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Real-time aquatic monitoring system for tilapia farming

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Dedication

This thesis is dedicated to our families, whose love, patience, and support have been invaluable throughout our academic journey.

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ملخص

الطرق التقليدية لمراقبة جودة المياه ليست فعالة نسبيا وتستغرق وقتا طويلا, لذلك كان الافضل تصميم نظام حديث لمراقبة المياه .يعرض هذا المشروع نظام مراقبة لحظي لجودة المياه في احواض اسماك البلطي تقنية انترنت الاشياء,.يدمج النظام حساسات مع متحكم مما يخلق شبكة من انظمة المراقبة في الوقت الفعلي , توفر هذه الحساسات قياسا مستمرا لقيم الملوحة ,درجة الحموضة, درجة الحرارة, وغير ذلك من المعطيات ,يتم التحكم فيها بواسطة متحكم ESP32.

هذا النظام يمكن من تحسين وتطوير مجال الاستزراع المائي, ويضمن صحة الاسماك, يساهم في تقليل المراقبة الدورية المتعبة للفلاحين بتكلفة صغيرة وفعالية كبيرة.

الكلمات المفتاحية : الزراعة المائية ,تكنولوجيا تربية الاحياء المائية, زراعة البلطي, انترنت الاشياء, جودة المياه, البيانات في الوقت الفعلي, ESP32.

Résumé

Les méthodes de traditionnelles de surveillance de la qualité de l'eau sont relativement inefficaces et prennent beaucoup de temps. Il est donc préférable de concevoir un système moderne de surveillance de l'eau. Ce projet présente un système de surveillance en temps réel de la qualité d'eau dans les bassines d'élevage de tilapia, basé sur la technologie de l'internet des objets IoT. Le système intègre des capteurs avec ESP32, créant un réseau de surveillance en temps réel. Ces capteurs mesurèrent en continu des paramètres tels que la salinité, le Ph, la température, et d'autres données gérées par ESP32.

Ce système permet d'améliorer et de développer le secteur de L'aquaculture, Garantit la santé des poissons et réduit l'effort de surveillance manuelle régulière pour les agricultures. Le tout à faibles coûts et avec une grande efficacité.

Mots-clés : aquaculture, technologie aquaculture, élevage de tilapia, internet des objets, qualité de l'eau, données en temps réel, ESP32.

Abstract

The traditional methods for monitoring water quality are relatively inefficient and time-consuming. Therefore, it is better to design a modern system for water monitoring. This project presents a real-time water quality monitoring system for tilapia fish, utilizing Internet of Things (IoT) technology. The system integrates sensors with ESP32, creating a network of real-time monitoring systems. these sensors continuously measure parameters such as salinity, pH level, temperature, and other data, which are managed by ESP32.

This system enhances and advances the aquaculture sector, ensures fish health, and reduces the burden of regular manual monitoring for farmers, all at a low cost and high efficiency.

Keywords: aquaculture, aquaculture technology, tilapia farming, internet of things, water quality, real-time data, ESP32.

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List of Acronyms

ADC: Analog to digital converter

AI: Artificial intelligence

BNC: Bayonet Neill–Concelman connector

CAGR: compound annual growth rate

COAP: Constrained Application Protocol

DAC: digital to analog converter

DC: direct current

DO: dissolved oxygen

FAO: food and agriculture organization

FCR: feed conversion ratio

GPIO: general purpose input/output

HTTP: Hypertext Transfer Protocol

HVAC: heating, ventilation, and air conditioning

I2C: inter-integrated circuit

I2S: Inter-IC Sound

IC: Integrated Circuit

IOT: internet of things

MAC: Media Access Control

MQTT: Message Queuing Telemetry Transport

NTU: nephelometric turbidity unit

OLED: Organic Light-Emitting Diode

ORP: oxidation-reduction potential

OTG: on-the-go

OSI: Open System Interconnection

P2P: Peer-to-Peer

PGA: Programmable Gain Amplifier

PH: potential of oxygen

PPM: parts per million

PPT: parts per thousand

PSRAM: pseudo-static random-access memory

RAS: recirculating aquaculture system

SDA: Serial Data Line

SCL: Serial Clock Line

SPI: serial peripheral interface

SRAM: static random-access memory

TDS: total dissolved solids

TCP: Transmission Control Protocol

UART: universal asynchronous receiver/transmitter

UDP: User Datagram Protocol

USB: universal serial bus

General introduction

General introduction

The world has witnessed the rapid expansion of aquaculture in food production because seafood demand rises while hyped population levels demand sustainable protein sources alongside a dwindling wild fish population.as traditional fisheries face overfishing, climate change, and habitat degradation challenges, aquaculture presents a sustainable alternative to meet global protein needs while reducing pressure on marine ecosystems [1].

Nile tilapia (Oreochromis niloticus) stands as one of the most successful fish species for aquaculture because of its fast growth pattern [2], ability to thrive in many environments, and effective conversion of fish feed. Tilapia farming plays a critical role in food security and economic development, as well as rural livelihood development, specifically in developing countries. The success of tilapia aquaculture needs proper management of water quality parameters like temperature and dissolved oxygen (DO), pH, and ammonia, alongside turbidity, because these factors directly impact fish wellness, growth rates, and survival chances [3].

Conventional aquaculture monitoring methods rely on manual measurements, which are time-consuming, labor-intensive, and susceptible to human error. To overcome these challenges, the aquaculture industry increasingly adopts Internet of Things (IOT) technologies for real-time water quality monitoring and automated management [4].

This thesis explores the system of monitoring in tilapia aquaculture by leveraging devices such as the ESP32, and sensors. This thesis examines global aquaculture trends, the challenges of tilapia farming, and the impact of digital innovations in revolutionizing the industry.

This system will contribute to the advancement of precision aquaculture, offering a scalable and cost-effective solution for small and large-scale fish farmers. By integrating IoT, this system can help ensure optimal growing conditions, reduce waste, and promote sustainable aquaculture practices, ultimately supporting food security and economic growth in the aquaculture sector.

Chapter I: Generalities about aquaculture

I.1.Introduction

Aquaculture is one of the domains witnessing rapid development due to the growing demand for seafood. A fast-growing population and climate change have made dependence on fish farms vital to ensure a source of protein in addition to the sea fish stocks [5].

Aquaculture plays a critical role in the economies of many countries and creates many job opportunities. It has become a source of income for many developing countries. Also, it's an important solution to reduce the pressure on wild stocks, offering a stable and reliable source of protein to ensure food security[6].

Aquaculture can help us to enhance the quality of fish and meet demand by controlling the feeding and breeding conditions and the environmental conditions, and the number of fish in ponds to avoid diseases and death of the fish [5].

The aquaculture system has become a part of the global food system since 2000. in Africa and Asia, they used inland aquaculture, while in the Americas, Europe, and Oceania, they used marine aquaculture.

Fish farms offer numerous benefits, like the minimization of habitat destruction and water pollution, and increased catch. Aquaculture helps to preserve the marine ecosystem and can be designed to minimize environmental impacts [5].

I.2.Aquaculture system

I.2.1. Definition

Aquaculture is a word referring to fish farms or aquatic agriculture; it is the farming of aquatic organisms like fish, aquatic plants, or other aquatic species, with the control of conditions to increase the production and ensure sustainable yields [5].

I.2.2. Aquaculture production systems

I.2.2.1. ponds culture

Ponds are a closed or semi-closed environment; it is one of the most traditional methods in aquaculture. This method has been especially used in Asia and Africa for thousands of years. This method is used to produce carp, tilapia, catfish, goldfish, gourami, trout, palaemonids, and

salmonids. The most commonly cultured species include grouper, red sea bream, yellowtail, and various marine shrimp species [7].

In Asia, fish ponds are predominantly freshwater or brackish water, with marine ponds being relatively rare. In China, pond culture is traditionally centered on freshwater species. Carp and tilapia farms dominate aquaculture production in Africa [7].

Low-risk methods include filtering and treating the discharged water from ponds. The concept of high-risk methods is draining pond wastewater without filtering, which pollutes the surrounding environment [8].



Figure I.1 Pond culture **[9]**

I.2.2.2. Cage culture

It's a high-risk aquaculture method because it allows the exchange between the farms and the surrounding environment, which can pose a danger to fish, especially in the case of the exchange of waste, chemicals, and disease. Also, there is a possibility for fish to escape; this method is used with Salmon farms [8].



Figure I.2 cage culture **[10]**

I.2.2.3. Pen culture

It is an aquaculture system where fish or other aquatic organisms are raised in enclosed spaces, placed in natural water bodies like lakes, rivers, reservoirs, or coastal areas. This method is widely used in fish farms due to its cost-effectiveness and efficient use of water resources [11] .



Figure I.3 Pen culture **[12]**

I.2.2.4. Raceway culture

It is a flow-through aquaculture system where fish or aquatic organisms are raised in running water. Water is continuously supplied to long and narrow channels or tanks to rear aquatic organisms. This method has two forms: linear type and lateral type. Each one of these forms has its own specification and advantage [13].



Figure I.4 race-way culture **[14]**

I.2.2.5. Recirculating aquaculture system (RAS)

RAS is a fish farming system using recycled water. The water is filtered and reused, only a small part of the water is changed daily (less than 10%), which includes many mechanisms for removal of solids, biofiltration, degassing, aeration, and disinfection [15].

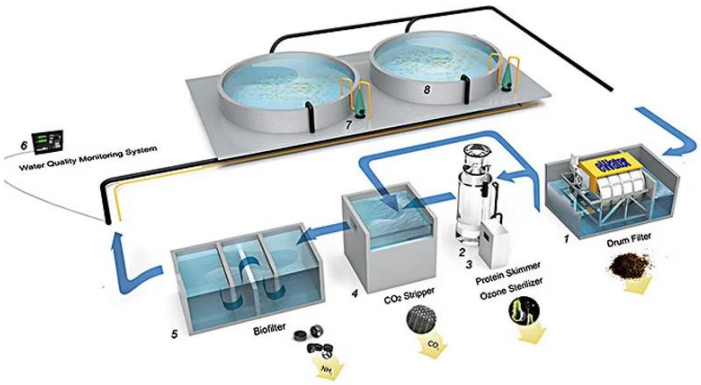


Figure I.5 Recirculating aquaculture system **[16]**

I.3.Aquaponics

Aquaponics is an agricultural system that integrates aquaculture and hydroponics systems, where fish waste is exploited to feed plants in an aquatic environment. This creates a circular system where the fish and plants benefit from each other, without the use of pesticides or chemical fertilizers [17].



Figure I.6 Aquaponic system **[18]**

I.4.Overview of aquaculture in the global food

The global consumption of food has risen at an average annual rate of 3.1% from 1961 to 2018, fish food consumption increased from 9.0 kg in 1961 to 20.5 kg in 2018 with an average of annual growth rate of 1.5%, world aquaculture production reached to 114.5 billion tonnes which represent a high record in aquaculture industry with a total sale of 263.6 billion dollar in 2018, this production contains 82.1 million tonnes of aquatic animals with sale value of 250.1 billion dollar, 32.4 million tonnes of aquatic algae with a sale value of 13.3 billion dollars and 26,000 tonnes of ornamental seashells and pearls with a sale value of 179,000 dollars [6].

In 2018, fish dominated aquaculture production, with 47 million tonnes from inland aquaculture and 7.3 million tonnes from marine and coastal aquaculture. From 2001 to 2018, the aquaculture production of farmed aquatic animals increased by an average of 5.3% per year but the growth rate was 4% in 2017 and 3.2% in 2018 [6].

Asia has dominated the world aquaculture production of aquatic animals, while Africa and the Americas have increased their shares in the global production of farmed aquatic animals. Production in Europe and Oceania has decreased [6].

Egypt, India, Indonesia, Vietnam, Bangladesh, Chile, and Norway are among the larger producers of farmed aquatic animals. Since 1991, China has produced more farmed aquatic food than the entire rest of the world combined [6].

Different cultural methods, practices, facilities, and integration with other agricultural activities are used in aquaculture production. Methods used in aquaculture production include ponds, raceway tanks, cages, and pens [6].

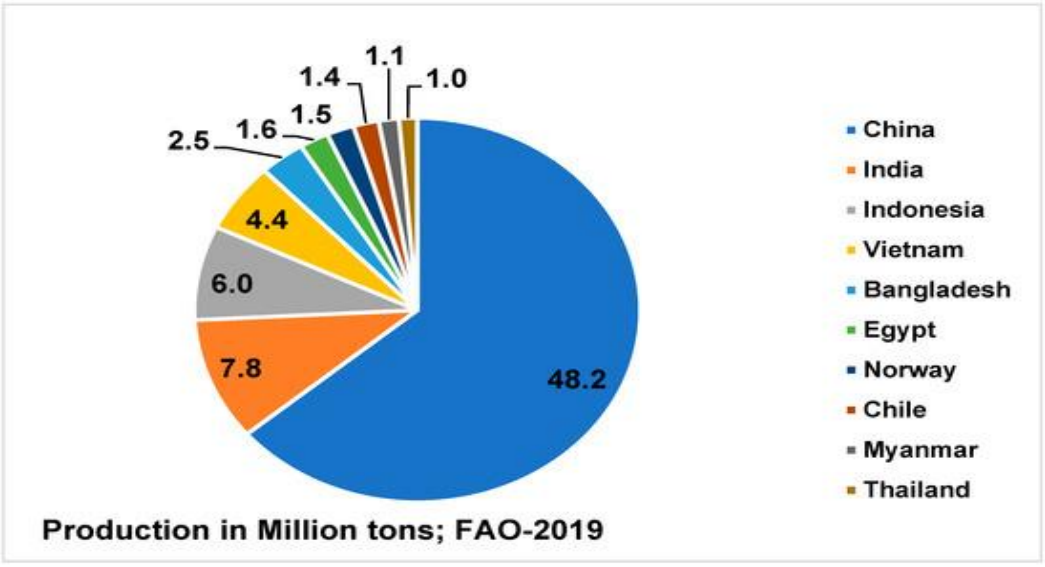


Figure I.7 global aquaculture production **[19]**

I.4.1. A historical review of Aquaculture in Algeria

I.4.1.1. Total fisheries production

Between 1950 and 2020, Algeria's total fisheries production experienced significant growth, increasing from around 27,000 tonnes in 1950 to over 100,000 tonnes by 1988. Despite fluctuations, Production continued to rise, reaching nearly 150,000 tonnes in 2007. However, it gradually declined to below 90,000 tonnes by 2020. These trends mainly reflect the performance of capture fisheries, while the contribution of aquaculture remained minimal and barely noticeable in the chart [20].

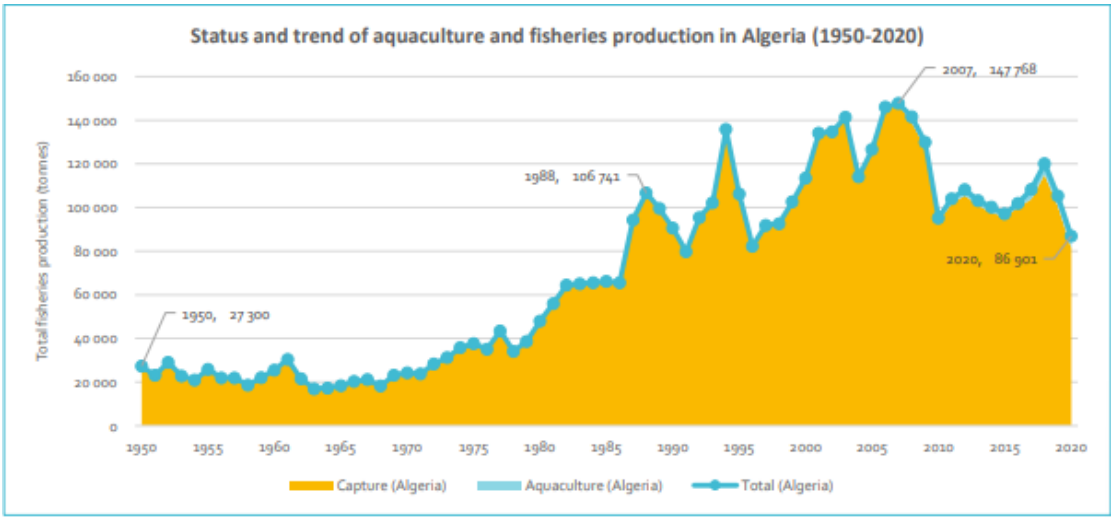


Figure I.8 Aquaculture and fisheries production in Algeria (1950-2020) **[21]**

I.4.1.2. Capture fisheries production

In Algeria, capture fisheries production dropped from 113,160 tonnes in 2000 to 81,465 tonnes in 2020. This represents an average annual decline of 1.63 percent, which is significantly higher than the global average decline of 0.18 percent over the same period. In contrast, capture fisheries production in both Africa as a whole and the Northern Africa region increased overall during this time [20].

