115]. Adequate DO is a necessary condition for the survival and growth of fish and microorganisms in aquaculture. The oxygen level also plays an important role in plant growth; it is necessary to provide enough oxygen to the root to prevent oxygen depletion [116]. Therefore, oxygen enrichment equipment is needed to improve the DO content in water.

Traditional methods of increasing oxygen can add air to water through aerators [117], air pumps [88], air blowers [89]–[93], [97] and compressors. By agitating the water, the aeration process can increase the amount of contact between the air and a larger surface area of water, and the gas exchange is enhanced by using blowers as auxiliary equipment [114]. However, with increasing culture density, the demand by fish for oxygen and the decomposition of organic matter in water consume a large amount of oxygen. This consumption makes it difficult for traditional aeration methods to meet the DO requirements in water, and there is only approximately 21% oxygen in the air [83]. Therefore, the use of pure oxygen can be delivered in a powerful way (for example, an oxygen cone) to achieve rapid oxygen enrichment and increase the DO content in the water; this method has become the main trend of current development. Oxygen saturation cones can fully oxidize the water by feeding pure oxygen into the device [118]; now, they are also used in aquaponic systems [83], [98]. In addition, improving the DO content in water has been studied at home and abroad. Pade [119] used an airlift to carry low oxygen into the water to increase the oxygen content when pumping, and this method was more beneficial to the overall health of the system. Fang *et al.* [120] used an air compressor to supply oxygen to a fish pond, and through experiments, semi-aeration was proven to achieve higher benefits. Khater and Ali [121] used oxygen generator as pure oxygen source to add pure oxygen gas to water, which ensured the appropriate dissolved oxygen content for fish and plant growth in the system.

Oxygen enrichment technology is the most critical factor for the growth of fish and vegetables, creating a high DO water environment for water circulation systems. It is the premise and important environmental factor for promoting the good growth of fish and vegetables.

D. OTHER EQUIPMENT

In the aquaponics system, in addition to the equipment used in the water treatment process mentioned above, there are two other pieces of necessary equipment. One is the use of sewage disinfection to reduce the microbial load, i.e., the ultraviolet disinfector, and the other is the baiting machine used for feeding.

Ozone and ultraviolet are mainly used for sterilization and disinfection in the RAS. However, because ozone treatment easily produces residuals and its optimal sterilization concentration is not easy to control, ultraviolet devices are widely used in actual aquaculture production. UV irradiation prevents ozone-associated fish mortality [122]. An ultraviolet disinfector, which is usually placed between biological filters and hydroponics, achieves biological filtration followed by sterilization to improve the effectiveness of ultraviolet technology [123]. Short-wave ultraviolet (UVC) with a wavelength of 250-260 nm (the optimum is 254 nm) is used as the most effective bactericidal band to treat aquaculture water [82]. Its main function is disinfection and purification, which can reduce the load of bacteria and pathogens in the water. This method improves fish health and reduces water exchange without adding chemicals [124]. It is currently a highly efficient and environmentally friendly sterilization and disinfection technology. The clarification of aquaculture water or the reduction of flow rate can improve the UV penetration rate or increase the radiation intensity, which can control the microbial population to a greater extent [123]. Pantanella *et al.* [125] carried out an experimental comparison between sterilization and non-sterilization in aquaponic systems to evaluate microorganisms, which proved that the use of an ultraviolet sterilizer could effectively reduce Escherichia coli, and the number of bacteria in the system was reduced by nearly 3 log. Yang *et al.* [126] proposed a modular water cleaning device that could effectively decompose and eliminate organic pollutants using UV-LED.

The feed rate ratios can provide a balanced ecosystem for fish, plants and bacteria under sufficient conditions of biofiltration [127]. Feed is the main factor determining aquaculture efficiency and cost, and there is a significant linear relationship between the feeding rate and growth rate in the range of the optimal feeding rate [128]. Therefore, the real-time adjustment of fish feed by intelligent feeding controls to meet the feeding requirements of fish is of great significance to reduce costs and maximize efficiency [129]. With the introduction of machine vision and intelligent control algorithms, the feeding of bait is no longer limited to manual operation. Feed control through feed detection and behavior analysis [129] not only changes the shortcomings of manual bait throwing, which is time-consuming and laborious but also ensures the amount of used bait is precise and ensures that fish can grow healthily and obtain maximum benefits. Lee *et al.* [130] could detect the number of fish and plan the feeding time by designing a visual system based on LabView. Chang *et al.* [131] designed a rotating plate feeding machine with timing control and combined it with an intelligent feedback control system to realize automatic stop feeding according to eel behavior. Soto-Zarazúa *et al.* [132] proposed a new baiting machine based on fuzzy-logic control algorithms by considering the factors of temperature and DO to provide accurate food quantity.

A circulating water treatment system realizes the purification and recycling of aquaculture wastewater through physical filtration, biological filtration, oxygen enrichment, sterilization and other equipment. Cooperative control among various links is helpful to realize the efficient recycling of water resources. The current RAS is developing toward more integrated equipment and more intelligent control. Currently, the automation of biofiltration, the full automation and semi-intelligence of the baiting machine, and the equipment for increasing oxygen no longer rely on manual operation. The development of this equipment controls the water quality and develops an optimal balanced state of control, which lays a foundation for the realization of intelligent monitoring and control. An RAS realizes the automation and intelligent control of each link by using electronic and information technology combined with the current aquaculture environment and the growth status of the fish. Finally, under the premise of healthy fish growth, the automatic circulation of aquaculture water can be achieved, and more economic benefits can be obtained. This method promotes the whole aquaponics system to realize intelligent monitoring and control.

