Universidade Fernando Pessoa

IoT architecture for sustainable monitoring and management of smart aquaponics systems in urban environments

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Abstract

Aquaponic systems provide a sustainable combination of fish and vegetable farming, i.e., join fishes in tanks (aquaculture) together with growing plants without soil (hydroponics). Fishes provide natural water fertilisation for the plants, and plants help purify the water for fishes. Aquaponic systems are therefore sustainable solutions to provide fresh fish and vegetables to families, communities or even be explored as future enterprise businesses in any climate.

Aquaponic farming systems take advantage of the symbiosis between fishes and vegetables, thus becoming more sustainable and allowing to grow more food with less water, land, and labor than traditional agriculture. However, one of the problems in aquaponic systems is the presence of high levels of ammonia that is toxic to most fish. For this reason, it is essential to measure the levels of ammonia weekly.

The IoT system presented in this research provides an intelligent way to measure the toxicity of the ammonia in an aquaponics system, as a function of the ammonia concentration and the pH present in the system. The proposed solution combines the use of colorimetric tests commonly used in the measurement of ammonia, with computer vision and pH sensors, to automate the detection of information about the toxicity of the ammonia in water samples. The developed solution was also integrated in an IoT Cloud Computing architecture for supporting the autonomous management of aquaponics systems and their sustainable use in urban environments.

Resumo

Os sistemas aquapónicos proporcionam uma combinação sustentável de piscicultura e horticultura, ou seja, juntam peixes em tanques (aquacultura) com plantas em crescimento sem solo (hidroponia). Os peixes fornecem fertilização natural da água para as plantas, e as plantas ajudam a purificar a água para os peixes. Os sistemas aquapónicos são, portanto, soluções sustentáveis para fornecer peixe fresco e legumes a famílias, comunidades ou mesmo para serem explorados como futuros negócios empresariais em qualquer clima.

Os sistemas agrícolas aquapónicos aproveitam a simbiose entre peixe e legumes, tornando-se assim mais sustentáveis e permitindo cultivar mais alimentos com menos água, terra e mão-de-obra do que a agricultura tradicional. No entanto, um dos problemas nos sistemas aquapónicos é a presença de elevados níveis de amónia que é tóxico para a maioria dos peixes. Por esta razão, é essencial medir semanalmente os níveis de amónia.

O sistema IoT apresentado nesta pesquisa fornece uma forma inteligente de medir a toxicidade da água num sistema aquapónico, em função da concentração de amónia e do pH presente no sistema. A solução proposta combina a utilização de testes colorimétricos comummente utilizados na medição da amónia, com visão por computador e sensores de pH, para automatizar a deteção de informação sobre a toxicidade da amónia em amostras de água. A solução desenvolvida foi também integrada numa arquitetura de Computação em *cloud* IoT para apoiar a gestão autónoma de sistemas aquapónicos e a sua utilização sustentável em ambientes urbanos.

I want to dedicate this dissertation with the utmost love to my parents for all of their unwavering support and for giving me the chance to get both my bachelor’s and master’s degrees.

I would especially like to thank my brother, and girlfriend who supported and encouraged me throughout my entire academic journey and continuously gave me the energy to continually strive for more and never give up on my dreams.

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List of Acronyms

ADC	*Analog-to-Digital Conversion*	22
API	*Application Programming Interface*	1
CV	*Computer Vision*	1
DO	*Dissolved Oxygen*	9
GPIO	*General Purpose Input/Output*	28
GSM	*Global System for Mobile communication*	8
GUI	*Graphical User Interface*	7
IoT	*Internet of Things*	9
ISE	*Ion-Selective Electrode*	11
JWT	*JSON Web Tokens*	25
LED	*Light Emitting Diode*	7
LCD	*Liquid Crystal Display*	8
PPM	*Parts Per Million*	16
RGB	*Red Green Blue*	14
SEM	*Scanning electron microscope*	14
SMS	*Short Message Service*	7
SBC	*Single-board Computer*	1
TAN	*Total Ammonia Nitrogen*	1

Chapter 1

Introduction

Aquaponics results from the combination of aquaculture (the raising of fish in ponds) and hydroponics (growing plants without soil), linked by a system of water recirculation. Aquaponics systems are a sustainable solutions to provide fresh fish and vegetables to families, communities or even be explored as future enterprise businesses in any climate. Our current food production needs to expand and intensify due to the continual increase in global population (Munguia-Fragozo et al., 2015). Aquaponics systems could help mitigate this problem.