Table I.1 Status and trend of capture fisheries production **[21]**

Country/area	Capture fisheries of all species (tonnes)		Annual growth (%)
	2000	2020	
world	94 780 558	91 420 562	-0.18
Africa	6 812 485	9 825 262	1.85
Sub-Saharan Africa	5 255 546	7 792 701	1.99
Northern Africa	1 609 949	2 070 221	1.27
Morocco	914 824	1 397 533	2.14
Spain	1 063 175	804 396	-1.38
France	694 453	465 872	-1.98
Egypt	384 315	418 683	0.43
Turkey	503 352	364 411	-1.60
Italy	304 157	141 771	-3.74
Tunisia	94 671	103 253	0.43
Algeria	113 160	81 465	-1.63
Greece	99 344	71 476	-1.63
Sudan	n.a.	37 660	n.a.
Libya	49 969	31 627	-2.26

I.4.1.3. Aquaculture production

Algeria's aquaculture production grew significantly from 351 tonnes in 2000 to 5,436 tonnes in 2020. The annual growth rate of 14.68 percent exceeded the subregional, regional, and global averages, making it the highest among Algeria's neighboring countries[20].

Table I.2 Status and trends of aquaculture production, 2000-2020 **[21]**

Country/area	Aquaculture production of all species (tonnes)		Annual growth (%)
	2000	2020	
world	43 016 624	122 580 187	5.38
Africa	451 264	2 354 294	8.61
Sub-Saharan Africa	107 338	731 848	10.07
Northern Africa	344926	1 632 296	8.08
Egypt	340 093	1 591 896	8.02
Turkey	79 031	421 411	8.73
Spain	311 429	276 571	-0.59

France	266 802	191 350	-1.65
Greece	95 418	131 737	1.63
Italy	216 525	122 778	-2.80
Tunisia	1 553	23 486	14.55
Algeria	351	5 436	14.68
Morocco	1 889	1 618	-0.77
Libya	40	10	-6.70

I.4.1.4. Aquaculture Production in Algeria

Aquafarming in Algeria has experienced significant growth, though it has also shown considerable fluctuations over the years. From around 450 tonnes two decades ago, production reached 4,779.29 tonnes in 2021, with a value of USD 20.733 thousand. However, compared to the top 10 African countries, Algeria's aquaculture production remains relatively low, accounting for just 0.21% of the continent's total production. Despite this, Algeria has seen a relatively high annual growth rate of 12.49%, exceeding sub-regional, regional, and global averages. Except for Tunisia, Algeria boasts the highest growth rate among its neighboring countries[20].

The country's commercial aquaculture production has been modest and highly variable over the years. Production dipped from 407 tonnes in 1990 to 368 tonnes in 2005, before surging to 2,779.91 tonnes in 2008. However, there was a significant decrease to 1,759 tonnes in 2010, followed by another drop to 1,332 tonnes in 2015. A notable increase occurred in 2020, reaching 5,436 tonnes, though production slightly decreased to 4,779.29 tonnes in 2021. Despite these fluctuations, the share of aquaculture in Algeria's total fisheries production has steadily increased, rising from less than 0.5% before 2005 to nearly 6% in 2021[20].

Table I.3 Status and trends of aquaculture production, 2001-2021 **[22]**

Country/area	Aquaculture production of total species (tonnes)		Annual growth (%)
	2001	2021	
world	34617654.72	90863706.34	4.94
Africa	405675	2322023.3	9.11
Northern Africa	348629	1638558.1	8.05
Egypt	342864	1576189.4	7.93
Spain	311591	279880.43	-0.54
France	251620	198505.7	-1.18
Italy	218330	145861.9	-2.00
Greece	97512	143863.47	1.96
turkey	67244	471686	10.23
Tunisia	1868	25957.2	14.06

Morocco	1403	1922.18	1.59
Sudan	1000	9900	12.15

I.4.1.5. Taxonomic composition of aquaculture production in Algeria

The distribution of aquaculture production in Algeria has been diverse between 2001 and 2021, with contributions from various fish species of the total production of 4,779.29 tonnes, marine fish species, particularly gilthead seabream and European seabass, made up over 53% of the production, with shares of 45.85% and 7.85%, respectively. Carp species, including common carp and crucian carp, contributed over 28% to the country's aquaculture output. Freshwater fish species, represented by various unidentified species (Freshwater fishes), accounted for almost 6% of the total production [20].

Other notable contributors included barbel (3.28%), pike-perch (2.80%), tilapia spp. (2.20%), mulet spp. (1.35%), and Mediterranean mussel (1.09%). The remaining species collectively represented 1.60% of the total production. These species include roach, freshwater bream, European eel, tench, Pacific cupped oyster, gilthead seabream, European seabass, common sole, North African catfish, Penaeus shrimps, largemouth black bass, bleak, bighead carp, cyprinids spp., grass carp (white amur), long-finned charr, caramote prawn, grooved carpet shell, and meagre. This diversity highlights the wide range of species contributing to aquaculture production in Algeria, with marine fish and carp species playing dominant roles in the industry [20].

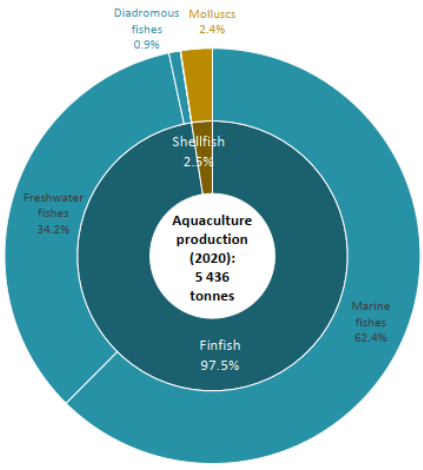


Figure I.9 Aquaculture production (2020) **[21]**

I.5.Tilapia Aquaculture

The production of tilapia farms represents 3.8% of the global production of fish farming, with an estimated production of 40 million tonnes. in 2002, tilapia aquaculture production was about 1.5 million tonnes. During the two decades, tilapia culture recorded the highest rate of annual growth among all finfish species. Tilapia culture is relatively easy because tilapia fish can grow in different environments. most tilapias are raised in brackish ponds or freshwater systems like tanks, ponds, and cages, and some of them grow in lakes and rivers[23].

Tilapia farming is very efficient because the fish grow quickly and use feed effectively, and can reproduce easily in captivity. Tilapia farming is widely popular in many countries due to its lower infrastructure and management costs compared to other aquaculture species[23].

I.5.1. Global tilapia production

The Nile tilapia (Oreochromis niloticus) is among the most extensively cultivated fish species in global aquaculture, contributing significantly to food security, economic development, and the advancement of sustainable aquaculture practices. Its popularity stems from key biological advantages, including high adaptability to varying environmental conditions, rapid growth rates, and strong resistance to diseases, making it a preferred choice for fish farmers worldwide. According to the Food and Agriculture Organization, tilapia ranks as the third most farmed fish species globally, with annual production exceeding 6.5 million metric tonnes [24].

In 2022, the global market value of tilapia reached approximately USD 9.7 billion, with projections indicating a steady compound annual growth rate (CAGR) of 3.9% driven by increasing consumer demand for affordable, high-protein aquatic products Major exporting countries include China, Indonesia, Egypt, and Brazil, while the United States, the European Union, and several Middle Eastern nations remain the largest importers. Given its economic and nutritional importance, enhancing Nile tilapia aquaculture through advanced technologies, such as multi-objective optimization and artificial intelligence-driven strategies, is essential to achieving cost-effective, high-yield, and sustainable production to meet the growing global demand[24].

Tilapia farming is widely practiced across the globe, with China leading as the largest producer at 1,241,410 tonnes, followed closely by Indonesia (1,172,633 tonnes), Egypt (954,154 tonnes), Brazil (343,596 tonnes), and Thailand (205,971 tonnes) [25].

I.5.1.1. China

As of 2022, China remains the leading producer of tilapia, with an output of 1.75 million tonnes, followed by Indonesia with 1.2 million tonnes and Egypt with over 1 million tonnes. Egypt's production has increased by approximately 80% over the past decade, with the vast majority of it consumed domestically. Collectively, these three countries account for nearly 75% of global tilapia production. Other countries such as Bangladesh, the Philippines, and Thailand are also expanding their production, with Bangladesh surpassing 370,000 tonnes and continuing to show strong growth potential[26].

I.5.1.2. The US

The United States remains the largest importer of tilapia globally; however, domestic production has remained stagnant for several years due to its inability to compete with low-cost frozen whole tilapia from Asia and fresh fillets from Latin America. As a result, large U.S. producers, such as Blue Ridge Aquaculture in Virginia, recognized as the world's largest indoor tilapia farm, have focused on a niche strategy of supplying live tilapia primarily to Asian markets across the U.S. and Canada. This approach allows them to command premium prices, driven by growing consumer interest in traceability, freshness, and locally produced food with low environmental impact ("low food miles")[26].

I.5.1.3. ASIA

In Asia, Vietnam is significantly expanding its tilapia production, driven by government initiatives aimed at boosting output and establishing tilapia as an additional whitefish export commodity. The country plans to double its production by 2023. Similarly, the Philippines is increasing its tilapia production to meet strong domestic demand. A notable innovation in the Philippines comes from Vera Bella, a new company marketing unique products such as tilapia ice cream and tilapia cookies, which have gained good traction in supermarkets. Additionally, India has made significant strides in tilapia production, aiming to replicate the success seen in Bangladesh[26].

I.5.1.4. Indonesia

While Chinese tilapia production is experiencing a slowdown, Indonesia is on a steady growth trajectory, with most of its tilapia produced for the domestic market. In 2022, Indonesia produced approximately 1.2 million tonnes of tilapia, and this figure is expected to rise to around

1.4 million tonnes in 2023. As with all tilapia-producing nations, disease control remains a significant challenge. To ensure sustainable growth, the Indonesian sector must adopt effective tools for tilapia health management. [26].

I.5.1.5. The Middle East

The Middle East has been a latecomer to tilapia aquaculture, but rising food security concerns and increasing importation costs are prompting many countries in the region to invest heavily in aquaculture as a means to reduce their reliance on costly imported products. However, significant challenges remain, including high imported feed costs, limited seed availability, and a shortage of local technical expertise. In response, numerous high-tech recirculating aquaculture systems (RAS) and aquaponics projects are currently under development across the region. Saudi Arabia, in particular, has showcased the potential of aquaculture, highlighted by the success of its large-scale shrimp farm, demonstrating the feasibility of such ventures in the region [26].

I.5.1.6. Africa

While Africa is the birthplace of tilapia, its aquaculture industry has only recently begun to expand. Investors are eager to capitalize on the rising demand for tilapia across the continent, driven by the dramatic decline in capture fisheries due to overfishing in recent years. Key industry players such as Aller Aqua, Skretting, Nutreco, and De Heus have established new feed mills to provide high-quality, affordable feed, supporting the growth of the sector. Additionally, many new hatcheries are emerging to supply quality fry and fingerlings, further boosting the industry's development[26].

In terms of production, African tilapia output is largely dominated by Egypt, with only a small portion spread across other countries in the region. However, new farms are being planned in Namibia, Rwanda, and Uganda, where Uganda's "Aquaculture Parks" on Lake Victoria are playing a central role in driving expansion. Companies like Yalelo, Chicoa, and Victory Farms are significantly increasing their production to meet the rising demand, driven by the collapse of wild fish catches. Recently, Victory Farms secured USD 35 million in funding to support its farms in Kenya and Rwanda, with plans to expand further into Ethiopia, Uganda, and Tanzania[26].

I.5.2. Tilapia production in Algeria

To foster the development of tilapia cultivation in Algeria, tilapia fingerlings and adult fish were imported from Egypt in 2002. These imports were then distributed to fish farmers with

the necessary infrastructure and water resources. Several intensive farming areas were established for O. niloticus and red tilapia, including locations such as Fat Step in the Saida district, with a production target of 100 tonnes per year; Pesca de da Duna in the Ouargla district, with a total capacity of 14,400 m^3 and an expected production of 1,000 tonnes per year; and Ezzahra in the Ghardaïa district, which employs a semi-extensive breeding system and has an anticipated production of 490 tonnes per year. These farming areas are supplied with water through drilling, with a capacity of 200 liters per second[27].

Additionally, several ongoing private sector projects are focusing on extensive, semi-extensive, or intensive tilapia breeding, emphasizing the growing significance of tilapia farming across various regions of the country[27].

I.5.3. Tilapia fish

Tilapia is one of the most prevalent fish in with its mild flavor, durable texture, and exceptional ability to grow in diverse environments. Tilapia has become a popular choice in global cuisine and fish farming systems. This kind of fish is not just an economic or a nutritious food source; it plays a vital role in enhancing food security and promoting sustainability in the global fisheries sector [28].

Tilapia includes many farmed species such as Nile tilapia, blue tilapia, red tilapia, and Mozambique tilapia. it is considered one of the most widely speared fish in aquaculture globally due to its environmental resilience (tolerating varying temperature and salinity), making it a strategic choice for enhancing food security, especially in areas with limited resources [28].

I.5.4. Physical characteristics

Tilapia resemble sunfish or crappie in shape but are easily recognized by their interrupted lateral line, a trait typical of the Cichlid family. Their bodies are deep and laterally compressed, featuring long dorsal fins. The front part of the dorsal fin contains strong spines, with additional spines found in the pelvic and anal fins. Fry, fingerlings, and sometimes adults commonly show broad vertical stripes along their sides [29].



Figure I.10 tilapia fish **[30]**

I.5.5. Average weight of tilapia:

Table I.4 average weight of tilapia

category	Weight range	Maximum range
Farmed Tilapia	400-600 grams	1.2-2 kilograms
Wild tilapia	200-250 grams	-
Nile Tilapia	-	Up to 5 kilograms
Blue Tilapia	-	up to 3 kilograms
Mozambique Tilapia	-	Up to 1 kilogram

I.5.6. Feeding

Most wild tilapia are omnivores, feeding on a wide variety of plant and animal matter, unlike many fish species with more specialized diets. Like other fish, tilapia require essential nutrients such as proteins, amino acids, fats, minerals, and vitamins. However, their nutritional needs differ depending on the environment. Fish raised in intensive recirculating systems have different dietary requirements compared to those in the wild. In their natural habitat, wild tilapia graze on blue-green algae and bacteria and must consume more food than farmed tilapia to meet the energy demands for growth and survival [31].

In intensive tank culture, natural food sources are limited, so all necessary nutrients must be provided through a formulated pelleted diet. Such diets offer improved quality and consistency, which supports better growth and health. Feeding rates vary depending on water temperature and the size of the fish. The correct feeding amount is calculated as a percentage of the fish's average body weight, and this percentage decreases as the fish grows. Therefore, daily feed amounts must be adjusted regularly to reflect changes in body weight [31].

I.6.Environmental requirements

I.6.1. Temperature

As long as their physical and biological conditions are appropriately properly regulated, tilapia can reach their full growth potential across various environments. Aquaculture systems require careful management of water quality parameters, particularly temperature, which plays a crucial role in fish physiology. Warmer water increases metabolic rates in fish, thereby raising their demand for food. Temperature directly impacts energy consumption and metabolism, influencing overall growth and development [31].

Fish growth rates, feeding behavior, and food intake are all sensitive to changes in water temperature. Typically, growth increases with rising temperatures up to an optimal point, after which it drops sharply. Food availability is also a key growth factor, with limited feeding options negatively impacting growth rates across temperature ranges. Most fish species, including tilapia, thrive within specific temperature ranges that support optimal growth and survival, and these preferences can shift with age and size. Each early life stage has its optimal temperature, influencing where and when fish populations are distributed [31].