IV. INTELLIGENT MONITORING AND CONTROL IN AQUAPONICS

The core of aquaponics system is to realize the recycling of resources. In the aquaponics system, the circulation of water resources and nitrogen elements are two major cycles that solve the serious problem of wastewater pollution, and play a dual role in providing vegetable nutrition for its needs and improving the efficiency of water resources utilization. The cycle of water resources and nutrients in the aquaponics system is shown in Fig. 3

The monitoring and control of environment and equipment through intelligent technology is the premise and foundation to ensure the stable operation of aquaponics system. A summary of the various degrees of control over the system is shown in Table 2, illustrating the development of an aquaponics system from early manual monitoring to the construction of the intelligent system to realize automatic control. It not only improves the efficiency of planting and breeding but also realizes the precise control of nutrients and healthy growth of fish and vegetables. At the same time, it improves the utilization efficiency of water resources and ensures the

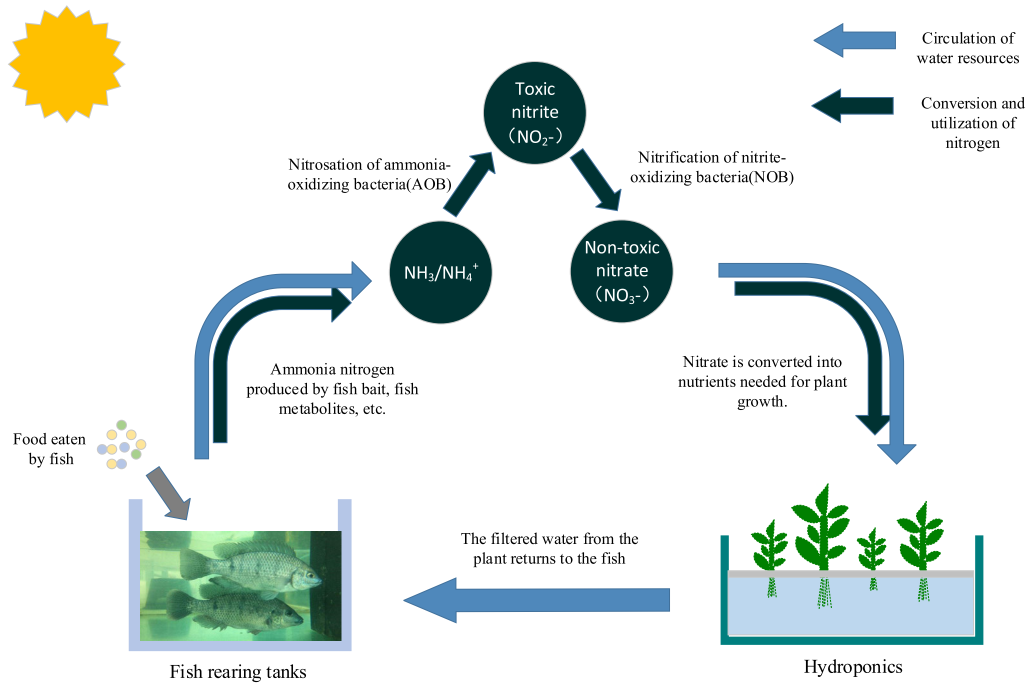

FIGURE 3. System diagram of aquaponics.

sound cycle of water resources. The intelligent methods or existing technologies for monitoring and controlling the greenhouse environment, monitoring and controlling water quality parameters and nutrient cycling control in aquaponics system are discussed.

A. MONITORING AND CONTROL OF ENVIRONMENT

Monitoring and controlling the greenhouse environment is the precondition and basis of ensuring the stable operation of aquaponic ecosystems. The continuous combination of greenhouse and aquaponic systems makes it very important to monitor and control the external growth environment of fish and vegetables. The intelligent greenhouse control system is a multivariable, large inertia, nonlinear and strong coupled time-varying system. To obtain and maintain balanced and safe optimal crops in the system and to ensure the stable and healthy growth of fish and vegetables, it is necessary to monitor and control some environmental parameters in the greenhouse, such as temperature, humidity, carbon dioxide, and light, in real time [13], [143], [144].

In a survey of commercial aquaponics conducted by Love D C and others in 2015, 46% of respondents used multiple settings for production because of the different environmental tolerances of fish and plants, with greenhouses being the most chosen facility [145]. Water from an RAS can be used in greenhouse hydroponics to enhance production through the more efficient use of resources, potentially reducing water by 20-27% compared with that in traditional agriculture [18]. To improve the financial prospects of aquaponic systems, in terms of alternative energy sources, a controlled greenhouse environment will make the system more economically viable [146]. The further development of aquaponic systems will provide the accurate control and monitoring of fish, plants and the environment, which can also be achieved through greenhouses [18]. There have long been examples of the combination of aquaponics and greenhouses, and this approach has been developing continuously [18], [125], [147]–[149]. Currently, most aquaculture research institutes in the United States and Europe adopt an aquaponics closed-loop circulatory system built in greenhouses. Commercial aquaponics also uses greenhouse and controlled environmental agriculture techniques to increase crop yields [150]. The temperature in the greenhouse is easy to control, so farmers can produce throughout the year by prolonging the growing season. Currently, most aquaponic systems use greenhouses with controllable environments [37], [109], [151]. By monitoring the parameters, the exhaust fan, evaporative cooler, warm lamp, greenhouse lighting and other equipment in the system can be intelligently controlled [143].