One of the problems in an aquaponics system is the presence of ammonia, which, even in small amounts, is toxic to most fish (Nelson, 2008). This way it is a necessity to monitor ammonium levels periodically (Sallenave, 2016).

Ammonia can interfere on the central nervous system of fish, which, depending on the concentration, can lead to effects such as hyperventilation, hyperexcitability, loss of balance, convulsions, coma, and death (Levit et al., 2010).

Ammonia in water exists as two compounds: ionized (NH_4^+) and un-ionized (NH_3) ammonia. The relative concentration of the two forms of ammonia is primarily a function of water pH (see Figure 1.1). The sum of NH_4^+ and NH_3 is called the *Total Ammonia Nitrogen* (TAN) or simply ammonia.

In this context, the field of aquaponics is increasingly being researched in order to improve the systems autonomy. The technology takes advantage of its potential to automate aquaponics systems, both to measure their quality and to detect possible disturbances and act upon them.

The proposed system was developed to monitor the toxicity of the ammonia present in an aquaponics system. For this purpose, a *Single-board Computer* (SBC) with an *Application Programming Interface* (API) combined with *Computer Vision* (CV) was used. Moreover, an SBC camera is added to capture a photograph of the colorimetric test result. We also use a light source to illuminate the system, and a pH sensor to read the pH value of the system.

The monitoring API analyzes parameters of ammonia concentration based on the pho-

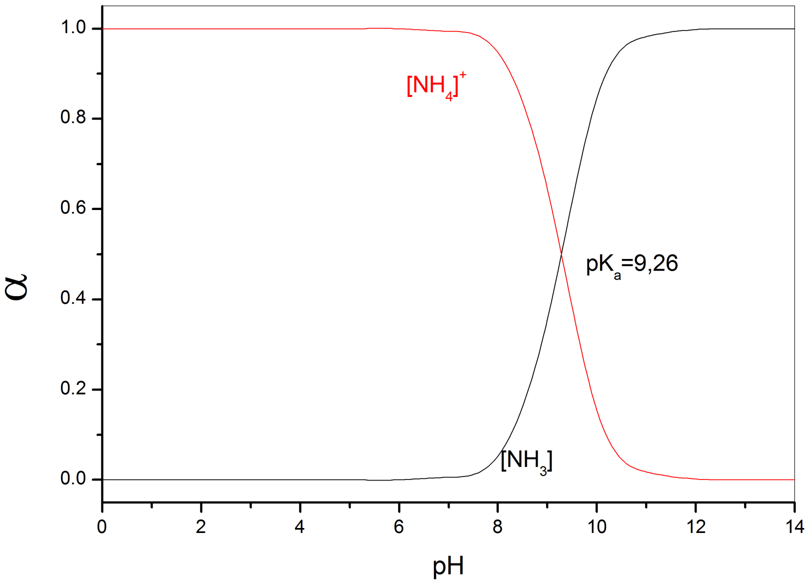


Figure 1.1: Balance of NH_4^+ and NH_3 (Fernandes, 2015)

tograph, containing the result of the colorimetric test, and the pH level in the system. Considering these parameters, it is possible to identify the toxicity of the ammonia present in an aquaponics system. If the ammonia concentration is indeed toxic to most fish, a warning will be sent to the user. With these warnings the user will be able to act and lower the toxicity of the ammonia present in the system.

1.1 Motivation

Aquaponics systems represents a way to produce food self-sufficiently. This area has had exponential growth (Bruce, 2021). Thus, it is a necessity to improve these systems and make them more independent and autonomous, i.e., without human interaction. As referred before, one of the major problems in aquaponics systems is the ammonia. Currently, the most common way to measure the concentration of ammonia present in the system is using a colorimetric test, which consists of applying reagents to a collected sample of the water and comparing the colour that resulted from the test with a colour palette (see Figure 1.2).