The optimal temperature range for tilapia growth is between 29 °C and 31 °C. At 20–22 °C, cooler temperatures, growth drops to approximately 30% of the maximum potential. On average, the minimum lethal temperature for tilapia is around 10–11 °C, while temperatures of 37–38 °C can induce stress and disease. Studies observing the impact of different temperatures (20, 24, 28, and 30 °C) on Nile tilapia with an average starting weight of 33.5 g over 30 days revealed that growth performance at 20 and 24 °C was not significantly reduced, and survival rates remained consistent across all treatments. Although the feed conversion ratio (FCR) increased with temperature, the difference between 28 and 30 °C was insignificant. These findings suggest that a thermal range of 20–30 °C is suitable for intensive Nile tilapia farming in terms of growth and survival[31].

Another report indicated that the optimal temperature range for tilapia is between 22 °C and 29 °C, with spawning typically occurring above 22 °C. Water temperature also influences the solubility of gases like dissolved oxygen; as temperature decreases, water's ability to retain oxygen diminishes. Experiments conducted under four temperature regimes, 22, 26, 30, and 34 °C, showed that growth and feed efficiency were significantly better at 26 °C and 30 °C, with no differences in

survival rates across temperatures. These results confirm that the optimal temperature for growth and feed utilization in Nile tilapia lies between 26 °C and 30 °C [31].

I.6.2. Salinity

The salinity tolerance of tilapia varies by species. Nile tilapia is the least tolerant, growing well in water with salinity up to 15 ppt and reproducing at levels between 10 and 15 ppt. However, fry production decreases beyond 10 ppt. blue tilapia, in contrast, thrives in brackish water up to 20 ppt and can reproduce between 10 and 15 ppt, though fry production declines above 10 ppt. It does not reproduce beyond 19 ppt but can survive direct transfer to water with salinity between 20 and 25 ppt [31].

Mozambique tilapia is the most salt-tolerant species, capable of surviving in water with salinity levels up to 75 ppt. It grows optimally at salinities between 35 and 40 ppt and can reproduce in full-strength seawater, though its reproductive performance declines above 10–15 ppt. The best growth occurs at a salinity of 17.5 ppt [31].

For optimal growth, tilapia generally perform best at salinities between 8.8 and 17.5 ppt. However, reproductive success is highest in water with salinity below 10 ppt [31].

I.6.3. Dissolved oxygen

Low DO concentration is associated with stress, poor appetite, slow growth, increased disease susceptibility, and mortality in fish. In pond culture, the minimum daily DO concentration is essential for fish health. As minimum DO levels decrease, growth rates decline significantly. In tilapia ponds, DO concentrations should not fall below 1 mg/L [31].

While tilapia can tolerate very low DO levels, even down to 0.1 mg/L, maximum growth is achieved at concentrations greater than 3 mg/L. Oxygen is essential for fish growth and survival, affecting respiration and the toxicity of compounds like nitrate and ammonia. For tilapia, the minimum recommended DO level is 5 mg/L. When DO levels drop, respiration and feeding activity decrease. Additionally, fish cannot properly utilize food when the DO is low [31].

Since fish are sensitive to water quality, poor water conditions can negatively impact their health. Feeding should be reduced or stopped when water quality, particularly DO, falls below certain thresholds. DO levels tend to decrease shortly after feeding, so maintaining levels above 5 ppm is ideal to ensure good growth. When DO is between 3 and 5 ppm, feeding should be reduced, and feeding should stop entirely if levels drop to 3 ppm or lower [31].

The optimal DO range for tilapia tanks is between 5 and 7 mg/L. Concentrations below 3.5 mg/L reduce growth and feed conversion efficiency. Short-term exposure (less than 10 minutes) to DO levels as low as 0.8 mg/L may still allow survival and recovery. Aeration and mechanical mixing are recommended when DO concentrations are low, as these interventions help minimize stress and prevent fish mortality due to oxygen depletion[31].

I.6.4. PH

Some tilapias are known to tolerate a very wide range of water PH. Tilapia shows best growth in water that is close to neutral or slightly alkaline. the optimal pH for the rearing and survival of different fish species varies. A pH range of 6.5 to 9.0 generally provides adequate protection for the life of freshwater fish. Outside this range, fish experience adverse physiological effects, which increase in severity as the deviation from the optimal range becomes greater, eventually reaching lethal levels. The pH range that is not directly lethal to freshwater fish is typically between 5.0 and 9.0, while the effects of chronic exposure to low pH are minimal between pH 4 and 6 [31].

However, the optimal pH range for fish also depends on the species, life stage, and other interacting water quality conditions. All life stages of Nile tilapia did not survive in acidified water with a pH of 3. This may be due to the toxic action of hydrogen ions affecting oxygen uptake, leading to acid stress, protein precipitation within epithelial cells, and/or blood acidosis. It may also result from erosion of the epidermal layer of the skin and gills, inhibition of sodium ion influx, organ damage (such as to the brain, kidneys, and spleen), lysis of red blood cells, and failure of the ion regulatory system, ultimately causing circulatory collapse. The incomplete development of the ion regulation system in fingerlings may underlie their reduced tolerance to acidic conditions[31].

Observations show that fingerlings, juveniles, and adult tilapia do not survive when exposed to pH 3. The high mortality rate among fingerlings at pH 4 and 5 may be attributed to the factors mentioned above, while their minimal survival could be due to gradual adaptation to the acidified environment. The survival of juveniles and adults at pH 4, 5, and 6 may be due to efficient ion transport systems, which help maintain salt balance better than in fingerlings. Mortality at these levels may still occur due to regulatory failure in salt balance, leading to hemoconcentration, circulatory collapse, and impaired oxygen uptake by hemoglobin. The production of mucus on the gill epithelium may also interfere with gas exchange and ion regulation, causing respiratory distress and osmotic imbalance, which are key symptoms of acid stress in fish[31].

The survival rates of juveniles and adults at pH levels 4, 5, and 6 align with previous observations, although some variation exists. The tolerance to acidity across different life stages supports the idea that pH tolerance increases with age. This suggests that Nile tilapia can be cultured in slightly acidified water, and this should be considered when breeding the species in aquaculture ponds, especially when sourced from naturally acidified environments [32].

I.6.5. Ammonia

Ammonia is a critical factor in aquaculture systems and can directly influence water quality. Its accumulation can be toxic to fish and high levels of ammonia inhibit the growth of fish or affect in negative ways on fish, and in lethal concentrations, it causes the death of fish [32].

Ammonia toxicity increases with temperature and pH. Each 1-unit increase in pH results in a tenfold rise in the NH_3 to NH_4^+ ratio, and every 10 °C rise in temperature doubles the ratio. This makes proper water quality management crucial, especially in intensive aquaculture systems[32].

The main source of ammonia is fish excretion, which is related to the feeding rate and the protein level in the feed. The other source of ammonia is the sediment of the fish ponds [33].

Ammonia can exist in two forms: non-toxic form is ionized ammonia, which has the chemical formula NH4+, and the toxic form is un-ionized ammonia, which has the chemical formula NH3 [33].

Fish are affected both directly and indirectly, depending on the levels present. At low concentrations, non-ionized ammonia is unsafe to fish species, as it can lead to slower growth, lower feed conversion rates, reduced fertility, and increased stress levels, enhancing susceptibility to bacterial infection and diseases [34]. At high concentrations, ammonia can cause damage to the gills and tissues, leading to lethargy and even death [34]. The levels of ammonia and pH in fish blood increase when there are high concentrations of ammonia [35]. The toxic effect of ammonia on aquatic life increases with elevated temperatures and high pH values [36].

I.6.6. Water turbidity

Water turbidity can be a significant issue. This turbidity comes from a variety of sources, including murky source water, precipitation runoff from clay-containing ponds dykes and bottom mud resuspension from fish and water movement.

High levels of suspended colloidal particles can negatively affect fish by reducing fertilizer effect, causing water acidity, and preventing light from penetrating. Fish growth, feed efficiency, and survival all declined significantly as water turbidity increased.

I.6.7. Water quality in aquaculture

Water is the most important component in aquaculture, and the choice of source must depend on its ability to provide an environment conducive to efficient and high-quality production. Poor water quality may affect fish health by impeding their growth and development, or may lead to the deterioration of product quality due to adverse effects such as a change in flavor or the accumulation of toxic substances that may pose a risk to human health. Therefore, criteria and guidance are important to determine the suitability of source water for use in aquaculture projects [34].

I.6.8. Nitrogen cycle in fish farms

It's crucial to reduce the ammonia concentration in fish tanks to ensure a healthy aquatic environment. The reduction of ammonia concentration is achieved through two processes [37].

The first process consists of transforming the ammonia through nitrification by using two kinds of bacteria Nitrosomonas and Nitrosospira to convert ammonia to nitrite in the first step and then to nitrate. The nitrite is also toxic to fish but encourages the growth of Nitrosospira bacteria, which convert the nitrite to a less toxic nitrate form [37].

The other process is using plants like algae, which use nitrogen as a feed for growth. in this case, the plants act like a sponge for ammonia, but these plants can affect the DO quantity, especially at night [37].

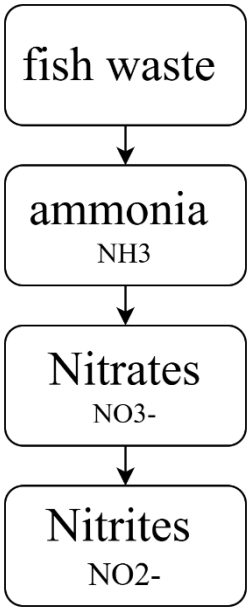


Figure I.11 Nitrogen cycle in fish farms

I.7.Ammonia management

Ammonia management procedures are limited, and there are some ways to reduce their levels in large aquaculture ponds, but some may increase other problems. There is no comprehensive long-term solution to this issue [37].

Reduce the feeding rate among the solutions it relies on to reduce ammonia levels because excess feed and fish excretion are the main sources of ammonia. Also, increasing aeration can help reduce fish stress by raising DO levels, but it may not significantly lower overall ammonia concentration due to limited aeration area. Strong aeration should be avoided to prevent stirring bottom sediment, which could increase ammonia levels. Adding phosphors is another solution to reduce ammonia levels, but it has little effect on lowering ammonia concentration because algae growth depends on light and phosphors, and nitrogen does not control how fast algae grow [37].

I.8.Challenges of tilapia aquaculture

While tilapia aquaculture shows great promise, it faces some key obstacles. Compared to fish like salmon, farmed tilapia have lower quantities of the omega-3 fatty acid. Moreover, while certain species like the Mozambican tilapia may survive in seawater, the majority of tilapia species suffer from high salinity. Also, tilapia suffer from cold temperatures. Tilapia aquaculture poses

environmental issues since inappropriate methods can degrade biodiversity and the ecosystem. Cage culture, offshore farming, and RAS systems can significantly reduce environmental impacts, and it is going to increase production and technological advancement. This system will be the key to the next generation of aquaculture [38].

I.9. Technological innovations in aquaculture

I.9.1. Aquaponic system

The system has been used since 2011. It is based on the integration of triple mesh parts. This system is suitable for aquaculture in open sea environments due to its drowning structure and the entire perimeter of the net. The system is kept under surveillance by divers and electronic devices [39].



Figure I.12 Aquaponic system **[40]**

I.9.2. Smart floating farms

The smart floating farms model is an effective system where aquaculture depends on technology. In this system, there are many layers. Solar panels are installed on the floor to ensure a source of energy to the system. In the middle layer, vegetables are produced and in the bottom layer, fish are produced in ponds. The smart floating farm includes an aquaponic system where fishpond wastewater is used in vegetable production [39].



Figure I.13 smart floating farms **[41]**

I.9.3. AI and IOT in aquaculture

IoT is used in many fields, including environmental monitoring, industrial automation, precision agriculture, healthcare, and smart cities. In the fisheries sector, IoT systems can help farmers and researchers to monitor, manage, collect, and analyze data to optimize fish farming and the aquatic environment using sensors, smart devices, and low-power long-distance communication in wide fields to increase productivity, efficiency, and sustainability[42].

Modern IoT technology has made considerable advances in aquaculture. IoT systems are able to produce and manage a vast volume of data from many different places. This data is processed and analyzed using analytics, machine learning, and AI. The results are used to facilitate real-time decisions and enable automation [42].

IoT can improve the health, survival, and growth rates of fish stocks. Through continuous monitoring of environmental conditions and fish behavior, IoT systems enhance disease detection and allow for faster response times to potential issues, thereby reducing losses[42].

In addition, IoT systems can automatically feed the fish and warn farmers before equipment breaks down, which means less work for people. It also prevents costly repairs and stops wasting food (over-feeding), resulting in using less energy and causing less pollution. IoT allows farmers to monitor and control their farms from any place using their phone or computer, which gives them more control and flexibility [42].

I.10. The impact of digital technologies on improving and supporting the aquaculture industry

Digital technology is being used more and more. It is becoming a big part of our daily lives. Digitalization integrates these technologies, transforming areas like society, the environment, sustainability, and climate research. It involves converting physical information into computer language, enabling the development of digital technologies like the Internet of Things (IoT) [43].

Several digital technologies are important for food. These include technologies like IoT, cloud computing, big data, machine-to-machine communication, and remote sensing. This enables fast communication across the global food supply chain. Additionally, technologies such as AI, machine learning, and digital twins provide advanced analysis, diagnostics, and predictive abilities, allowing for self-monitoring and automated issue evaluation [43].

I.11. Conclusion

In this chapter, we present the types of aquaculture farms and provide an overview of them. We then focused more specifically on information about tilapia fish and the conditions they need.

All of this is intended to give the reader or researcher a general understanding of what we are developing, to facilitate and advance the aquaculture systems.

Chapter II:System design

II.1. Introduction

To develop any intelligent system, we must first and foremost define an initial vision of what this system might look like and identify the components needed to create it.

This chapter introduces the core technologies that form the foundation of our project. We explore the hardware component employed, describing its functionalities, system roles, and main features.

II.2. Internet of Things (IoT)

IoT is a network of physical objects, including devices, vehicles, and appliances, that use sensors, software, and network connections to collect and share data. These smart objects can communicate with each other and with a centralized system to automate processes, monitor the environment, and enhance decision-making. IoT applications range from smart home and wearable health monitors to industrial automation and smart cities infrastructure [44].

II.2.1. IoT architecture

IoT systems are made up of several key parts. First, sensors collect information from the environment. Next, wireless connections like Wi-Fi or Bluetooth send this data. Then, the computer processes the information to find useful patterns. Finally, apps and dashboards let people see and control the system. All these pieces work together to make smart, automated solutions for homes, factories, and cities.

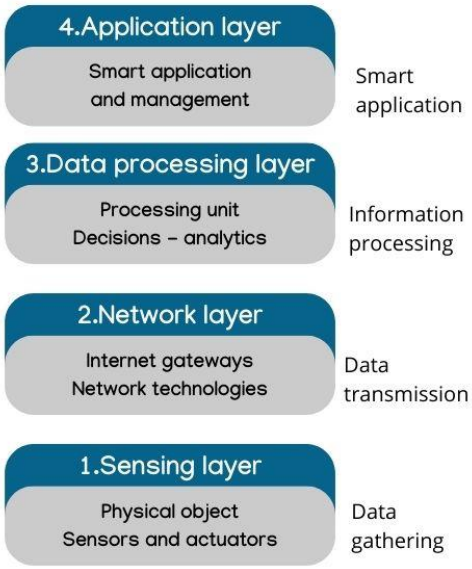


Figure II.1 IoT architecture **[45]**

II.3. Component choices

II.3.1. ESP32 S3

The ESP32-S3 is a high-performance and versatile microcontroller developed by Espressif Systems, designed for IoT and embedded applications. It offers increased computing power, advanced connectivity, and optimized energy consumption, making it an ideal choice for smart projects, from wearable devices to industrial systems.



Figure II.2 esp32 s3 **[46]**

II.3.1.1. ESP32-S3 features

The ESP32-S3 (N16R8) is powered by a dual-core 32-bit LX7 microprocessor designed for efficient low-power operation with clock speeds up to 240 MHz, while its hybrid 16/24/32-bit instruction set optimizes both dense code and computing performance. it offers high processing power while maintaining excellent energy efficiency. The module integrates full wireless connectivity with Wi-Fi 4 (802.11 b/g/n) and Bluetooth (LE+ Mesh), enabling stable and versatile communication [47].