Currently, increasing monitoring and control methods for greenhouse environments have been proposed. As a future development direction, the symbiosis of aquaponics in greenhouses is very important to realize the automatic and intelligent control of the environment. Nagayo and Jamisola [143] realized the design of wireless monitoring systems for aquaponic greenhouses based on cloud technology, monitored and controlled the environmental conditions of Nile tilapia, spinach and greenhouses automatically, and realized an intelligent and energy-saving aquaponic greenhouse system. Saaid *et al.* [142] established an indoor aquaponics system and effectively established a closed-loop

TABLE 2. Summary form for different control degrees of the aquaponic systems.

Degree of system control	Technique or method	Component	Ways of data acquisition	Time of data measurement	Data acquisition	Control unit	Effect	Advantages and disadvantages	References
Manual control for aquaponics	Manual Control Based on Experience	A fish rearing tank; A solids removal unit; Two hydroponic tanks; A reservoir (sump).	—	Monitoring several times daily.	Dissolved oxygen; Sludge; pH	Vertical-lift pump; Drain valve; Add small amounts of base to regulate	The system is well suited for Caribbean islands and other tropical regions where fresh water is scarce or level farm land is limited.	Low efficiency; Inevitable mistakes; More maintenance costs;	[133]
		Fish rearing; Solids removal; Hydroponic components;			Temperature; Dissolved oxygen; pH	Chillers and evaporative cooling towers; A 1/20-hp vertical lift pump; Demand feeders	Meet the need for more food fish and plant crop production in small Caribbean islands.		[134]
Auto-Control for aquaponics	Control by using timers	Fish holding tank; Associated biofilter; Hydroponic growth bed	Meter and Sonde probe; Multiparameter ion specific meter; Various reagents.	—	Constant flow	A submersible water pump; The airlift; The valve in the hydroponic bed drain line; The lighting unit	Managing the flow rate increases both biomass and yield.	Increased efficiency; Automation control is realized; Higher management accuracy.	[135]
		The recirculating aquaculture system (RAS).	The YSI multi-probe meter (model YSI 550A) and pH Cyber Scan waterproof.	Once a week	Temperature; Dissolved oxygen (DO) and pH.	Adjust the gate valves; Air stones, connected to an air blower.	Effectively guarantee of the flow rate of water; The stable operation of the system is guaranteed.		[136]
Smart Monitoring and Control System for Aquaponics	OpenWrt and WRTnode	Data acquisition; Mobile transfer; Intelligently interactive application	DHT11 digital temperature; Humidity sensor	Collect real-time environmental information	Temperature; Light; Water levels; Oxygen in water; E.coli levers; Humidity	Water pump; Air pump; Lamp; Feeding device	Monitor and control the smart aquaponics remotely; Man-machine interaction comes to fruition.	Store data in cloud storage; Data analysis with the help of intelligent technology; Automatic early warning; Continuous autonomous monitoring.	[137]
	Websocket	pH, water temperature monitoring system and controlling system	DS18B20 sensor; DFROBOT analog pH meter; Arduino water level sensor	Measure in the morning and the afternoon.	Water temperature; Water pH level; Water level	The lights; Water pumps; Lamp; Fan	The system designed very simple to monitor and control; Can be developed to monitor more parameter and control more devices.		[138]
	Internet of things	Automatic water supply; Automatic fish food feeder	Temperature sensor; Ultrasonic sensor; Moisture sensor;	The water level is stored at fixed intervals of time in the morning.	Temperature; The water level; Moisture content	Oxygen Pump; Fish feeder; Water pump; LED light	The climate has the least or no interference in the aquaponic system; Cost-effective; Less water consumption.		[139]
		Source node; Sink; Database server; Visualization on Mobile Application	Ultrasonic sensors; Temperature sensor; pH sensor; Ammonia gas sensor	—	Water pH; Water; temperature; Ammonia gas level; Water depth	Coolant; Heater; H_3PO_4 control motor; KOH control motor; Fish feed actuator; Ammonia warning procedure	Controlled NFT Aquaponic produces better vegetables compared with NFT Hydroponic in terms of a height of plants, a number of the leaf and the weight of a plant.		[140]
	Fuzzy logic	Arduino Uno; Fuzzy inference system; Relay Control	Water/air temperature sensor; pH sensor; luminance sensor	Measure data every 25 seconds;	Water; pH; Luminance; Temperature; Air temperature	Light; Heater; Alarm	Accurate, low maintenance, low cost and convenient.		[141]
	Arduino (Mega)	Controller; Actuators; Sensor	Temperature Sensor (DS18B20 and LM35); Float sensor	—	Water level; Temperature; Amount of food	Pump; Feeder; Dimmer	Effectively create a closed-loop control system; No fish dies and plants grow successfully.		[142]

control system through the integration of a controller, actuators and sensors. Savidov *et al.* [93] collected environmental parameters in a greenhouse using a specific probe and realized the real-time monitoring of some parameters by computer and the complete control of the greenhouse and circulation system. Licamele [18] has designed and engineered a state-of-the-art controlled environment aquaponics research greenhouse for intensive fish and vegetable production. Nagayo *et al.* [152] realized the monitoring and control of greenhouse environmental condition and key water quality parameters in aquaponics by using NI LabView software, microcontroller interfaced with sensors and GSM shield.

Currently, an intelligent aquaponics system with automatic monitoring and control can be built using the Internet of Things, wireless sensors and other technologies. However, due to the large fluctuation in control parameters in the greenhouse environment, it is necessary to combine the corresponding intelligent algorithm to solve the control of related parameters in a complex greenhouse environment. Traditional greenhouse climate control methods can be divided into three types: proportional-integral-derivative (PID) control methods [153], [154], fuzzy control methods [155], [156] and neural network control methods [157]–[159]. As research becomes more in-depth, an increasing number of new intelligent algorithms have been proposed and applied.