This colour palette (see Figure 1.2) contains the possible ammonia concentrations that the test can detect and their respective colours. Despite the clear utility of the colorimetric test, inconvenience issues are present. These consist on the user having to manually repeat the test each time it is desired to know the ammonia concentration present on the system. This reason motivated us to develop a device capable of evaluating the ammonia

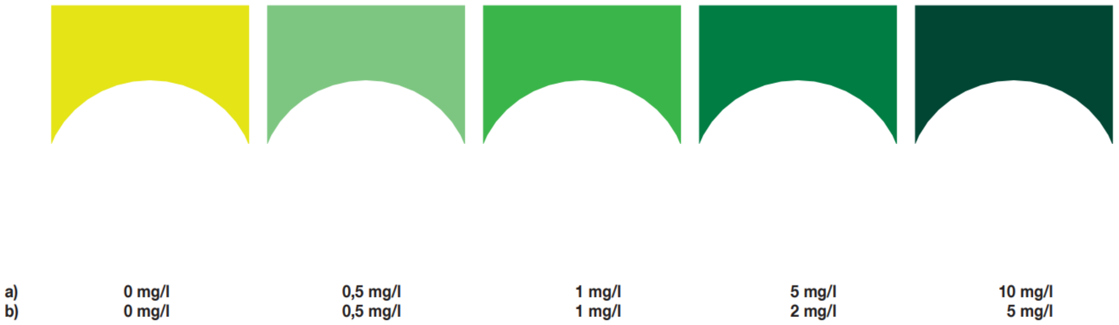


Figure 1.2: Colour palette, source: (sera GmbH, 2018)

concentration autonomously.

Another problem arises when a person suffering from color blindness, such as myself, tries to perform the colorimetric test, since it relies on our visual perception to compare and identify colors.

Our major motivation consists of developing a system accessible to anyone to monitor the ammonia concentration in an aquaponics systems.

1.2 Problem approach

Studying various ammonia monitoring techniques, it was possible to conclude that most solutions based their implementation using colorimetric tests.

This project intends to use a low-cost SBC, more specifically a Raspberry Pi Zero W, a camera, colorimetric tests and a pH sensor. The possibility of detecting the ammonia concentration presented in the system was researched through a picture. This contains the result of the colorimetric test, captured by a camera connected to an SBC.

This project brings together the following two modules: colour detection, and pH measurement (see Figure 1.3).

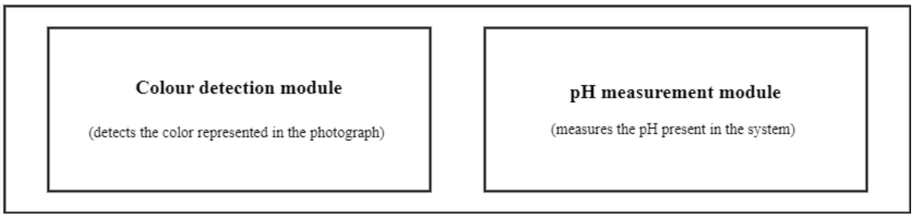
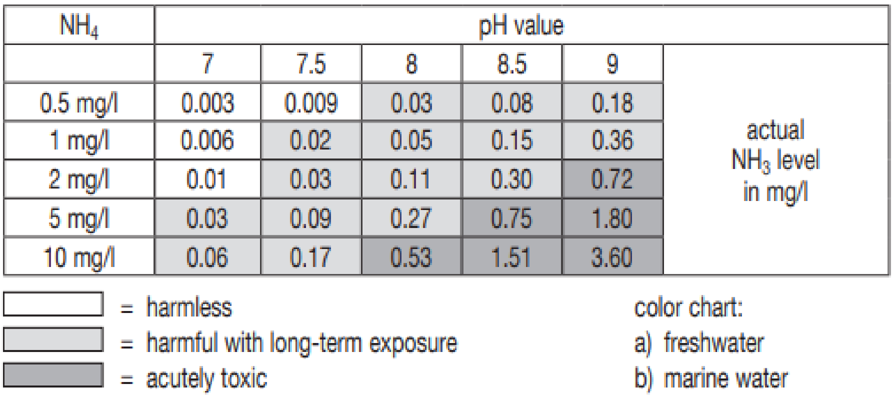


Figure 1.3: System modules

The presented system considers three possible states: harmless, harmful with long-term exposure or acutely toxic. Based on the result returned by the colorimetric test, it is possible to determine the ammonia concentration. Cross-referencing the ammonia concentration with the pH value present in the system, it is feasible to obtain the TAN and ammonia toxicity. The classification of the ammonia toxicity based on these two parameters is given by the colorimetric test result presented in the table 1.4.