The integrated USB OTG interface represents a key innovation, facilitating data exchanges without external components for embedded applications. The ESP32-S3 has an advanced memory configuration with 384 KB of Flash memory, 512 KB of SRAM memory, and 8MB PSRAM, delivering exceptional memory capabilities for advanced embedded applications. Also, the ESP32-S3 contains a 12-bit ADC and an 8-bit DAC for analog signal processing [47].

It supports various standard communication protocols through multiple SPI, I2C, UART, and I2S interfaces, enabling connections to a wide array of sensors and external devices. its 44 GPIO offers extensive flexibility for hardware interfacing, supporting everything from simple buttons to complex modules [47].

II.3.2. Comparison of ESP32 S3 with other microcontrollers

Table II.1 Comparison of ESP32 S3 with other microcontrollers

Feature	**Arduino uno**	**ESP32 S3**	**ESP32 S2**	**ESP32 WROOM**
processor	ATmega328p	Dual-core Xtensa LX7	Single-core Xtensa LX7	Dual-core Xtensa LX7
Architecture	8-bits	32-bits	32-bits	32-bits
Clock speed	16 MHz	240 MHz	240 MHz	240 MHz
SRAM	2KB	512 KB	320 KB	520 MHz
Flash memory	32KB	384 KB	128 KB	448 MHz
GPIO pins	14	45	43	34
WI-FI	None	2.4 GHz	2.4 GHz	2.4 GHz
Bluetooth	None	Bluetooth 5	None	Bluetooth 4.2
ADC channels	6(10-bits)	20(12-bits)	20(12-bits)	18(12-bits)

DAC channels	None	2(8-bits)	2(8-bits)	2(8-bits)
UART	1	3	2	3
I2C	1	2	2	2
SPI	1	4	4	4
Operating voltage	5V	3.3V	3.3V	3.3V
Power consumption	50mA (no sleep modes)	Deep sleep	Deep sleep	Deep sleep
Programming environment	Arduino IDE	Arduino IDE, ESP-IDF, MicroPython	Arduino IDE, ESP-IDF, MicroPython	Arduino IDE, ESP-IDF, MicroPython

II.3.3. Turbidity sensor

Turbidity is a physical characteristic of water; it is caused by the presence of materials in suspension or impurities that affect the clarity of water. It is an expression of an optical property of water and is determined using a nephelometer [48].

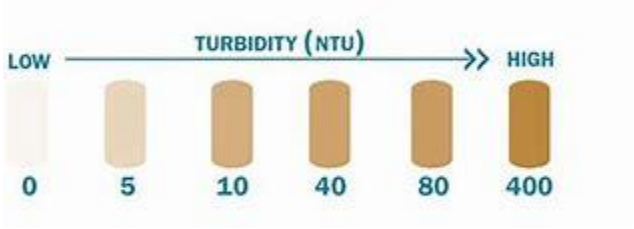


Figure II.3 Turbidity color scale **[49]**

II.3.3.1. TS-300B turbidity sensor

The TS-300B turbidity sensor is a reliable solution to measure water turbidity, This sensor provides a practical way to measure water cloudiness caused by suspended particles such as sediment, algae, and organic matter in water.It is ideal for applications like water quality monitoring, smart appliances.

The sensor operates on an optical principle by emitting infrared light into a water sample and measuring the intensity of scattered light caused by suspended particles.



Figure II.4 TS-300B Turbidity sensor **[50]**

II.3.3.2. Working principle of the TS-300B Turbidity Sensor

The sensor operates on an optical measurement principle, when the light passes through a water sample, the transmitted light intensity varies inversely with the water's soil content. When the particle concentration increases, less light passes through the sample. This sensor contains a light-emitting part that emits light into the water sample and a light-receiving part (the receiver receives a light intensity lower than that emitted when the particle concentration increases) [51].

II.3.3.3. Specifications of the turbidity sensor

Operating voltage: 5V DC

Response time: <500ms

Operating temperature: -20°C – 90°C.

Rati range (NTU): 0-1000

Working current: 40 mA.

Output mode: digital and analog input.

II.3.4. The temperature sensor

The DS18b20 is a popular digital temperature sensor widely used in aquaculture and many other environmental monitoring systems due to its specifications. It is very easy to use and integrates into the aquatic system. It communicates via a 1-Wire interface, requiring only one single

data line and ground connection to interface with a central microprocessor, moreover allowing multiple sensors to operate on a single data line. [52].



Figure II.5 Temperature sensor (DS18B20)**[53]**

II.3.4.1. Working principle of the DS18B20 temperature Sensor

The primary advantage of the DS18B20 is its use of the 1-wire protocol, which means that only a single data line is required for communication is for communication. This feature simplifies wiring, particularly in systems where many sensors are connected in parallel. The 1-wire protocol is robust and allows multiple devices to be connected to the same data bus [52].

The DS18B20 can communicate with a microcontroller by sending commands to red temperature data or configure the resolution settings. The device is capable of sending data over long distances, up to 100 meters [52].

The sensor measures the temperature continuously and updates the value when requested. However, users can initiate conversions manually or set the sensor to perform conversions automatically at regular intervals.

One of the most important features of DS18B20 is the configurable resolution of the temperature readings. The sensor measures temperature and converts it into a digital signal using an analog-to-digital converter, and it supports 9-bit to 12-bit resolution, with 12-bit being the default. A 9-bit resolution corresponds to temperature measurement with a precision of 0.5 °C, while a 12-bit resolution improves this precision to 0.0625°C. the higher resolution take a long time for conversion, as more bits require more processing power and time [52].

The sensor stores the temperature data in a 2-byte register, which can be accessed by the microcontroller. It can operate in parasitic power mode, which can draw power directly from the data line, eliminating the need for an external power source. Each DS18B20 sensor has a unique 64-bit serial code, allowing multiple sensors to be connected on the same data [52].

II.3.4.2. Applications of the DS18B20 Sensor

The DS18b20 digital temperature sensor is extensively utilized in various industries, thanks to its exceptional accuracy, waterproof construction, and 1-wire communication protocol. Notable applications encompass:

Home automation: smart thermostats and HVAC monitoring

Industrial monitoring: tracking the temperature of machinery and the environment

Weather stations: measuring outdoor temperatures

Medical devices: used in incubators and diagnostic tools

Aquaculture and aquariums: maintaining stable water temperatures for marine life

Its adaptability, robustness, and seamless compatibility with microcontrollers like Arduino and Raspberry Pi make it a perfect choice for IoT, automation, and precision monitoring systems.

II.3.4.3. Specification of the DS18B20 Sensor

Temperature range: -55°C to +125°C

Accuracy: ±0.5°C from -10°C to +85°C

Resolution**:** 9-bit to 12-bit

Interface: Uses a 1-Wire communication protocol

Power supply: 3.0V to 5.5V

Conversion time: maximum 750ms for a 12-bit temperature reading

II.3.5. TDS sensor

A Total Dissolved Solids (TDS) sensor measures the concentration of dissolved substances, such as salts, minerals, and metals, in water, providing an indication of its purity or contamination level. TDS is typically expressed in parts per million (ppm) or milligrams per liter (mg/L) [54].



Figure II.6 TDS sensor **[55]**

II.3.5.1. Working principle of the TDS Sensor

TDS sensors operate by assessing the electrical conductivity of water. Dissolved ions enhance water's ability to conduct electricity; thus, higher conductivity correlates with higher TDS levels. The sensor employs two electrodes submerged in the water sample to measure this conductivity. The resulting analog voltage is then converted into a digital TDS value using a microcontroller or signal processing circuit [56].

Temperature significantly influences conductivity readings. Therefore, many TDS sensors incorporate temperature compensation mechanisms to ensure accurate measurements across varying water temperatures [57].

II.3.5.2. Applications of TDS Sensors

TDS sensors are employed across several sectors to monitor water quality. In drinking water, they ensure safety standards are met. For hydroponics and agriculture, they track nutrient concentrations in the irrigation system. Industrial processes use them to manage quality in manufacturing. In environmental monitoring, they help assess the health of natural water bodies.

And importantly, in aquaculture, they are used to maintain optimal water conditions for aquatic life.

II.3.5.3. Specifications of the TDS sensor

Operating voltage: 3.3V to 5.5V DC.

Output voltage: 0 to 2.3V.

Working current: 3 to 6 mA.

TDS measurement range: 0 to 1000 ppm.

Accuracy: 10%

Temperature range: 0°C – 80°C.

II.3.6. DO803 dissolved oxygen sensor

A DO sensor measures the amount of oxygen dissolved in liquids, crucial for monitoring water quality in various applications such as aquaculture, wastewater treatment, and environmental studies. The two primary types of DO sensors are electrochemical and optical sensors, each operating on distinct principles [58]**.**



Figure II.7 DO803 sensor **[59]**

II.3.6.1. Application of DO sensor

DO sensors play a vital role in monitoring and maintaining water quality across various sectors. They are essential in wastewater treatment to support biological processes, aquaculture to ensure healthy aquatic life, and environmental monitoring to assess the ecosystem health. Additionally, DO sensors help control oxygen levels in the beverage and brewing industries, prevent corrosion in oil and gas operations, and optimize processes in water treatment plants. Integrated with temperature sensors and often used in wireless IoT systems, DO sensors enable real-time, accurate monitoring and control, ensuring product quality, regulatory compliance, and environmental protection.

II.3.6.2. Working principle of the optical DO Sensor

An optical DO sensor uses electrochemical methods to generate a signal that reflects the oxygen concentration in a liquid. Optical DO sensors operate using the principle of luminescence. this method is based on using special materials called luminophores that absorb energy from an excitation light source, causing their electrons to move to a higher energy state. The luminophore remains for a predetermined amount of time, and interactions with other molecules, such as oxygen, may take place during this state. Light is released by the electrons as they return to the first state from the excited state, exhibiting fluorescence or luminescence [60].

Luminophore materials have an interesting property related to gas (O2) in the excited state, affecting their fluorescence in two ways. When an oxygen molecule collides with the luminophore, energy is transferred from the luminophore to the oxygen, leading to two distinct effects:

1-The fluorescence intensity emitted by the luminophore decreases.

2-the lifetime of fluorescence becomes shorter.

As a result, by measuring one of these light emission properties, the amount off oxygen in the sample can be determined.

Optical DO sensors are able to identify fluorescence quenching by monitoring variations in intensity and fluorescence lifetime. There is a relationship between the amount of oxygen in the sample and the decrease in fluorescence intensity and lifetime. This relationship is explained by the Stern-Volmer equation [60].

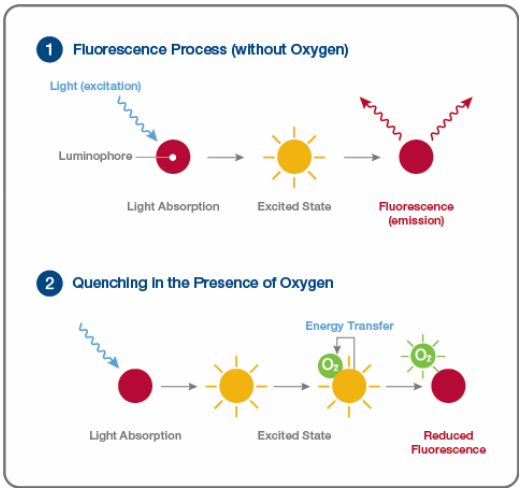


Figure II.8 Oxygen Quenching of Fluorescence **[60]**

II.3.6.3. Optical DO Sensor component

At its core, an optical DO sensor consists of the following key components:

- A light source.
- A transmission medium (which can be a fiber optic or a window).
- The luminophore.
- A photodetector to detect the light emitted from the fluorescent dye.
- Electronic circuit to convert the detected fluorescence intensity and lifetime into an electronic signal [60].

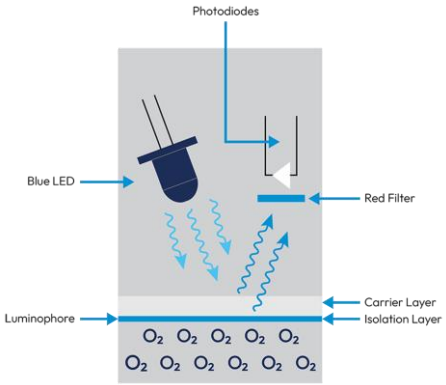


Figure II.9 The working principle of an optical DO sensor **[60]**

II.3.6.4. Specifications of the DO 803 sensor

Operating temperature: 0 to 50°C.

Temperature accuracy: ±0.5°C.

Operating voltage: 3.3V to 5.5V DC.

Accuracy: 2% or ± 0.2 ppm.

DO measurement range: 0 to 20 ppm (mg/l).

Response time: 90% in less than 30 seconds at 25°C.

II.3.7. Oxidation reduction potential (ORP)

Oxidation-reduction potential (ORP) quantifies the total sum of reaction potentials within a sample solution. Consequently, ORP is viewed as non-specific since, unlike PH, which precisely gauges hydrogen ion concentration, it doesn't measure any unique species.

ORP indicates the ability of a substance or solution to oxidize or reduce another substance; it indicates the tendency of a system to gain or lose electrons[80]. The typical range of ORP measurement is reported in volts or millivolts, ranging from -1000 mV to +1000 mV [61].

A positive voltage signifies that the solution has a great tendency to oxidize, meaning it is more likely to accept electrons from a species that has a lower oxidative potential [61].

II.3.7.1. The importance of ORP in aquaculture:

Keeping water quality at optimal levels is crucial for the health and growth of fish in an aquaculture system. ORP is a vital parameter in aquaculture, helping farmers maintain a safe and productive environment for fish or other aquatic species. ORP measures the balance between oxygen and waste in water. It can help to control disinfectant levels, like ozone, to ensure effective treatment without harming aquatic life [62].

II.3.7.2. Working principle of ORP sensor

ORP measures a solution's ability to oxidize or reduce substances. The sensor has two electrodes. One of the electrodes is a reference electrode immersed in electrolyte, which provides a stable voltage for comparison. The second electrode is the measurement electrode, which is usually made from platinum or gold, and it reacts with the solution [63]. The difference in electrical potential between the two electrodes creates a millivolt (mV) reading, which indicates the redox state of the sample [62].

Most ORP sensors combine the electrodes and the temperature sensor in one unit, because ORP depends on temperature, and the temperature at the same time of measurement must also be recorded [62].



Figure II.10 Orp sensor **[64]**

II.3.7.3. Specifications of the ORP sensor

Measurement range: -1500 mV to +1500 mV

Resolution: 1mV

Accuracy: ±20 mV.

Operationg temperature: 0°C to 60°C

Response time: < 1 minute

II.3.8. PH sensor

The PH201-H is a pH sensor or pH electrode commonly used for measuring the acidity or alkalinity of a solution by detecting the concentration of hydrogen ions, ensuring precise PH measurement. It is often utilized in industrial, environmental, and laboratory applications [41]. The PH201H sensor offers high sensitivity due to its specialized glass membrane. The PH201H sensor features a robust construction and high sensitivity, making it ideal for continuous, real-time monitoring applications [41].



Figure II.11 PH 201H probe sensor **[65]**

II.3.8.1. PH electrode anatomy

The glass membrane is made from a special pH-sensitive glass designed to react only with hydrogen ions in liquids.

The reference electrode maintains a stable electrical potential by using an internal potassium chloride (KCl) electrolyte solution, which serves as an unchanging reference point.

II.3.8.2. Working principle of the PH electrode

PH electrodes operate based on the Nernst equation, which relates the concentration of hydrogen ions (H+) in a solution to an electrical potential. An electrochemical principle that correlates the potential difference between the electrodes' internal and external environments to the

hydrogen ion (H+) concentration in a solution. Essentially, when the electrode's sensing surface interacts with H+ ions, it generates a measurable voltage. Since this voltage varies logarithmically with H+ activity, it directly reflects the solution's PH, allowing precise determination of acidity or alkalinity. This fundamental mechanism enables accurate and reliable PH measurement in various applications[41].

The glass membrane is the core component of a pH electrode. This specialized glass interacts with hydrogen ions, H+, in solution. H+ ions interact with the outer surface of the membrane, while the inner surface contacts a stable buffer solution. The difference in H+ concentration between these surfaces creates a voltage. This voltage change follows the Nernst equation[64].

The reference electrode maintains a stable electrical potential regardless. of the composition of the solution. This fixed reference point enables accurate PH measurement by serving unchanging baseline against which the variable potential of the glass electrode is compared. Its stability comes from an internal KCI electrolyte solution that maintains consistent ion activity, allowing it to function as a reliable reference in diverse test solutions[64].