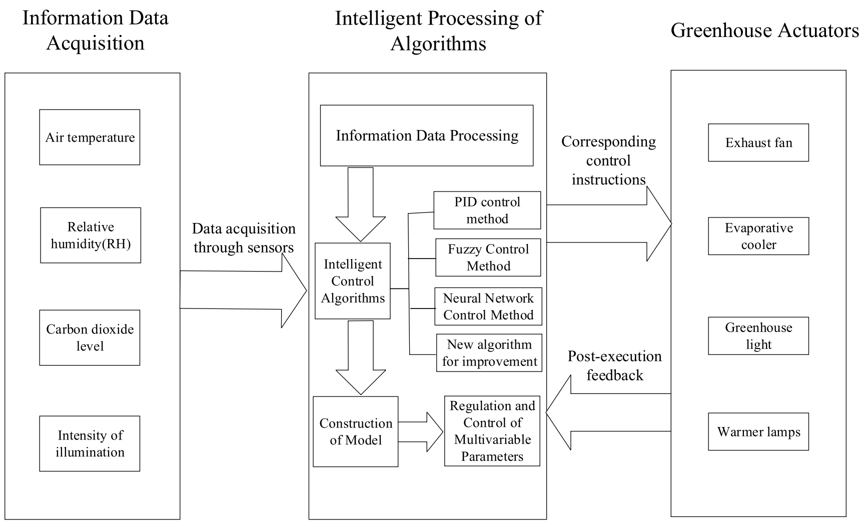

FIGURE 4. Schematic diagram of detection and control system for greenhouse environment.

Koutb *et al.* [160] used a genetic algorithm (GA) to optimize the parameters of the traditional PDF and the FPDF controllers. Compared with the traditional PDF controller, better results could be achieved in temperature and humidity control in the greenhouse. Chen *et al.* [161] proposed a model-free method based on Q-learning to achieve the coordinated control of greenhouse environmental factors and combined it with a CBR (an artificial intelligence AI method dealing with empirical knowledge) to achieve the optimal control of the greenhouse climate under the constraints of control costs. Ferreira and Ruano [162] proposed the Branch-and-Bound search algorithm in a discrete model of the predictive control of greenhouses, which greatly reduced energy consumption but did not significantly affect control accuracy. Zeng *et al.* [163] proposed a hybrid control strategy of the greenhouse climate based on the radial basis function (RBF) network and conventional PID controllers. Compared with the method of searching optimal gain parameters by GA, the adaptive control strategy has better adaptability, robustness and good control performance for a complex nonlinear greenhouse climate. Manonmani *et al.* [164] proposed a neural network model based on the time series of a nonlinear autoregressive with external input (NARX) model. Based on this model, a control scheme of the nonlinear autoregressive moving average controller (NARMA-L2) was proposed. The control effect of temperature and humidity shows that the controller is more stable and has good anti-interference ability and set point tracking. Gao *et al.* [165] combined the Kalman filter algorithm with the traditional PID control algorithm to control greenhouse temperature, which makes the control effect greatly improved, the response time shorter, the system stability higher and the convergence better. The monitoring and control framework of the greenhouse environment is shown in Fig. 4.

Intelligent greenhouse aquaponic systems greatly promote the development of aquaponic systems. Modern greenhouses can automatically monitor and control the environmental factors affecting the growth of fish and plants, thus resisting the harsh climate and environmental conditions that aquaponic systems have faced in the past. This approach improves the growth environment of crops, reduces costs and realizes high-efficiency production. However, an intelligent aquaponic greenhouse system has shortcomings, such as high costs, and the temperature difference between summer and winter is considerable. How to find high-quality materials to achieve better thermal insulation effects is the current problem that requires research to solve. Intelligent algorithms are widely used to realize the optimal control of traditional greenhouse environments. Therefore, it is the main direction for the future development of aquaponics to apply mature intelligent algorithms in greenhouse environments to greenhouse aquaponic systems. Intelligent monitoring and control can be realized by building models to ensure the healthy growth of fish and vegetables and to make the system run more efficiently.

B. MONITORING AND CONTROL OF WATER QUALITY

In the aquaponic system, the quality of water has an important impact on the growth of vegetables and fish. As a medium for connecting fish and vegetables, it not only provides the growth environment for fish but also transports basic nutrients to plants. The fish feeding density, growth rate, food intake rate and quantity and related environmental fluctuations may cause rapid changes in water quality [166]. Therefore, it is necessary to monitor and adjust the key parameters affecting water quality, and through monitoring and controlling the water quality, a healthy environment is provided for fish and vegetable growth [13], [127].

The water quality of aquaponic systems is determined by seven main parameters: temperature, pH, salinity, phosphate, nitrate, ammonia and DO [167]. According to the requirements of the fish and vegetable growing environment, each parameter has specific limitations. Therefore, it is

TABLE 3. Requirements of some parameters in systems.