NH_4	pH value					
	7	7.5	8	8.5	9	
0.5 mg/l	0.003	0.009	0.03	0.08	0.18	actual NH_3 level in mg/l
1 mg/l	0.006	0.02	0.05	0.15	0.36	
2 mg/l	0.01	0.03	0.11	0.30	0.72	
5 mg/l	0.03	0.09	0.27	0.75	1.80	
10 mg/l	0.06	0.17	0.53	1.51	3.60	

☐ = harmless
▨ = harmful with long-term exposure
■ = acutely toxic

color chart:
a) freshwater
b) marine water

Figure 1.4: Ammonia toxicity, source: (sera GmbH, 2018)

These modules allow obtaining information about the aquaponics system, with the measurement of certain parameters. The response of each of these modules is essential to find out the ammonia toxicity.

1.3 Objectives

The goal to be achieved with the development of the proposed work is to combine the use of colorimetric tests commonly used in ammonia measurement, with CV algorithms and pH sensors, to automate the ammonia concentration measurement in water samples from an aquaponics system, thus identifying the level of toxicity it presents to the system.

The camera connected to the SBC should capture a picture of the result of the colorimetric test specifically capturing it colour. The captured images will serve to detect the ammonia concentration and the pH sensor will obtain the pH value present in the system. The pH sensor must be in contact with the water of the aquarium or a sample of it. It is important to obtain both of these results since the ammonia toxicity depends on both of them. Finally, the system saves all these records which may be later consulted.

1.4 Document structure

This dissertation is organized into six chapters:

- **Chapter 1**: Introduction and description of the project's theme, the objectives, and the motivation.
- **Chapter 2**: Presentation of the developed ammonia monitoring. At the end of this chapter, a table comparing the systems discussed is presented.

- **Chapter 3**: This chapter lists the system requirements and the technologies used. It also depicts the system architecture that contains the flows of each of the modules.
- **Chapter 4**: This chapter describes the API and Cloud infrastructure developed for the system, divided into CV algorithms, light sources and equipment. This chapter extensively describes each of the modules developed.
- **Chapter 5**: This chapter evaluates the system in terms of its efficiency and analyse the obtained results.
- **Chapter 6**: Final remarks of the project are presented in this chapter, as well as the future work that can be carried out to improve the system's performance.

Chapter 2

Technologies for Intelligent Aquaponics Systems and Ammonia Measuring

The field of study and monitoring of aquaponics systems through technologies is currently a field that has been gaining interest. There are several systems and techniques for improving, obtaining information about, and acting on aquaponics systems. These can range from intelligent aquaponics systems that help with most of the parameters needed to sustain them, to systems that are designed to help certain parameters in particular, such as the ammonia problem.

This chapter describes various approaches studied for intelligent aquaponics systems and ammonia measuring. These presented approaches are divided into two branches for the development of the presented system: i) approaches that help with most of the parameters needed to sustain an aquaponics systems, and ii) approaches with greater focus on ammonia measuring.

Finally, a comparative analysis table of various parameters of all the papers discussed is presented.

2.1 Studies in intelligent aquaponics systems

Currently, this field of study has been gaining interest over the time. Most studies have a varying amount of sensors that read various values from the aquaponics system. With these, it is possible to have a dashboard containing most of the necessary information about the system.

Huang et al. evaluate the water quality and farming growth benefits of an intelligent aquaponics system (Huang et al., 2021). The time frame used in order to evaluate each aquaponics system was one year. The conclusion reached was that by using the aquaponics system, the water quality is improved, vegetables or flowers can grow quickly, and green energy can be used to automatically water plants and turn the nutrients in the water into fertilizer. Despite being simple, the circular farming facility provides valuable information. It gives people a new option for arable land while also conserving energy and preventing water pollution.

Vernandhes et al. developed a system that composed of a *Smart Growbox* containing sensor and actuators (Vernandhes et al., 2017). The sensors used in this system were: a temperature humidity sensor, and a soil moisture sensor. The actuators used were: two exhaust fan DC 12V, one mist maker, a 5V dc fan, two *Light Emitting Diode* (LED) Grow Light lamps and a 12V DC pump. A mobile application was developed to give the user access to the output of the sensors and control of the various actuators. An *Auto Mode* was also developed, which would turn the system into control, meaning that the system based on the sensor output would automatically take actions with the actuators. Despite this, the present system fails in certain parameters, such as analyzing the water quality.