II.3.8.3. Nernst equation

The voltage generated across the glass membrane directly corresponds to the hydrogen ion H+ concentration of the solution, following the fundamental Nernst equation principle.

$$\mathbf{E=E_0-(\frac{2.303*RT}{F}) \times \log [H^+]} \quad \mathbf{(II.1)}$$

Where:

E is the measured potential.

E_0 is the standard electrode potential.

R is the gas constant.

T is the temperature.

F is the constant of Faraday.

Log $[H^+]$ is the hydrogen ion concentration.

II.3.8.4. The pH module sensor PH-4502C

The module PH-4502C is a widely used PH sensor module with a PH electrode, typically connected via a BNC connector. The probe generates a voltage proportional to the pH level of the liquid it is immersed in. The PH-4502C module can process the voltage signal, amplify it, and provide an analog output voltage that can be easily read by the microcontroller.



Figure II.12 PH-4502C **[66]**

II.3.8.5. Specification of PH module PH-4502C

Input supply voltage: 5V.

Working current: 5- 10mA.

Measurement range: 0-14.

Temperature measurement range: 0-80°C.

Response time: ≤5s.

Stability time: ≤60s.

Output: analog.

Power consumption: ≤ 0.5W.

Working temperature: -10 to +50°C.

Working Humidity: 95%.

II.3.8.6. Application of PH sensors

pH sensors are vital for monitoring acidity/alkalinity in water treatment, food production, agriculture, pharmaceutical, and environmental science. In aquaculture, pH sensors help maintain optimal water conditions for fish health by continuously monitoring water acidity or alkalinity, preventing harmful levels of PH, which can directly impact fish health, growth, and survival.

II.3.9. ADS 1115

The ADS1115 is a 16-bit analog-to-digital converter. This versatile converter is capable of accurately measuring both positive and negative voltages. The ADS1115 can operate in several configurations, including single-ended differential mode or comparator mode, offering flexibility for various measurement applications [42].

Table II.2 operating modes and output capabilities of the ADS1115

Operating mode	output
Single-ended differential	This mode can measure positive voltages only. So, no negative output can be processed in this mode.
comparator	The comparator mode is capable of processing both positive as well as negative voltages. It becomes very useful when battery voltages are measured.

It has 16 bits resolution, allowing for much finer measurement of analog voltages compared to the typically lower resolution ADCs found on many microcontrollers. This translates 65.536 possible digital values to represent the analog input range [42].

It communicates using the I2C interface, which requires only two wires (SDA and SCL) in addition to power and ground wires, making it easy to interface with microcontrollers [68]. The ADS1115 can operate from a supply power voltage between 2.0V and 5.5V, making it compatible with both 3.3V and 5V logic levels [42].

An integrated PGA allows for amplifying smaller input signals to utilize the full range of the ADC, improving measurement precision for low-voltage signals. The programmable gain settings enable measurement range from ± 256 mV to ± 6.144 mV [42].

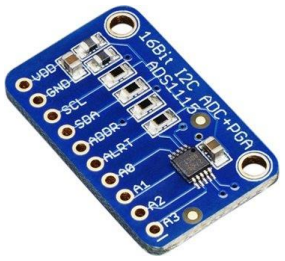


Figure II.13 ADS 1115 **[69]**

II.3.10. Level shifter

A level shifter is an electronic circuit used to convert signals from one voltage level to another. It's commonly used when two components in a system operate at different logic voltage levels, for example, shifting a 3.3V signal to 5V or vice versa, so they can communicate properly without damage or data errors [70].

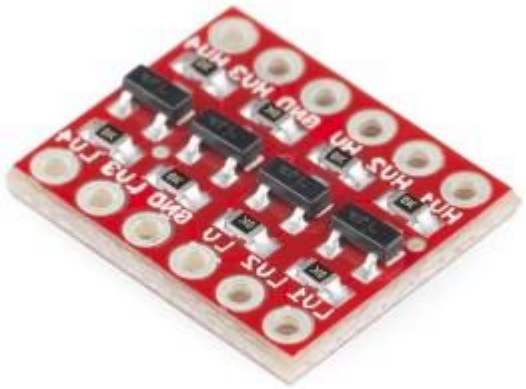


Figure II.14 Level shifter **[71]**

II.3.10.1. Types of level shifting

II.3.10.1.1. Unidirectional level shifter

A unidirectional level shifter, also called a level converter, converts a logic signal in one direction only. It is simpler than bidirectional shifters but requires separate circuits for input and output.

A basic Unidirectional logic converter can be built using one NPN transistor and two resistors to convert 5V signals to 3.3V signals [70].

II.3.10.1.2. bidirectional level shifter

A bidirectional level shifter converts a logic signal automatically in both directions without direction control pins. A bidirectional level shifter can be built using an n-channel MOSFET and two resistors to convert a 5V signal to a 3.3V signal and the opposite [70].

II.3.10.2. Uses of level shifter

A level shifter allows communication between devices operating at different voltage levels, like the interfacing chips of different logic families such TTL and CMOS, also it can ensuring compatibility between low-voltage microcontroller and higher voltage sensors or peripherals, moreover it used to safely shit signal levels in serial communication interfaces [70].

II.3.11. Water pump DC-6 12V

The DC6 12V water pump is a compact, energy-efficient water pump designed for small-scale aquatic and fluid applications. Its low voltage operation (6- 12V DC) makes it safe for use in aquariums and cooling systems while striking a balance between performance and power efficiency.

The DC6 12V mini water pump is a compact, energy-efficient device designed for small aquariums, fountains, hydroponics, and cooling systems. It ensures safe, low-power fluid circulation while striking a good balance between performance and efficiency. Its small size makes it perfect for small tanks and applications with limited space.



Figure II.15 Water pump **[72]**

II.3.11.1. Specifications of DC-6 12V

Operating voltage: 6- 12V DC.

Operating current: 0.5- 0.7A.

Maximum suck range: 2m.

Maximum head range: 3m.

Life cycle: up to 2500 H.

Resist water temperature up to 80 °C.

II.3.12. Horizontal float water level sensor

A horizontal float water level sensor is a device used to detect the level of liquid in a tank or container. It operates with a float that moves sideways (horizontally) as the water level changes. When the float shifts, it activates a magnetic switch, triggering an electrical signal to indicate whether the liquid has reached.



Figure II.16 Horizontal float water level sensor **[73]**

II.3.13. OLED

OLED stands for Organic Light-Emitting Diode. It's a display technology where each pixel emits its own light using organic compounds, allowing for deep blacks, vibrant colors, and ultra-thin screens. Unlike traditional LCDs, OLEDs don’t need a backlight, which makes them more energy-efficient and capable of producing sharper contrast.



Figure II.17 OLED display module **[74]**

II.3.14. Solenoid valve

A 12V solenoid valve is an electrically controlled valve that uses a 12V (DC) power Supply to open or close fluid or gas flow. These valves are widely used in applications requiring low-voltage control, such as automotive systems, irrigation, water filtration, battery-operated devices, and industrial automation.



Figure II.18 solenoid valve

II.3.15. Relay module

A relay module is an electronic switching device that allows low-power signals to control high-voltage actuators. It uses an internal electromagnetic coil to open or close contacts. This enables microcontrollers to safely operate devices like pumps, lights, or motors. Relay modules provide electrical isolation between the control and load sides.

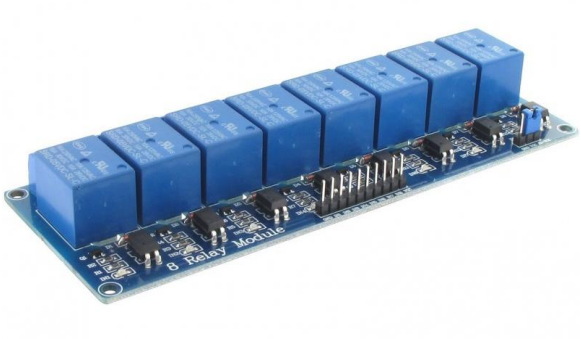


Figure II.19 Relay module **[75]**

II.4. Conclusion

This chapter, has provides a comprehensive exploration of IoT and the careful selection of components essential for building a real-time monitoring system. The detailed review of chosen components includes the ESP32 microcontroller, various environmental sensors.

Together, these elements form the backbone of a robust IoT system capable of real-time monitoring, laying a strong foundation for the successful implementation of our system.

Chapter III:Practical implementation

III.1.Introduction

This chapter presents the practical conception of the system, detailing the testing procedures, calibration procedures, hardware and software integration, and performance evaluation. The implementation phase encompasses the integration of sensors, microcontrollers, and communication interfaces.

III.2.System working principle

The automated water quality monitoring system for fish ponds uses a pump to draw water into a measurement chamber, where sensors analyze key parameters, such as pH, DO, and temperature, at specific intervals. When the moment comes, the monitoring node sends a message to the filling node to start the process of filling the basin, by controlling solenoid valves and pump. as the filling node contains a sensor to measure the water level in the basin when the basin is full, the electric valve is closed, the pump is stopped, and a message is sent to the monitoring node to measure the different parameters. After analysis, an electro valve at the bottom opens to drain the water, followed by a cleaning cycle with fresh water to ensure accuracy for the next reading. The process repeats at scheduled intervals, maintaining consistent water quality assessment while preventing contamination, making it ideal for aquaculture.

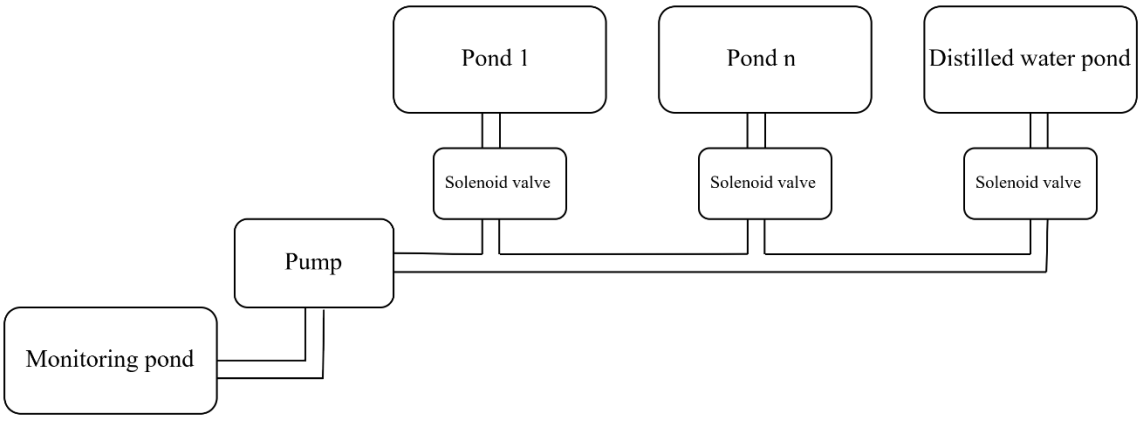


Figure III.1 General structure of the system

III.3.Monitoring pond design

The monitoring pond is a compact tank designed for accurate water quality analysis. It features immersed sensors, such as pH, TDS, ORP, temperature, and DO, and turbidity probes positioned in the upper section. A solenoid valve at the bottom allows controlled drainage after each test. A level sensor is also installed to monitor the water level and ensure consistent measurement conditions. The pond remains empty by default to avoid contamination, and water is introduced only during the measurement cycle. This setup ensures clean, reliable, and automated readings for applications like aquaculture monitoring.

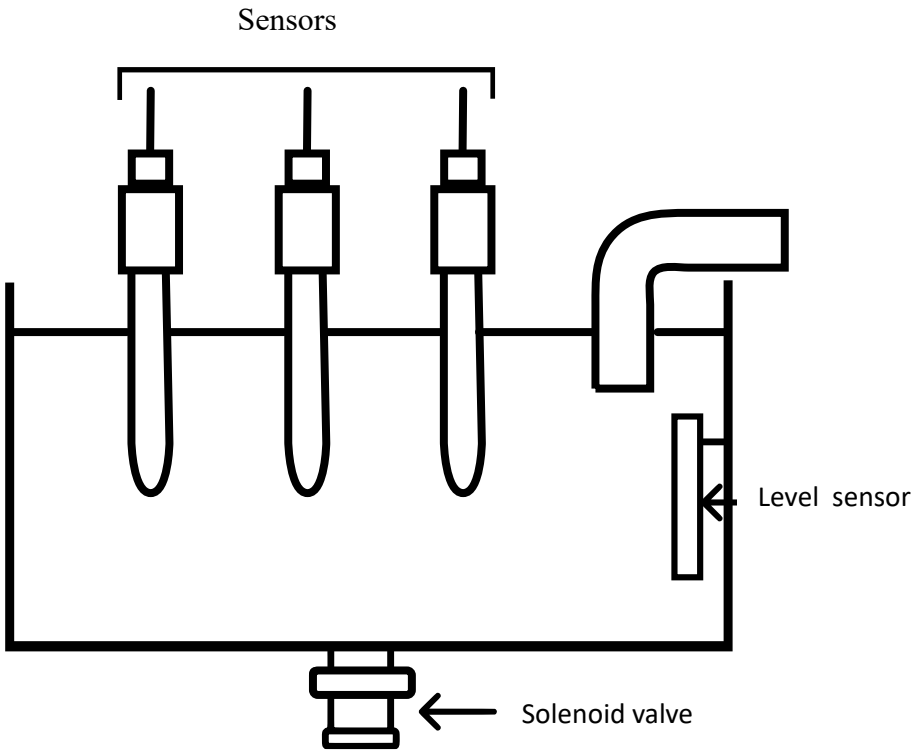


Figure III.2 Monitoring Pond Design

III.4.Architecture of the system

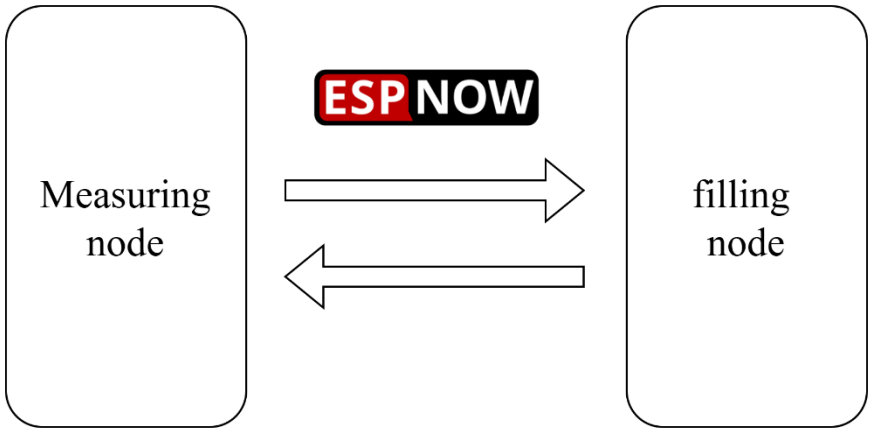


Figure III.3 Architecture of the system

This system is composed of two ESP32-based nodes communicating wirelessly via the ESP-NOW protocol:

III.4.1. Node 1 – monitoring node

Responsible for collecting data from various sensors such as PH, ORP, TDS, turbidity, dissolved oxygen, and temperature. It performs local data processing and sends measurement updates to the IoT platforms.

III.4.2. Node 2 – filling node

Acts as a remote actuator controller, receives from and sends to the node 1 data and orders. It activates solenoid valves and pumps to refill or drain the measuring pond. and equipped with a detector of water level.

III.5.Synoptic diagrams

III.5.1. Monitoring node

The monitoring node is designed to monitor water quality conditions within the aquaculture environment. It integrates multiple sensors to measure essential parameters such as pH, DO, temperature, turbidity, TDS, and ORP.

Built on the ESP32 platform, which has connectivity with Wi-Fi to send to the dataset each specific period of time, and gives us access to real-time monitoring and historical analysis.