The type of system	pH	Temperature（°C）	DO (mg/L)	Nitrite (mg/L)	Nitrate (mg/L)	TAN (mg/L)	Ammonia (mg/L)	EC (mS/cm)	References
Hydroponic systems	5.5-6.5	Warm-season plants：15.56 -26.7 Cool-season plants：10-21 For the whole：20-25	>3	—	—	—	—	1-3	[66] [86] [92] [109] [115] [168]
Average Element Content of Nutrient Solution in Hydroponics System:(ppm) Main nutrient elements: Nitrogen 150, P phosphorus 55, K potassium 175, Ca calcium 105, Mg magnesium 90, and S sulfur 125 Micronutrient element: Fe 1.0, Mn 0.36, B 0.008, Zn 0.046, Cu 0.026, Mo 0.001 TDS: between 1,000 and 1,500 Na:< 5 mmol/L(1.15 gr/L)									[86] [98] [169]
Aquaculture systems	6.5-8.5	Warm water fish：25–30 Cold water fish：15-20	5 to saturation	<0.1	20-100	—	<0.98	—	[109] [115] [170] [171] [172]
Nitrate-N: The nitrate level can reach 20 ppm to 100 ppm depending on what source the information is drawn from. An upper limit of dissolved carbon dioxide: 15-20 mg/L. The pH for tilapia is 5.0-10.0 and the temperature for tilapia is 25.5-26.6.									[28] [83] [92]
Aquaponic	6-7 Optimum: 6.8-7.0	18-30	>5	<1	5-150	<1	<1	0.3-1.1	[168] [170] [173] [174]
pH: maintaining acidity and basicity by adding calcium hydroxide and potassium hydroxide. Optimum pH range for nitrifying bacteria: between 7.0 and 8.0, and below a pH of 6.8, nitrifying bacteria are inhibited. Nitrite-N: between 0.02 and 0.8 mg/L Phosphate: below 50 micrograms per liter (μg/L) CO2: 340 to 1300 ppm Stocking density: two gallons per pound of fish TDS: 200 to 400 ppm									[86] [118] [152] [175] [176]

necessary to obtain an ecological dynamic balance through active dynamic monitoring. The key parameters affecting water quality in hydroponic systems, aquaculture systems and aquaponic systems are described in Table 3.

With the continuous development of information technology, there are increasing instances of real-time monitoring and control of water quality in aquaponic systems through the Internet of Things technology. De Silva and De Silva [177], based on industry 4.0, used a fuzzy adaptive controller to control water quality. They could automatically correct the deviation in the aquatic animal model according to the received data and realized intelligent data acquisition and automatic control. Vernandhes *et al.* [178] realized the remote monitoring of air temperature, humidity and soil humidity in the aquaponics system with smart phones and the control of corresponding actuators by introducing the Internet of Things technology. Manju *et al.* [179] used wireless sensor devices to identify and monitor various water quality parameters in the aquaponics system and used the Internet of Things to achieve remote access. Valiente *et al.* [180] established an automated aquaponics system (using Nile Tilapia and Romaine Lettuce) through the Internet of Things technology to monitor and control the acidity, basicity, temperature, illumination, water refilling and baiting in the system, which saved time and increased the growth speed of fishes and plants.

The healthy growth of vegetables and fish requires appropriate water quality conditions. To ensure the stability of water quality in the aquaponics system, it is necessary to carry out the intelligent control of water quality to avoid the impact of water quality fluctuations on fish and plants.

With the increasing complexity of the system, a monitoring and control system built only with intelligent devices may ignore the importance of specific details in a large number of data. Therefore, the intelligent monitoring and control of water quality in aquaponic systems by introducing intelligent algorithms and building models has become one of

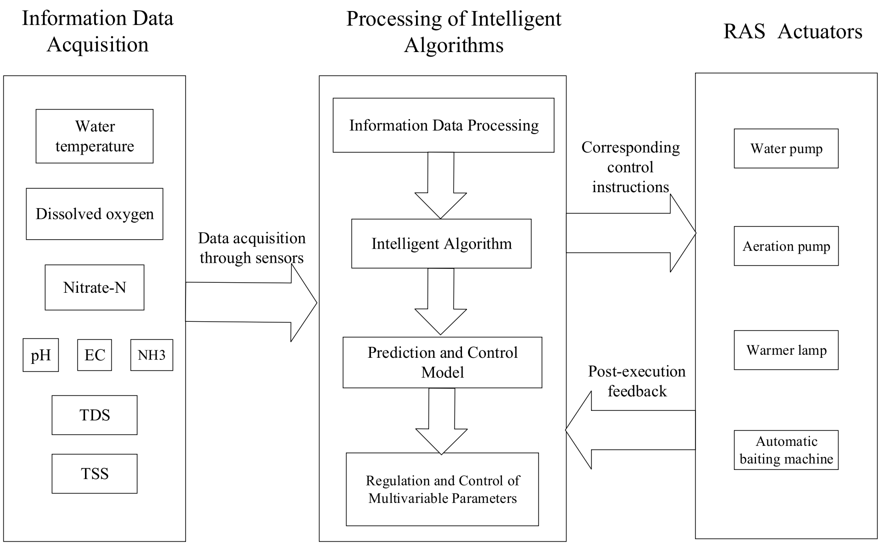

FIGURE 5. Schematic diagram of detection and control system of the water quality environment.

the hotspots of current development. Related research has been carried out at home and abroad. da Silva *et al.* [181] designed a new toxicity early warning sensor for water quality monitoring in RAS, established a toxicity prediction model, and realized the near real-time monitoring of water quality. Ren *et al.* [182] proposed a DO prediction model based on a fuzzy neural network and optimized it with a GA, which overcame the shortcomings of poor stability and low accuracy of the traditional algorithm and realized the intelligent and accurate prediction of the DO concentration and change trend. Karimanzira *et al.* [183] applied the optimal control method of a fish growth model based on metabolite constraints to the aquaponics system and maximized the benefits by optimizing and effectively utilizing aquaculture resources. McLaughlan and Brandli [184] used artificial intelligence technology to data mine the sensor data from aquaponic systems. By using nearest neighbor models and artificial neural networks, the potential ability of predicting events and determining appropriate behaviour in aquaponic systems could be revealed. The monitoring and control framework of the water quality environment is shown in Fig. 5.