Kyaw and Ng have also developed a system that contains sensors and actuators (Kyaw and Ng, 2017). The sensors used were: a water temperature sensor, a water flow sensor, a digital light sensor, a pH sensor and an ultrasonic ranger sensor. For the actuators they used: an alarm unit, a water heater, a secondary water pump, an LED grow light, and a fish feeder. A mobile app, web app and cloud server have been created for the user's convenience, this way it is possible for the user to control all the actuators manually, even though the system does it automatically. He is also be able to see all the sensors output. The system also sends a *Short Message Service* (SMS) warning, email, and push notification to the user if the system has any faults. Although this system contains more sensors and actuators and warns the user in case something fails, in terms of water quality analysis only the pH value is read. There are still some parameters that need to be improved, such as reading the ammonia values.

Jie Ong et al. developed a smart outdoor aquaponics system consisted on sensors and an actuators (Jie Ong et al., 2019). The used sensors are: a digital light, an ultrasonic, an air temperature and humidity, an electrical conductive and pH sensor. These are connected to an Arduino microcontroller unit in order to acquire environmental climate and water quality data of the system. Depending on the data collected by the sensor, actuators such as fish feeder, water heater and grow lights, were activated or deactivated. An alert and notification system, via SMS and e-mail, was also developed with the purpose of warning the user when the system enters in an unhealthy state. To complement the alert system, a presence of a visual warning, an LED, is present. This LED presents the green color when the system is healthy and a red color when it is not. In conjunction with the LED and the alert system, there is also a buzzer. It is also activated when the system enters the unhealthy state. In order to ensure user-convenience, a central control and processing unit was created where it is possible to analyse all sensors outputs in a web or desktop *Graphical User Interface* (GUI). It is also possible to control the threshold where the actuators should be turned on or off. To complement the system a Raspberry Pi with a camera module was also used in the system, enabling the user to always have a live stream of the system. Even so, only the pH value, electric conductivity and temperature is read while analyzing the water's quality. Other metrics, including measuring the ammonia levels, still need to be improved.

Dutta et al. system features to monitor the pH value, temperature and humidity and water level using sensors (Dutta et al., 2018). The system also uses a relay in order to be able to autonomously control the light and switch them between on and off based on a predefined time. A 16 x 2 *Liquid Crystal Display* (LCD) is used to display all system parameters measured by the sensors. Additionally, a web server was also developed to give the possibility to the user to access all the system parameters remotely. The pH sensor responsible to give the pH value of the system was connected to an Arduino nano while the rest of the sensors, temperature, humidity and water level, and the LCD were connected to a Raspberry Pi. However, while evaluating the water's quality, only the pH value is read, additional metrics, such as assessing the ammonia levels, still need to be improved.

Haryanto et al. elaborated a system that utilizes an ultrasonic sensors to measure the water level, a pH sensor to read the pH present in the system and a temperature sensor that reassures the temperature of the water (Haryanto et al., 2019). It also featured a local display in order to show the user the sensor outputs. The actuators used are: a pump, a fish feeder, and an emergency electricity source in case the power goes out, electricity still continuous to flow into the system. To complement the system an Android interface, and a web interface were created in order to show the sensors values remotely. A notification system was also implemented. The developed worked also enter in depth of the development of the tilapia, common name for species of fishes, and lettuce along the time. Only the pH value is read while analyzing the water's quality. Other factors, such as reading the ammonia levels, need to be implemented to obtain a more thorough water analysis.

Autos et al. developed a system which consisted on the use of sensors, actuators, an Arduino Mega, and an LCD (Autos et al., 2020). In order to measure water parameters the sensor used are: a pH level, a dissolved oxygen, a total dissolved solids, and a water flow. A room temperature sensor is employed to gauge the humidity and temperature needed for the plant to thrive. The level of fish feed is also measured using an ultrasonic sensor. As of the actuators, these consist of: an aquarium heater, a cooling fan, an aerator, a grow light, a water pump, and a servo motor. The readings from the sensors are used to operate these. If there is a crucial parameter, the data will be shown on the LCD and an LED light will flash as an indicator. An SMS would also be delivered to a mobile phone using the *Global System for Mobile communication* (GSM) module to serve the purpose of notifications. Although the parameters related to the measurement of water quality are improved when compared to previously described works, the measurement of ammonia is still missing.