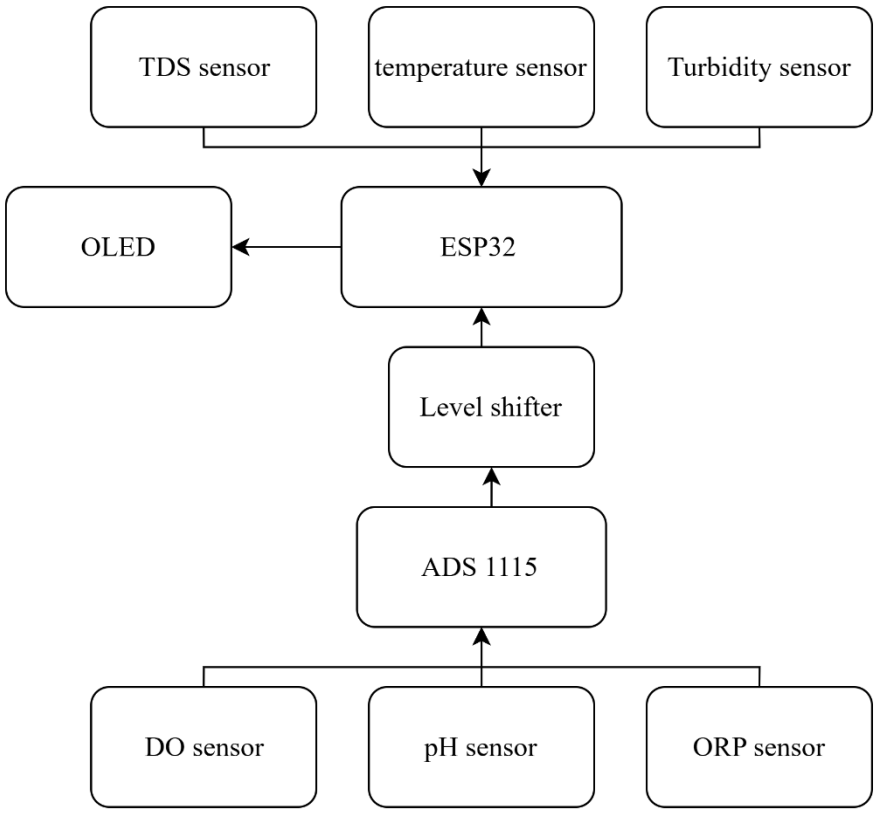


Figure III.4 Synoptic diagram of the monitoring Node

III.5.2. Filling node

The filling node is responsible for managing the controlled flow of water from the main source into the measurement chamber or basin. Its main function is to ensure that a precise and consistent volume of water is delivered for accurate sensor reading. Typically, the filling node includes a pump to draw water

In the filling node, three main components work together: a pump, an electrovalve, and a level sensor. The pump draws the water from the main source, such as a pond or tank, and pushes it toward the measurement chamber. The electrovalve regulates the flow by opening and closing once the desired level is reached. The level sensor monitors the water level inside and sends a signal when the target volume has been achieved. Together, these components ensure that the measurement chamber is consistently filled with the correct amount of water.

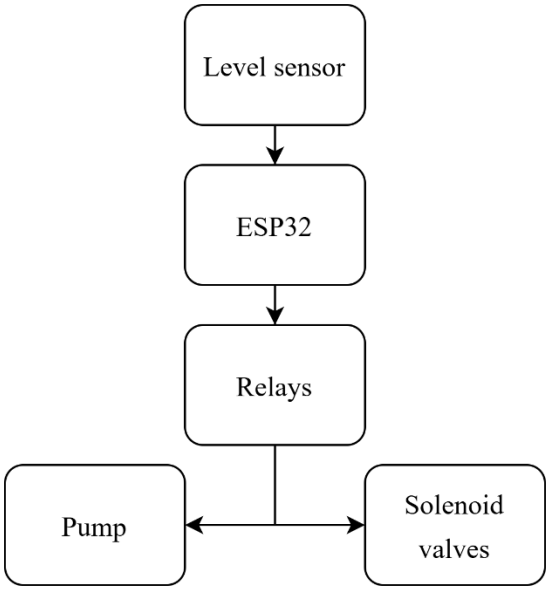


Figure III.5 Synoptic diagram of the filling node

III.6.Electrical diagram of the system

III.6.1. monitoring node

This figure represents the electrical diagram of the monitoring node. This node has an OLED display and 6 sensors to measure different parameters. The sensors that have an output of 5V, like pH, ORP, and DO, are wired with an external analog-to-digital conversion and a level shifter to ensure voltage compatibility between those sensors and the ESP32.The turbidity and TDS sensor linked with ADC input pins and the temperature sensor is wired to digital input pin.

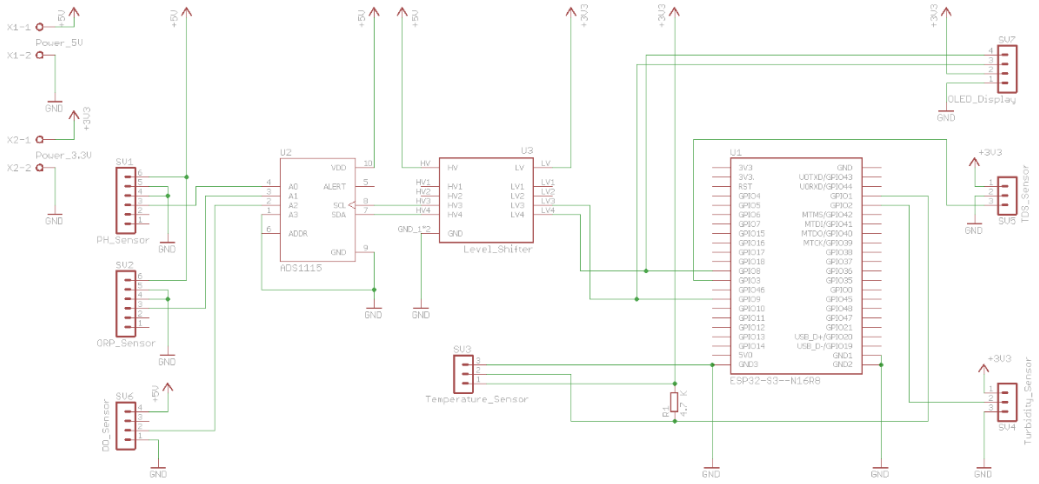


Figure III.6 Electrical scheme of the monitoring node

III.6.2. Filling node

This figure represents the electrical diagram of the filling node; this node has a level sensor wired with ESP32 S2 and has several relays to control the pumps and solenoid valve.

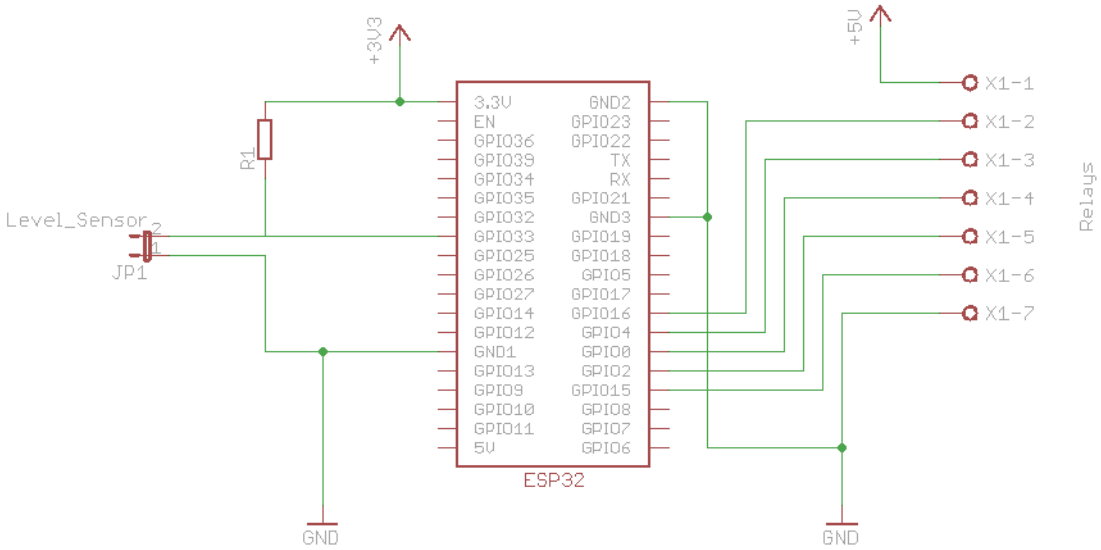


Figure III.7 Electrical scheme of the filling node

III.7.The system program diagram

III.7.1. Monitoring node diagram

This diagram represents the system functionality of the Monitoring node using ESP-NOW communication with the other node and sensor data transmission to ThingSpeak. The process begins with defining the necessary libraries and functions, followed by the initialization of the ESP-NOW protocol and the sensors. The system then enters a timed loop, where it checks if 1 hour has passed. If the condition is met, it sends a message to node 2. If a confirmation message is received, the node proceeds to read the sensor values. These values are then sent to the ThingSpeak platform

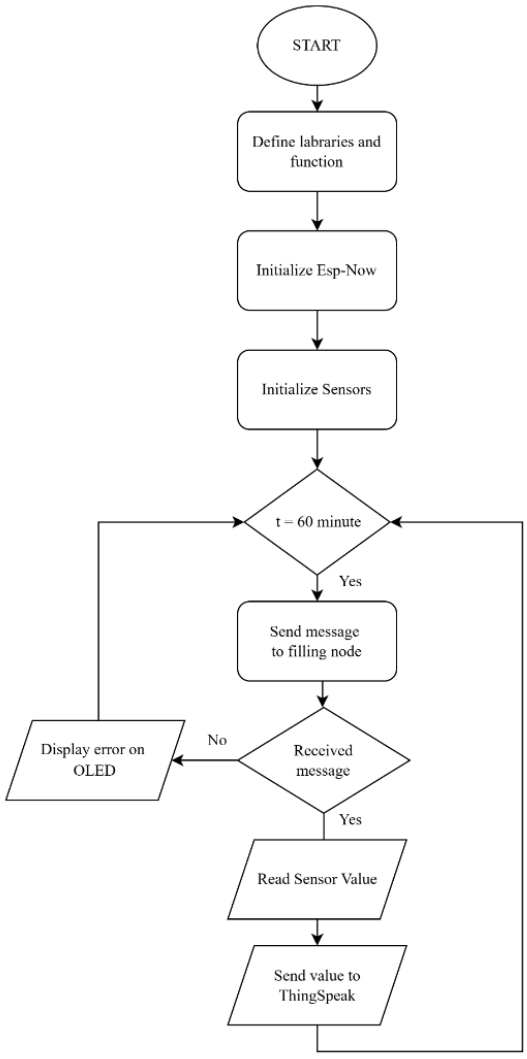


Figure III.8 Monitoring Node program Diagram

III.7.2. The filling node system

This diagram represents the system functionality of the filling system, beginning with the initialization of the essential libraries and functions. Following this, sensors are activated to monitor specific conditions (level). After that, the system then checks for a specific signal or data value, in this case, the "30" value. Upon receiving this value, the pond is filled with water. The system sends a signal labeled as "Send the value 50" and waits for 3 minutes. Then clean the pond with fresh water. Once these steps are complete, the process loops back to await the same data again.

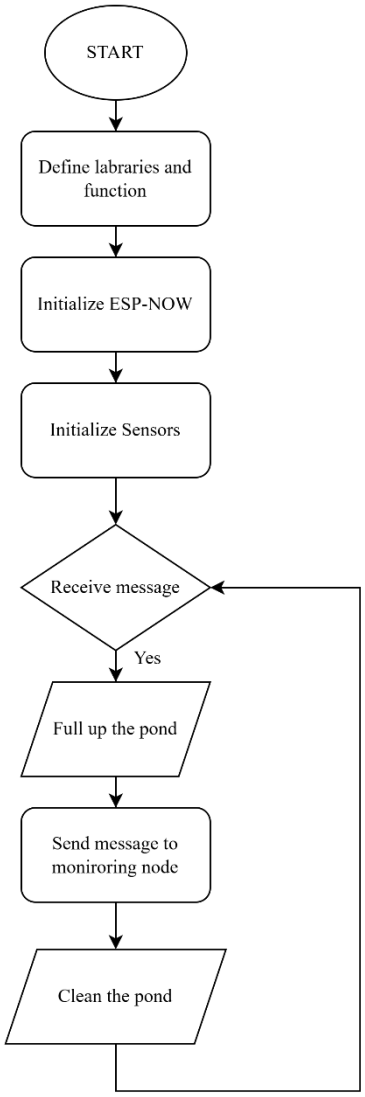


Figure III.9 The filling node program diagram

III.8.Communication protocols

III.8.1. MQTT

MQTT is a lightweight, publish-subscribe-based protocol. Devices send messages to the central hub, and others listen to these messages. It is highly efficient, making it ideal for low-power and low-bandwidth devices. One of the key features is its simplicity [76].

III.8.2. HTTP

HTTP is the foundational web protocol used in browsers and IoT for client-server communication via requests (GET/POST) and responses. It offers simplicity and broad compatibility but requires more bandwidth than lightweight alternatives like MQTT, making it better suited for connected devices than power-constrained ones [76].

III.8.3. CoAP

The CoAP protocol (Constrained Application Protocol) is a specialized web transfer protocol designed for resource-constrained devices in the Internet of Things. It enables low-power, limited-capability devices to communicate efficiently over the Internet while minimizing power consumption, bandwidth usage, and processing requirements. As a lightweight alternative to HTTP, CoAP maintains similar RESTful principles but is optimized for machine-to-machine (M2M) applications in constrained networks [76].

Table III.1 Communication Protocol

feature	MQTT	HTTP	CoAP
Protocol type	Publish-subscribe	Request-response	Request-response/ Publish-subscribe
Transport layer	TCP	TCP	UDP
Overhead	Low	High	Very low
Power consumption	Low	High	Very low
Latency	Low	moderate	Very low
Message size	Small (header as low as 2 bytes)	Large(headers+ metadata)	Very small
Use cases	IoT (sensors, real-time updates)	Web APIs, RESTful services	IoT

complexity	Moderate (need a broker)	High (stateless, many features)	Low (designed for constrained devices)

III.9.ThingSpeak

ThingSpeak is an advanced IoT platform that allows you to easily collect, store, analyze, and visualize data from sensors and devices. It provides a simple and intuitive interface for connecting your devices to the cloud and creating powerful applications with minimal coding required. ThingSpeak allows users to send data from their devices efficiently, offers immediate visualization of real-time data, and provides capabilities to set alerts [77].



Figure III.10 Thingspeak platform logo **[78]**

III.9.1. The key feature of ThingSpeak

Thingspeak offers real-time IoT data monitoring and analytics, featuring live data collection and storage, instant visualization through dynamic dashboards, and advanced MATLAB-powered processing for in-depth analytics. It supports custom alerts and notifications based on user-defined criteria, accommodates multiple data formats (CSV, JSON, etc.) and protocols (MQTT, HTTP, etc.), and seamlessly integrates with popular IoT platforms and devices. Additionally, it provides comprehensive APIs for customization and extensibility, making it a versatile solution for real-time data-driven applications [77].

III.9.2. Sending data to Thingspeak

Data can be sent to Thingpeak through three primary methods:

HTTP GET/POST requests: a straightforward way for devices to communicate and send data.

MQTT protocol: an efficient option, particularly suited for real-time applications and low-power devices.

Libraries: dedicated libraries for platforms like Arduino, Raspberry Pi, and esp32 simplify the process of transmitting data to Thingspeak.

III.9.3. User interface

ThingSpeak acts as the cloud service that receives, stores, and displays the water quality data sent from esp32 device. This enables remote access to sensor data through dashboards and supports data logging for analysis. It provides a simple interface and integrated visualization tools and streamlines data transfer via HTTP requests, and offers built-in visualization tools, making it ideal for monitoring aquaculture system parameters online.

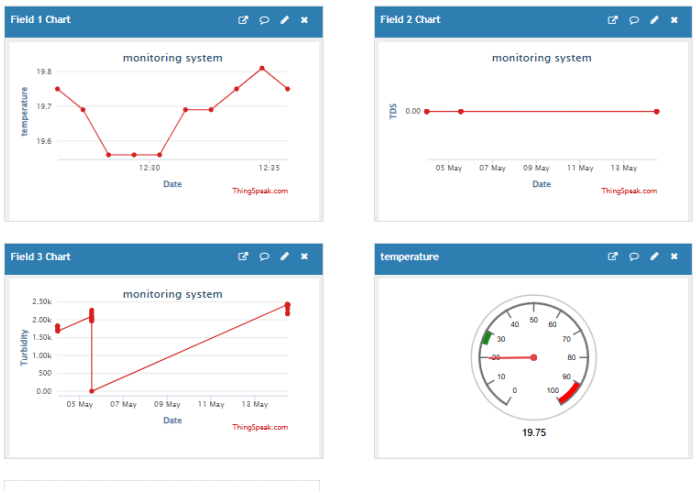


Figure III.11 User interface

III.10. ESP-NOW

ESP-NOW is a wireless communication protocol developed by Espressif, the company behind the ESP32 Microcontroller MCU. Designed for quick, low-power, and direct device-to-device communication without the need for a Wi-Fi, Wi-Fi router, or Internet connection. It is widely used in applications such as smart home appliances, and remote controls and Sensor networks [79].