The methods of monitoring and controlling water quality in aquaponic systems are developing toward intelligence and automation. From manual measurements to the introduction of intelligent devices, intelligent algorithms have been used in the establishment of water quality models. We can predict the changes in water quality parameters and then achieve control to ensure the stability of the water quality environment for fish and vegetable growth. This approach makes the management of water quality in the aquaponics system more efficient, precise and intelligent and also saves the costs of resources and maximizes the benefits.

Although the current research on water quality is more extensive and the application of algorithms in water quality prediction is more mature, the successful application of prediction algorithm to water quality control has not been studied in depth. The stability of water quality parameters will be affected by various aspects of the outside world. Therefore, how to consider various factors and find an optimal balance point is still a key direction of future research.

C. MONITORING AND CONTROL OF NUTRIENT SOLUTION

In aquaponic systems, the wastewater from recirculating aquaculture is a source of nutrients for hydroponic vegetables [147], [185]. Aquaculture wastewater can provide basic nutrients, such as N, P, K, Ca, Mg, S, and Na, for vegetables [108], [186]. Endut *et al.* [136] showed that the removal rate of water quality parameters and plant yield could reach the maximum when it reached a plant-to-fish ratio of 8, which was equivalent to the fish feeding rate of 15-42 g/m2 of the plant growth area.

However, there are some problems, such as different concentration changes caused by the uneven proportion of soluble nutrients supplied by aquaculture wastewater and different growth cycles of fish in the actual breeding process. When wastewater cannot meet the standard requirements of vegetable nutrition, it is necessary to monitor and control the nutrient solution and adjust the proportion of nutrient elements in real time to meet the optimal growth of crops. Nutrient circulation control is an important support measure required to ensure the healthy growth of vegetables in aquaponic systems. Monitoring and controlling the nutrient solution means that in addition to accurately controlling the basic nutrient components of the nutrient solution (six essential nutrients: N, P, S, K, Ca and Mg), the pH (5.5-6.5), EC, DO and temperature should also be controlled to improve the yield and quality of crops to a certain extent [187]. The monitoring of nutrient components mainly includes two parts: the monitoring of crop growth and the monitoring of nutrient solution content.

Whether crops lack nutrients and what nutrients are missing are the prerequisites for the rational supply of a nutrient solution; thus, we can detect crop growth by introducing ontology sensors. The nutrients needed by plants can be reflected by different aspects; for example, the chlorophyll concentration in leaves is closely related to the nitrogen availability [188]. Plants absorb more purple light when they lack nitrogen and more green light when they lack phosphorus. Therefore, through the detection of plant physiological states, we can judge the current lack of nutrients in crops. New nondestructive sensor technology can help us detect nutritional needs [189] and then adjust the elements in the nutrient solution needed by plants. Lee and Searcy [190] established an in-field hyperspectral sensor system that could evaluate the nitrogen status of maize plants to achieve accurate fertilization.

In all modern soil-less systems, irrigation and fertilization are integrated into one system, and the nutrients necessary for crops (macro and micro nutrients) can be supplied through hydrosoluble fertilizer salts [19]. Compared with the soil system, the hydroponic crop production system can more strictly control the nutrient input [191]. In hydroponic systems, the plant roots reside in hydroponic solutions optimized for plant growth [18]. The nutrient solution needed in hydroponics is precisely formulated with some chemical fertilizers according to the nutrient requirement law of vegetables under natural growth conditions. The dissolved nutrients of fish are similar to those required for the hydroponic growth of plants [11].

The content of any nutrient element will affect the growth of plants [191]. Previous methods for monitoring ion concentrations in nutrient solutions include introducing sensors for measurement [191], [192], ISE-based technology [193]–[195], and building models to realize automatic monitoring and controlling systems [196]–[198]. As plants grow, nutrients are often depleted and become deficient, and minerals are usually added subsequently to meet the optimal growth requirements of plants and fish. For example, Zweig [148] maintained the nutritional balance for vegetable growth by adding 500 g dolomite (magnesium-rich) limestone to each pond. Additionally, 500 g powdered, garden-variety limestone was used to maintain high alkalinity, assuring good decomposition and nitrification in the pond water. Rakocy *et al.* [199] needed to supplement 2 mg/L iron nutrients every three weeks in the UVI system with raft hydroponics. In the batch production of basil, there was a lack of nutrition, and plants could not grow healthily. Although adding nutrients manually can ensure the normal operation of the system, the input of inorganic minerals will increase the cost, and the nature of the nutrient solution will change with the growth cycle of the crops. Therefore, it is necessary to adjust and control the elements in a nutrient solution intelligently and in real time to ensure that the quality of the nutrient solution remains at the optimal level [200], [201].