Menon devised a system consisting of sensors, focusing mainly on measuring the quality of the water and the growing bed present in the aquaponics system (Menon, 2020). In terms of water quality, this system presents a ammonia, nitrate, chlorine and pH sensors. On the other hand, in the grow beds it is used a wetness sensor. There is also an end-user application that allows the user to check all the sensor outputs. If there is a variation in the preset values of any of the variables (pH, ammonia, and nitrate) a warning is sent to the user. Regarding ammonia, it is preset that any concentration above 0.5 mg/l is considered harmful, and a warning will be sent to the user, but as seen in Figure 1.4 it is a necessity to cross-reference the ammonia concentration with the pH value to detect whether the ammonia is harmless, harmful or toxic.

Manoj et al. proposes a system focused in the water quality for fish ponds using *Internet of Things* (IoT) and sensors that are designed to be underwater (Manoj et al., 2022). Such sensors used were pH sensor, temperature sensor, *Dissolved Oxygen* (DO) sensor, that is responsible to read the gaseous oxygen dissolved in water, nitrogen sensor, sensor used in measurement of NO_3 in water and ammonia sensor, detects the ammonia concentration in water. All these sensors would be integrated in an IoT Cloud architecture, meaning that a Raspberry Pi or Arduino would collect the sensors values; send them to the Cloud, and subsequently grant user access to the values via a mobile application. Those values could also be used in order to have actuator execute their jobs depending on these on an autonomous way. The sensor in discussion have high financial cost, being unsuitable for the present system developed.

Wang et al. designed an aquaponics system with the purpose of teaching computational intelligence (Wang et al., 2020). The aquaponics experiment system includes Power Line Communication, LabVIEW, Open Platform Communications technology, sensors and actuators. The sensors used evaluate the water temperature, conductivity, and dissolved oxygen concentration. The ammonia nitrogen concentration and nitrite nitrogen concentration are also analyzed by laboratory once a day. The actuators used consist on illumination, heating, water pump, electric magnetic valves and others. Although the ammonia nitrogen concentration in the water is measured, it requires a laboratory. For this reason this approach is not suitable for the present system developed.

Abu Bakar et al. devised a system using a micro controller, sensors, and a GSM module (Abu Bakar et al., 2022). The sensors used in this aquaponics system consist of: pH, humidity and temperature, and ultrasonic. The pH sensor is responsible for determining the pH of the observed water. The humidity and temperature sensor measures ambient temperature and humidity. Finally, the ultrasonic sensor is responsible for measuring the water level. The system also incorporates a warning system. This is activated if the values from the sensors are not between average values. The warning system consists of a buzzer and an LED. All sensor values are displayed to the user by two ways: i) an LCD, and ii) via SMS wich is sent by the GSM module. However, since only the pH value is analyzed when assessing water quality, additional metrics, such as measuring ammonia levels, still need to be improved.

Wan et al. developed a aquaponics monitoring system based on embedded edge-computing and IoT technology (Wan et al., 2022). This system as the objective of reaching full supervision and abnormal monitoring of water quality, planting environment, and plant growth conditions. In order to monitor the water quality, they used sensors and a microcontroller. These sensors consist of water temperature sensors, DO sensors, and pH sensors. To monitor the planting environment, the sensors used consist of temperature-humidity sensors, CO_2 sensors, light intensity sensors. Finally, a Raspberry Pi with a camera attached was also used with the purpose of monitoring plant growth conditions by deep learning. These being plant height, plant stem, leaf area, etc. All the information from the sensors would be read by the microcontroller and sent to the Raspberry Pi. There, each value would be analysed. The Raspberry Pi, with a camera, would also monitor plant growth conditions. All these information would be sent to the *cloud* using MQTT protocol. Later, the *cloud* would transmit all this information to the desired user, also using MQTT protocol. Although there is an improvement in the water quality control, the ammonia concentration is not considered.