ESP-NOW operates on the 2.4 GHZ Frequency band. However, instead of connecting through a router, Devices in an ESP-NOW network can communicate directly with each other.

In this so-called peer-to-peer network, devices must be paired by their MAC addresses. If one device in the network loses power, it will automatically reconnect if powered again .

Espressif simplified the communication process by merging the application, transport, and network layers of the traditional OSI model into a signal layer. Additionally, there is no need for Packet headers or unpackers at each layer, which leads to a quicker response and reduces the delay caused by packet loss in a congested network [80].

III.10.1. Communication protocol of ESP-NOW

ESP-NOW operates as a peer-to-peer (P2P) protocol, meaning it allows direct communication between two ESP8266 or ESP32 devices without the need for a central server or access point. Each ESP device has a unique MAC address, which is used to identify the receiving board.

III.10.1.1. One-way communication

In One-way communication mode, one device (the sender) can send data to another device (the receiver) without expecting a response. This mode is often used for scenarios where one device provides data or commands to another device, such as remote sensor readings or control commands [80].



Figure III.12 one-way communication of ESP-NOW **[81]**

III.10.1.2. Two-way communication

In two communication modes, both devices can exchange data bidirectionally. This mode enables a back-and-forth exchange of information between the devices, allowing for more

interactive and responsive communication. It's suitable for applications where devices need to send and receive data from each other, such as remote-control systems or interactive IOT devices [80].



Figure III.13 Two-way communication of ESP-NOW **[81]**

III.10.2. Key features of ESP-NOW

Low latency: ESP-NOW is designed to quickly transmit data, with very low response times.

Low power consumption: Since it does not require a full wi-fi connection, ESP-NOW consumes less energy, making it ideal for battery-powered devices.

Direct connection: Devices communicate directly with each other, without needing an access point or router.

Easy implementation**:** with libraries and examples provided by Espressif, it is easy to implement the ESP-NOW in ESP32 projects [82].

III.11.Interfacing a 5V sensor with ESP32

The ESP32 operates at a 3.3V logic level, whereas many sensors require a 5V power supply and communication voltage. Connecting them directly to ESP32 can damage the microcontroller. But extra steps can help avoid damage. This discrepancy necessitates careful consideration of voltage level shifting and integrity to ensure proper functionality and prevent damage to hardware.

There are several solutions available to safely connect a 5V. There are various solutions that exist to ensure safe communication, each tailored to different needs and signal types. These methods help regulate voltage levels, protect components, and maintain reliable data transmission.

III.11.1. How to connect a 5V sensor to ESP32

III.11.1.1. Voltage divider

A voltage divider uses two resistors to step down a 5V signal to a safe 3.3V level for the ESP32. The resistor creates a ratio that reduces the voltage based on the formula:

$$V_{out} = V_{in} * (R2 / (R1 + R2)) \quad \text{(III.1)}$$

This method is simple, affordable, and easy to use. However, it only works for one-way communication, may not handle fast signals well, and resistor tolerances can cause slight variations in output voltage. Making it unreliable for critical applications.

III.11.1.2. Logic level shifter

A dedicated logic level shifter IC or a MOSFET-based circuit converts voltages bidirectionally between 5V and 3.3V. this approach maintains signal integrity, making it effective for I2C, SPI, and UART communication. The main advantage is reliable bidirectional voltage conversion; its limitation is that it requires additional components, increasing complexity and cost compared to a simple resistor-based solution.

III.11.1.3. Zener diode with resistor

A 3.3V Zener diode, combined with a current-limiting resistor, can clamp voltage to prevent exceeding safe levels. When the voltage surpasses 3.3V, the diode conducts, keeping the ESP32 protected. This method is simple and provides basic overvoltage protection. However, its limitation is that it does not precisely regulate voltages, making it less effective for accurate signal processing.

III.11.2. Safe and efficient methods to interface 5V sensors with ESP32

One innovative method for interfacing a 5V sensor with an ESP32 is using ESP32 with ADS1115 and a level shifter to ensure accurate analog-to-digital conversion while maintaining proper voltage compatibility. The ADS1115, a 16-bit ADC, converts analog signals from sensors into digital values and communicates with the ESP32 via I2C (SDA and SCL pins). Since the ESP32 operates at 3.3V logic, but the ADS1115 can be powered at 5V, a level shifter is required to safely translate voltage levels to convert 5V signals from the ADS1115 to 3.3V for the ESP32. this ensures stable communication without damaging components.

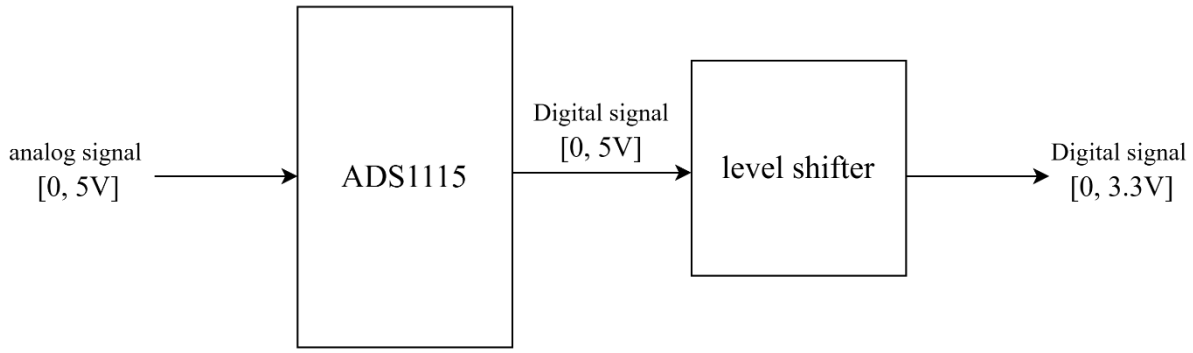


Figure III.14 Interfacing 5V sensor with ESP32

III.12. Calibration

III.12.1. PH Sensor calibration

To make sure the PH-4502 sensor board with the ESP32 gives reliable PH readings, you need to establish the right voltage offset.

III.12.2. Offset adjustment

In order to establish the neutral PH baseline. First, remove the pH probe from the BNC and short-circuit the BNC. Next, measure the voltage at the sensor module's P0 using a multimeter and adjust the POT 1 (the offset potentiometer) until it reaches 2.05V to ensure precise calibration. This change centers the sensor output so that pH 7 equals the midway voltage [83] .



Figure III.15 BNC Connector for pH Sensor Interface **[84]**

III.12.3. Two-Point calibration using buffer solutions

Firstly, rinse the probe with distilled water, then immerse it in a pH 7.0 buffer solution and wait for the reading to stabilize. The ESP32 input read close to 2.5V. Next, rinse the probe again and immerse it in a second buffer solution, typically at pH 4.0 or pH 10.0, and record the voltage reading at this point [83].



Figure III.16 Premade buffer solution for pH sensor

Calculate the slope (m) of the voltage to PH conversion using the formula:

$$\mathbf{m} = \frac{7 - PH\ buffer}{2.5 - V\ buffer} \qquad \textbf{(III.2)}$$

use this slope in ESP32 code to convert voltage to pH with this formula, which compensates for sensor sensitivity and non-idealities to provide accurate PH measurement:

$$\mathbf{PH = 7 - (2.5 - Vmesured) * m} \qquad \textbf{(III.3)}$$

The calibration process for the PH-4502 sensor using the ESP entails the adjustment of a suitable voltage offset to ensure precise PH readings. Generally, the sensor board generates a voltage that correlates with the pH level, where a PH of 0 equates to 0V and a PH of 14 corresponds to 5V.

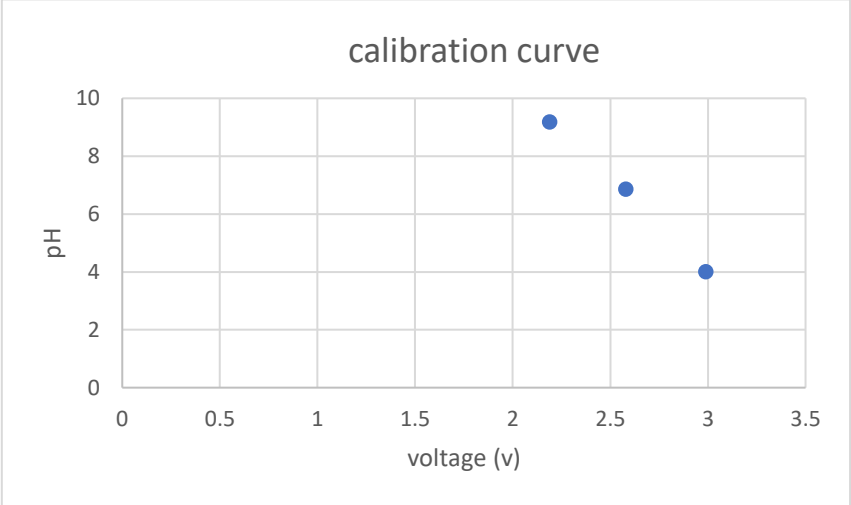


Figure III.17 calibration curve of pH sensor

$$m=\frac{2.99-2.58}{4.01-6.68} = -0.15 \quad \text{(III.4)}$$

III.12.4. TDS sensor calibration

TDS sensors are critical for water quality monitoring in applications ranging from hydroponics to industrial process control. Calibration ensures accurate readings by aligning sensor output with known reference solutions.

This report provides a detailed methodology for calibrating TDS sensors using the ESP32 microcontroller, integrating hardware configuration, software adjustments, and environmental compensation techniques.

To calibrate the TDS sensor, use a commercial standard TDS calibration solution with a known value (commonly between 90 ppm and 1000 ppm) at around 25°C for best accuracy. Then rinse and dry the TDS sensor probe to remove any contamination or residues that can affect readings, place the sensor probe into the calibration solution, and wait for 10 seconds for the readings to stabilize.

The conversion from voltages to TDS (ppm) is calculated using the formula:

$$\text{TDS= K*V comp * 1000} \quad \text{(III.5)}$$

Where K is a calibration factor determined during calibration, and Vcomp is the temperature-compensated voltage.

Temperature compensation is applied by adjusting the voltage with the equation:

$$\text{Vcomp} = \frac{V}{1+a\,(T-25)} \qquad \text{(III.6)}$$

Where a is the temperature coefficient and T is the current water temperature in Celsius. This correction normalizes the measurement to a standard temperature of 25°C, improving the accuracy of TDS readings under different temperature conditions.

III.12.5. ORP sensor calibration

To calibrate an ORP sensor, first power it on and allow it to stabilize for about 5 to 10 minutes. Rinse the probe with distilled water, then place it in a standard ORP calibration solution (typically 225 mV). Once the reading stabilizes, compare the measured value to the known reference. If there is a difference, calculate the offset by subtracting the measured value from the reference value, and apply this correction in the code or in the system.

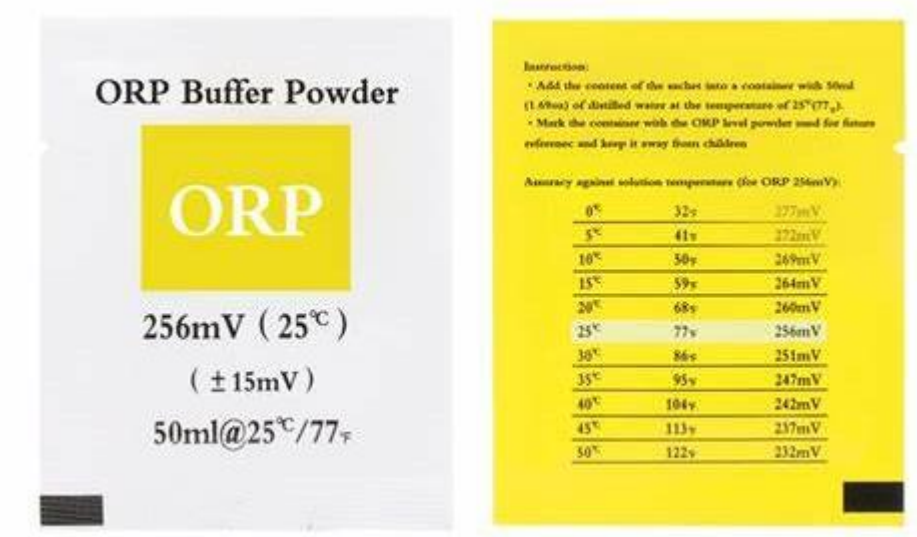


Figure III.18 Premade buffer solution for ORP sensor **[85]**

III.12.6. Turbidity sensor calibration

The calibration procedure for the TS-300B turbidity sensor involves using a 0 NTU standard solution (purified or distilled water) to establish a baseline. It is important to ensure that no air bubbles are present on the sensor surface during the calibration, as the bubbles can interfere

with the light path and affect the reading. The sensor should be rinsed with distilled water before and after calibration to remove any contamination that might skew results. The TS-300B does not feature an automatic calibration mode, so calibration adjustment must be performed in the software by mapping the sensor's voltage output to the known NTU value of the calibration solution. For more precise calibration, additional standard solutions with known NTU values, such as 10 NTU or 100 NTU, can be used to create a multi-point calibration curve.

Table III.2 Turbidity sensor calibration

	Turbidity value (NTU)	Output voltage (v)
Clean water	0	1.88
Dirty water	100	0

We performed linear regression on the collected data to determine the best-fitting line. The resulting equation expresses the relationship as:

$$V = m * turbidity + b \quad \text{(III.7)}$$

We use the two-point method to calculate the slope m and intercept b:

$$m=\frac{V2-V1}{turbidity1-turbidity2} = -0.018 \quad \text{(III.8)}$$

$$b= V1 - m * turbidity1 = 1.8 \quad \text{(III.9)}$$

The equation is:

$$V = -0.018 * turbidity + 1.8 \quad \text{(III.10)}$$

III.13. Tests and results

To evaluate the performance and accuracy of the designed water quality monitoring system, a series of tests were conducted using real water samples.

The primary objective was to assess the system's ability to reliably measure key water quality parameters, including temperature, TDS, turbidity, pH, and ORP.

III.13.1. Temperature measurement

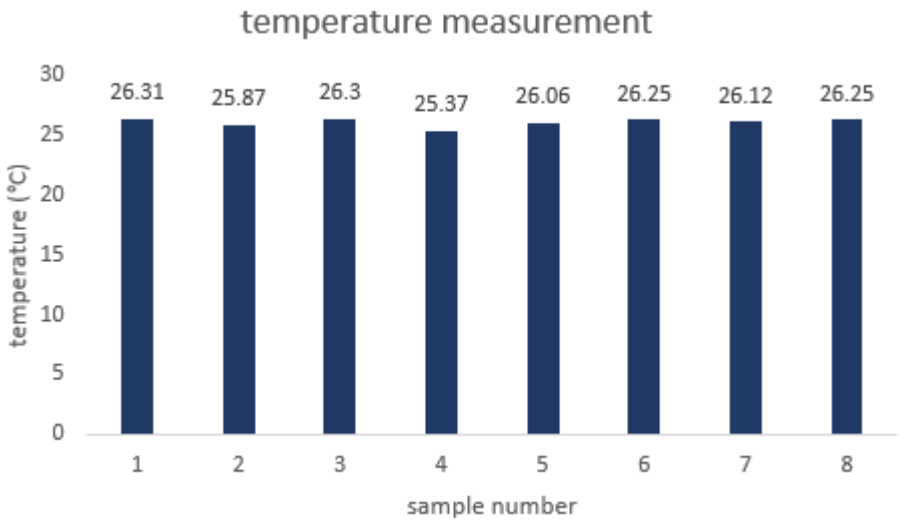


Figure III.19 Temperature measurement on different samples

Figure III.19 represents bar charts showing temperature readings for 8 samples, with a noticeable trend. The temperature ranges from 24.8 to 26.4, and we notice the temperature varying from one sample to another. The highest temperature is recorded at sample 1, which is 26.31 °C, and the lowest temperature is recorded at sample 4, which is 25.37.