Precise control of the nutrient solution based on crop types and growth stages is an important means to ensure the healthy growth of vegetables. Morimoto and Hashimoto [202] realized the intelligent control of a nutrient solution concentration based on a GA and a neural network so that the system could quickly reach the set optimal value and ensure the optimal growth of plants. Massa *et al.* [203] constructed an empirical model of sodium absorption concentration in hydroponic rose production, which could not only predict sodium concentration in nutrient solution but also output electrical conductivity effectively and optimize the management of nutrient solution. JSM and Sridevi [201] proposed a new GA based on a Mamdani fuzzy inference system (FIS) to control nutrient solutions in hydroponics. Experiments showed that the algorithm was superior to the traditional error-based control algorithm in terms of convergence speed and resource utilization. Morimoto and Hashimoto [204] adopted a self-adaptive control method combining feedback control based on fuzzy logic and feed-forward control based on a neural network for the pH value of a nutrient solution in a deep hydroponic culture to realize the stable and automatic regulation of the nutrient solution's acidity and alkalinity. Zhu *et al.* [205] used the least squares method to estimate the parameters and controlled the nutrient solution accurately in the hydroponic system using the DFT. Compared with the traditional PID control method, the oscillation phenomenon was effectively avoided. Sun *et al.* [206] introduced the dynamic matrix control into the nutrient liquid circulation process and introduced the excitation signal into the non-self-balancing object to make it a first-order stable system. A predictive control method was used to control the ion concentration of the nutrient solution at a set value. Qin *et al.* [207] designed and constructed a nutrient liquid circulation control system in which the least squares fitting method was used to establish the measurement model of an ion-selective electrode, and the dynamic matrix control algorithm was used to control the concentration of ions to realize the online monitoring of nutrient liquid in soil-less cultivation of a greenhouse. The system diagram of nutrient solution monitoring and control is shown in Fig. 6.

As a key technology in hydroponics, the circulation control of the nutrient solution meets the nutrient requirement of vegetables in the growth process. With the development of modern information technology, the introduction of crop ontology sensing technology and intelligent algorithms, cyclic control is becoming more precise and intelligent. It not only makes the nutrient solution more accurate and convenient in early allocation but also realizes the dynamic balance of specific nutrient elements in different external environments and different growth cycles. It guarantees that vegetable will grow under the optimum conditions and reduces the management cost.

Currently, intelligent algorithms are used to monitor nutrient solutions. The main values that are monitored are the pH and EC. However, there are many components that have an impact on nutrient solution, so how to achieve the simultaneous monitoring of multiple parameters is a future research direction. At the same time, monitoring the physiological status of plants is an important index to determine whether the

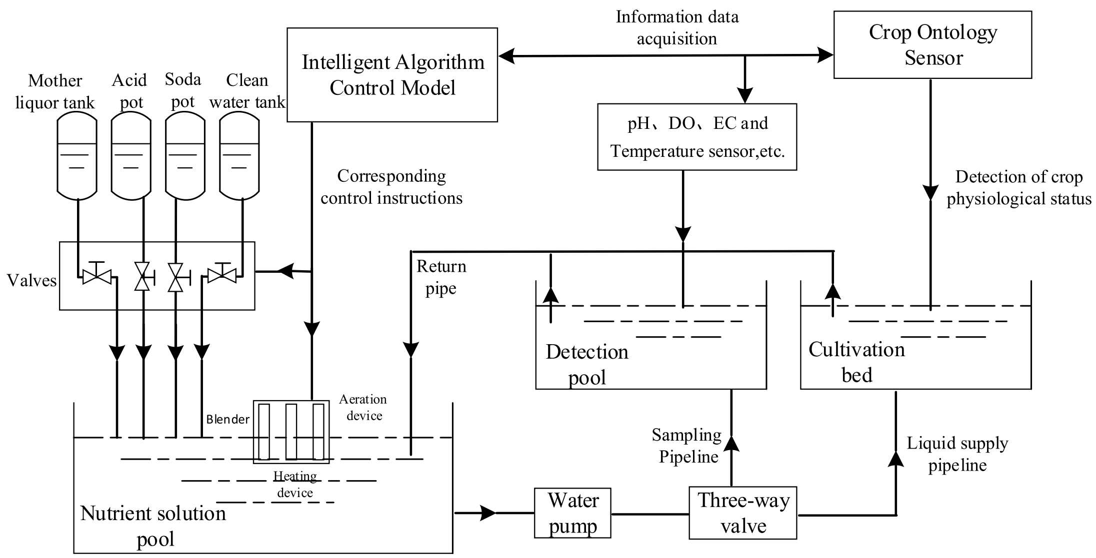

FIGURE 6. Schematic diagram of nutrient solution detection and control.

current crop lacks nutrient elements and what type of nutrient elements it lacks. However, when monitoring and controlling a nutrient solution, there are few studies on this topic, which is an important development direction in the future.

The aquaponic system can monitor the greenhouse environment, aquaculture water quality and nutrient solution dynamically in real time and intellectualize control to create a suitable growth environment for fish culture and vegetable cultivation.

A greenhouse environment can use intelligent sensor equipment and the Internet of Things technology to detect the external factors affecting planting and breeding, such as humidity, temperature, carbon dioxide and light. Intelligent fusion algorithms, such as neural networks, are used to accurately control the corresponding equipment, which ensures that the growth indicators of fish and vegetables are in the optimum ranges. In water quality management, an intelligent algorithm is used to construct a prediction and control model to monitor and control the main parameters affecting water quality, such as pH, temperature, nitrate, dissolved oxygen and ammonia, in real time. This approach avoids the impact of fluctuations in aquaponic systems and ensures the stability of the water quality environment. For the essential nutrient solution in aquaponic systems, monitoring can be realized from two aspects: one is to obtain the physiological state of crops by the use of an ontology sensor to know the missing nutrient elements; the other is to monitor the nutrient solution composition online by intelligent and new sensors. The precise control of the ion composition in a nutrient solution by a neural network and GA meets the need for the dynamic balance of nutrient elements in vegetables in different growth periods and ensures the healthy growth of crops.