III.13.2. pH measurement

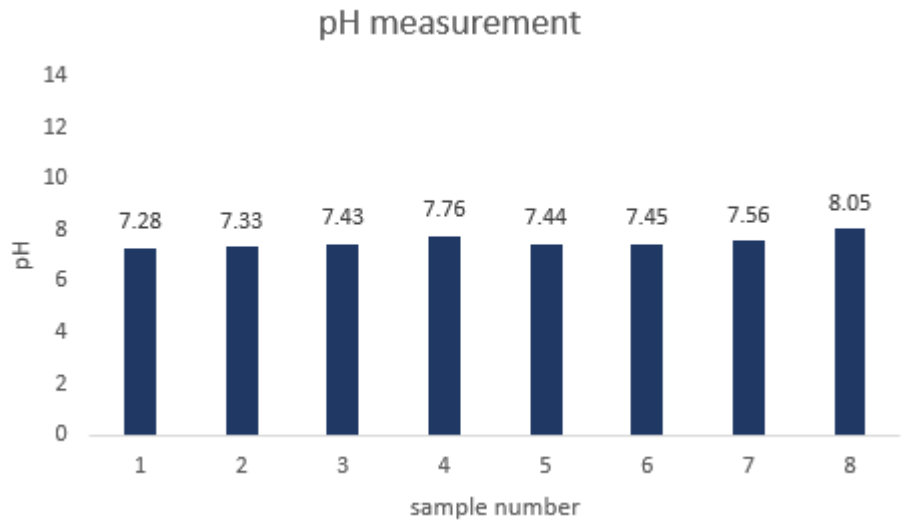


Figure III.20 pH measurement on different samples

Figure III.20 represents bar charts showing pH values recorded for 8 different samples. The pH values range from 7.28 to 8.05. A clear observation from the bars is the significant variability in pH across the samples.

Sample 1 shows the lowest pH, which is 7.28, indicating a neutral value, and sample 8 shows the highest pH, which is 8.05, indicating an acidic value. Samples 2, 3, 4, 5, 6, and 7 appear to be neutral.

III.13.3. ORP measurement

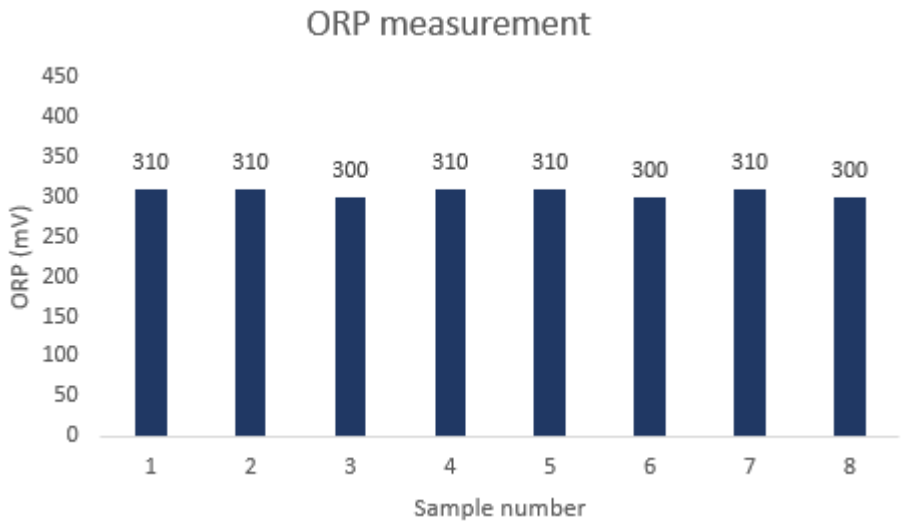


Figure III.21 ORP measurement on different samples

Figure III.21 depicts a bar chart representing the ORP of different samples. The ORP values range from 0.30 to 0.31. This range indicates remarkable stability and uniformity in ORP across all samples. An ORP value in this range (equivalent to 300-310 mV) generally suggests an oxidizing environment.

III.13.4. TDS measurement

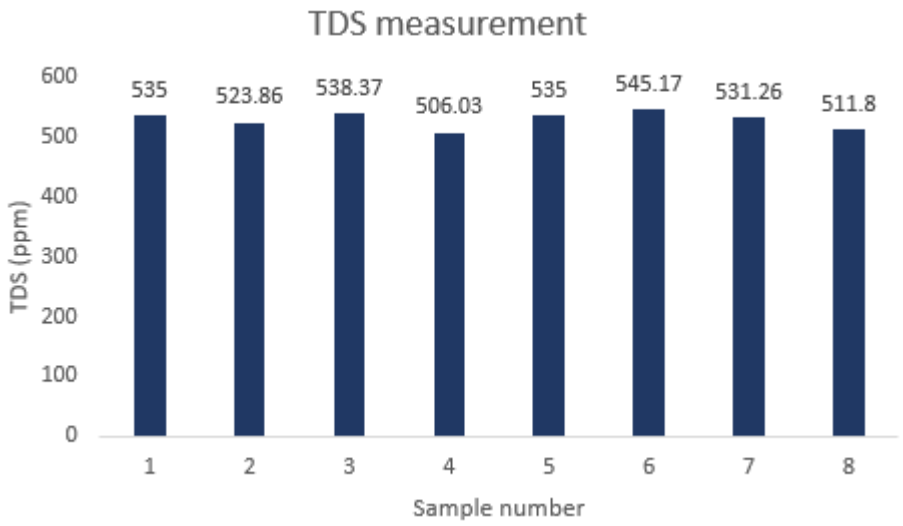


Figure III.22 TDS measurement on different samples

The Figure III.22 represents a bar chart, illustrating the TDS measurement recorded for for eight samples, showing a consistent range of values from 506 ppm to 545 ppm. The highest TDS value is recorded at sample 6, which is 545.17 ppm, and the lowest temperature is recorded at sample 4, which is 506.03 ppm.

With an overall TDS level above 500 ppm, a moderately high concentration of dissolved solids is indicated.

III.13.5. Turbidity measurement

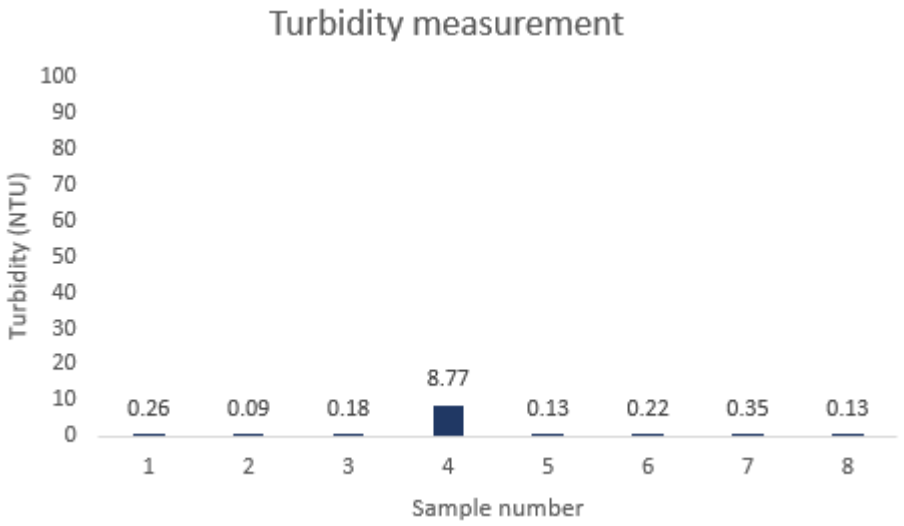


Figure III.23 Turbidity measurement on different samples

Figure III.23 represents turbidity measurements for eight samples; the bars show very low levels of turbidity, ranging from 0.09 NTU to 0.26 NTU. Since 0 NTU indicates very clear water, and 100 NTU represents polluted water.

This narrow range indicates that all samples exhibit excellent clarity and very low suspended solids content, while the values are all well within acceptable limits for many applications.

III.14.Conclusion

This chapter presented a comprehensive overview of the proposed system, detailing the integration of sensors with ESP32, including the analysis of sensor operation, calibration procedures, testing, and results.

General conclusion

General conclusion

In this thesis, we have targeted the aquaculture farms of tilapia and their water conditions.

We focused on the practical implementation of an automated water quality monitoring system. through the integration of ESP32, a variety of sensors (pH, ORP, TDS, etc.), and wireless communication protocols like ESP-NOW, the system achieved robust, real-time monitoring.

The system architecture, consisting of a monitoring node and a filling node, enables autonomous basin control without human intervention

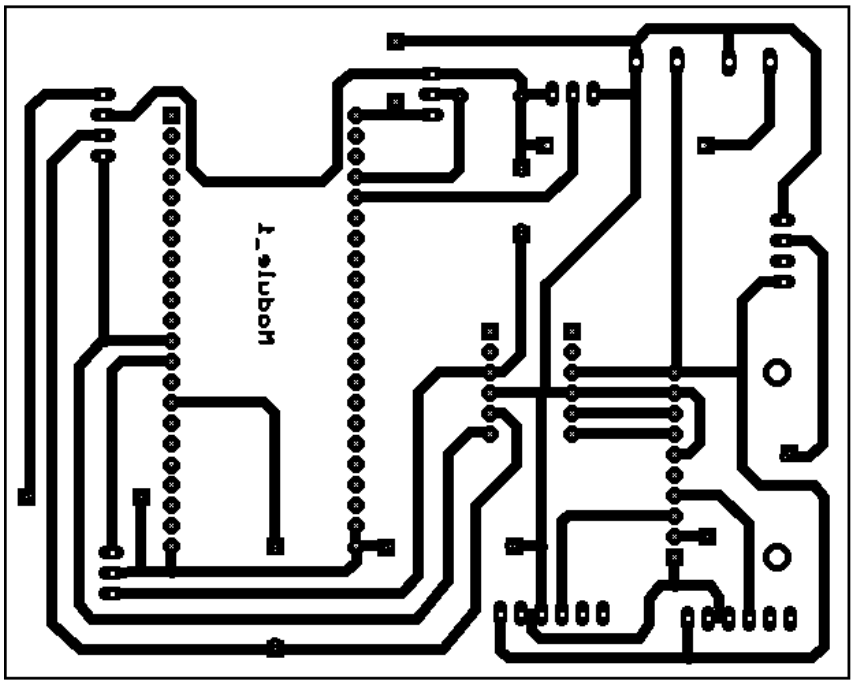
Calibration procedures for each sensor were carefully performed to ensure accurate readings. The data acquisition and communication processes were successfully managed using ThingSpeak and ESP-NOW.

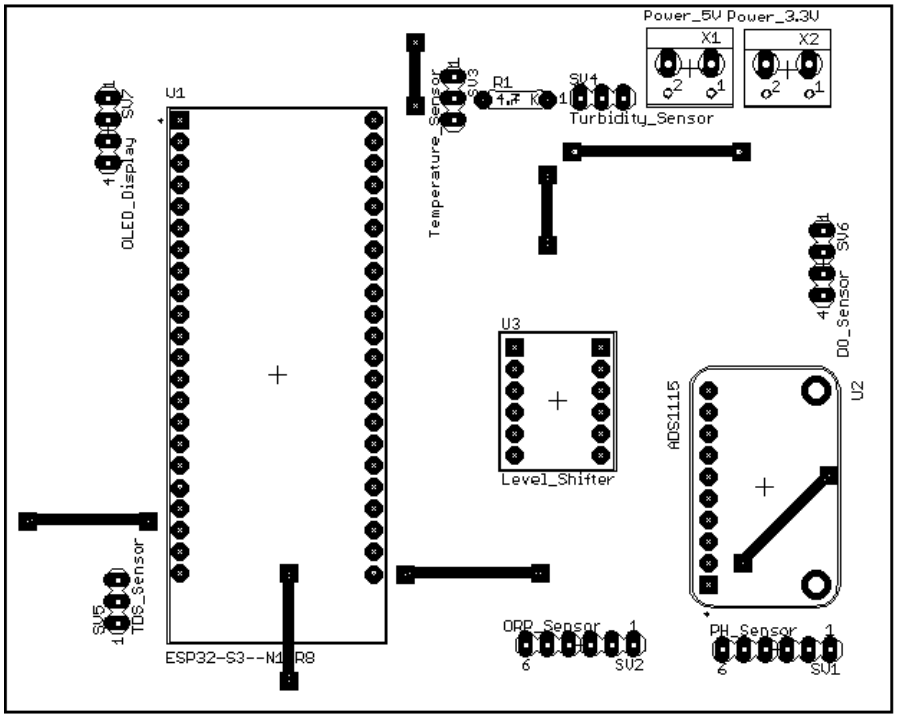
Testing with real water samples validated the system's ability to track essential water quality parameters with consistent accuracy. Variation observed across samples confirmed the sensor's responsiveness and the system's practical utility in monitoring a dynamic aquatic environment.

Overall, the developed system proves to be an effective and scalable solution for smart aquaculture applications, combining real-time monitoring, remote control, and reliable performance using open-source hardware and software.

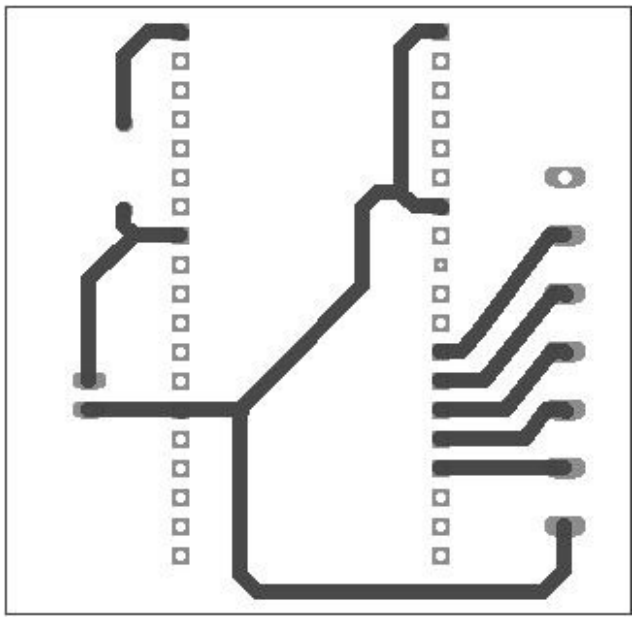
Annexe

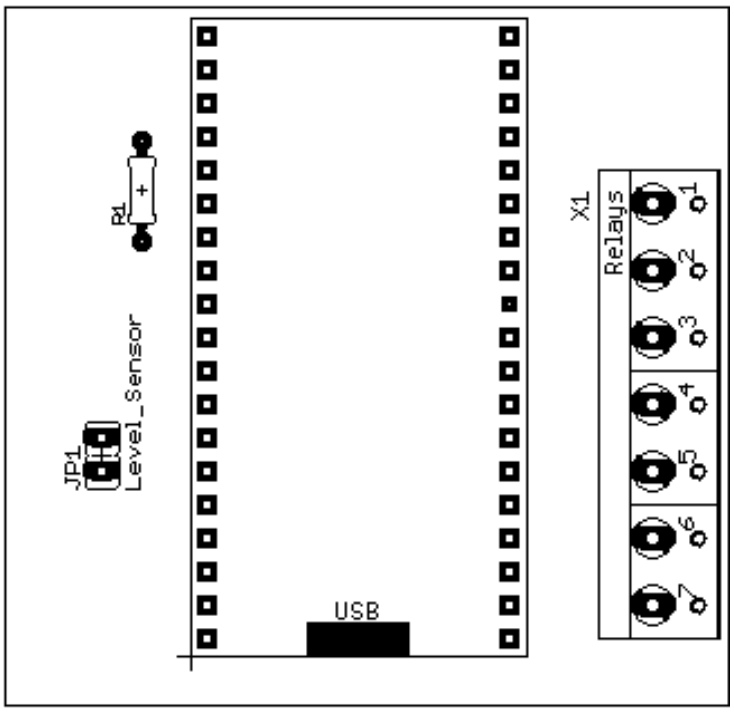
Monitoring node PCB / Circuit





Filling node PCB / Circuit





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