With the rapid development of information technology, the Internet of Things, big data and other technologies have mature applications in the aquaponics system. The introduction of intelligent devices, such as wireless sensors, makes the monitoring and control of the system simpler and more accurate. The intelligent algorithm is a hotspot of current research in monitoring and control, and it is also the direction of continuous development in the future. It can accurately predict all parameters monitored in aquaponic systems and can then carry out the corresponding control. It saves time and energy relative to traditional manual operations, reduces the cost, improves the efficiency of system operation, and makes the aquaponics system more automated, efficient and intelligent.

V. CONCLUSION AND FUTURE PROSPECTS

On the premise of ensuring the healthy growth of vegetables and fish, it is the core of aquaponics technology to realize the efficient recycling of water resources. In this paper, the planting and breeding equipment involved in aquaponics and the monitoring and control of planting and breeding environment are systematically analyzed and summarized. Aquaponics equipment mainly includes vegetable cultivation and fish culture equipment. The vegetable cultivation equipment mainly introduces three vegetable planting methods in common facilities with hydroponics as the main method: the nutrient film technique (NFT), the deep flow technique (DFT) and the floating capillary hydroponics (FCH). This paper systematically analyzed the advantages and disadvantages of three hydroponic planting methods. Hydroponics has become the main planting mode in the aquaponics system because of its high degree of facility and easily realized automatic monitoring and control. The paper analyzed and summarized the water treatment equipment for physical filtration, biological filtration, sterilization and oxygen enrichment of aquaculture wastewater in the recirculating aquaculture system. The application of new water treatment equipment to a large extent improves the water treatment capacity, which is the main development direction of current and future recirculating aquaculture.

The key to the reliable operation of an aquaponics system is to realize real-time online monitoring of the greenhouse environment, aquaculture water quality and nutritional components of crops. Combined with an intelligent information processing model and intelligent control model, the key parameters of the aquaponics system, such as temperature and humidity, light, pH, nitrates, DO, EC and nutrient components, are intelligently regulated and controlled. In recent years, methods applied in greenhouses, recirculating aquaculture and other fields are constantly proposed, but the research on multifactor collaborative control of the environment, the intelligent optimal control of water quality and the precise control of nutrients in the complex environment of aquaponics has lagged behind. At the same time, the high cost, poor stability and reliability of animal and plant physiological and ecological sensors and water quality sensors limit the development of technology to a certain extent. Developing a new sensor suitable for the complex environment of aquaponics, improving the algorithm to adapt to the complex environment, and improving the control accuracy are all the main research directions in the future.

The development goal of aquaponics technology is to achieve high quality, high efficiency and resource recycling in planting and breeding. Effective planting and breeding equipment and monitoring and control technology are the premise and foundation to achieve these goals. Additional directions include the rapid development of aquaponics equipment technology and information technology, the research and development of efficient vegetable cultivation technology and recycling water treatment technology, the research on the high reliability of animal and plant physiological and ecological detection technology and environmental detection sensors, and the development of animal and plant growth models and environmentally optimal regulation models. On the basis of precise monitoring of animal and plant statuses and environmental information, the precise optimization and regulation of water resources, nutrient resources, and the planting and breeding environment in the aquaponics system will be realized, and the high quality and efficiency of production, resource saving, and water and nutrient recycling can be realized.

AUTHORS' CONTRIBUTIONS

All authors contributed extensively to the preparation of this manuscript. Y. Wei, D. An, and D. Li participated in designing the conceptual framework and supervised the writing. Y. Wei and W. Li compiled the information and participated in drafting the body of the text of this manuscript. Y. Jiao and Q. Wei contributed to the conceptual design. D. An and D. Li reviewed and proofread this manuscript.

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YAOGUANG WEI received the B.S. and M.S. degrees from Chongqing University, in 2001, and the Ph.D. degree from the University of Science and Technology Beijing, in 2005.

He is currently an Associate Professor with the College of Information and Electrical Engineering, China Agricultural University. His current research interests include underwater robot and intelligent agriculture.

WENSHU LI received the B.E. degree in computer science and technology from Huazhong Agricultural University, in 2018. She is currently pursuing the M.E. degree with the College of Information and Electrical Engineering, China Agricultural University, Beijing, China.

Her research interest includes the classification of patterns.

DONG AN received the Ph.D. degree from the Institute of Institute of Semiconductors, Chinese Academy of Sciences, in 2005.

She is currently a Professor with the College of Information and Electrical Engineering, China Agricultural University. Her current research interests include image processing, underwater robot, and intelligent agriculture.

DAOLIANG LI received the Ph.D. degree from the College of Information and Electrical Engineering, China Agricultural University, in 1999.

He is currently a Full Professor with the College of Information and Electrical Engineering and the Director of the Beijing Engineering Research Center for the Internet of Things in Agriculture, China Agricultural University. His principal research interests include ICTs in aquaculture and agriculture, including information processing, smart sensors, and smart control systems in fish farming.

YISHA JIAO received the B.E. degree in Internet of Things project from Shanxi Agricultural University, in 2018. She is currently pursuing the M.E. degree with the College of Information and Electrical Engineering, China Agricultural University, Beijing, China.

Her research interest includes motor fault diagnosis based on deep learning.

QIONG WEI received the B.E. degree in network engineering from Henan Normal University, in 2017. She is currently pursuing the M.E. degree with the College of Information and Electrical Engineering, China Agricultural University, Beijing, China.

Her research interest includes autonomous underwater vehicle control.