Reyes Yanes et al. devised a framework for the development of a digital twin for an aquaponics system. (Reyes Yanes et al., 2022). A digital twin is a virtual representation created to faithfully represent a physical object. This framework is tested by creating a digital replica of the aquaponics system's grow beds for real-time monitoring of parameters like pH, electroconductivity, water temperature, relative humidity, air temperature, and light intensity. This digital replica also supports the use of artificial intelligence tools to, for example, predict the growth rate and fresh weight of the crops that are currently growing. The sensors incorporated into the system are pH, electroconductivity, water temperature, air humidity, air temperature, and luminosity. The system also includes a humidifier, two cameras (one at the top and one at the side of the grow bed), a water pump, a heater, artificial growing lights, and a camera ring light (to provide consistent light to the cameras). An Arduino Nano is employed as the sensing unit, and a Raspberry Pi is chosen as the main controller. Nevertheless, additional metrics, like monitoring ammonia levels, still need to be improved since only the pH value, electroconductivity, and water temperature are evaluated when assessing water quality.

2.2 Technologies for ammonia concentration measuring

2.2.1 Ammonia concentration measurement using reagents

Li et al. reviewed many ammonia nitrogen detection methods including spectrophotometric methods, *Ion-Selective Electrode* (ISE), optical detection, electrochemical detection, and biological enzyme detection (Li et al., 2020). One of the conclusions reached after analysing the various methods for determining ammonia nitrogen or TAN was that most of the optical detection's of ammonia nitrogen require reaction regents. Other conclusion was that a portable ammonia nitrogen sensor is desired for various field-based applications and in order to improve detection performance, coupling techniques will become increasingly important.

Cho et al. researched the use of one of the reagent studied in the last mentioned research (Li et al., 2020), the Berthelot's reagent (Cho et al., 2018). This reagent uses a colorimetric response, meaning that different ammonia concentrations will result in different colors after the reagent been applied to the sample. The work discussed can measure ammonia for the range of 10-200 mg/L. A small low-cost colorimetric ammonia gas sensor has been manufactured by easy filtration of modified Berthelot reagents onto a porous paper substrate. In this way, a sample can be measured by simply pouring it onto the porous paper substrate. Within fifteen minutes a colorimetric response will be shown on the porous paper. While this is an innovative approach, it is highly complex and unsuitable for the current developed system.

2.2.2 Ammonia concentration measurement using spectrophotometric techniques

Spectrophotometry is based on the quantitative measurement of light absorption by solutions, where the concentration in solution of the absorbing substance is proportional to the amount of light absorbed (see Figure 2.1). These measurements are performed by equipment called spectrophotometers (see Figure 2.2), which can measure the intensity of a beam of light at different wavelengths. Although spectrophotometry is most commonly applied to ultraviolet, visible, and infrared radiation, modern spectrophotometers can interrogate wide ranges of the electromagnetic spectrum, including X-ray, ultraviolet, visible, infrared, and/or microwave wavelengths.

Using spectrophotometric techniques, Frances used the colorimetric sensor AS7341 spectral sensor to develop a simple spectrophotometer (Frances, 2020). This experiment had the purposed of measuring a substance concentration using a red LED, a 3D Printed Case and the AS7341 spectral sensor. In this experiment Frances used five different samples with different concentrations and a pure water sample. Based on the spectrophotometric principle (see Figure 2.1), using the AS7341 Spectral Sensor and by having a

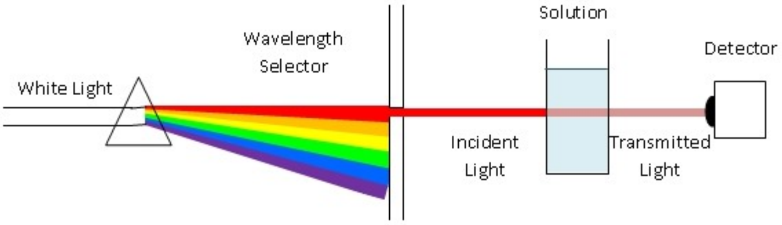


Figure 2.1: Spectrophotometric principle

Figure 2.2: Table-top spectrophotometer

controlled environment, it was possible to conclude that the higher the concentration the lower amount of total light reached the sensor.

Lin et al. researched in detail various analytical methods for determining ammonia nitrogen or TAN in natural waters from 2014 to mid-2019, including methods based on spectrophotometric, fluorometric, and electrochemical detection (Lin et al., 2019). The conclusion reached after analysing the various analytical methods for determining ammonia nitrogen or TAN was that the spectrophotometric methods continues to be predominant between the three due to its wide range of application and relative feasibility. These devices are high value in financial terms and laboratory grade, which makes it difficult to implement them in an affordable and convenient approach for the user.

2.2.3 Ammonia measurement using sensors

Xu et al. have devised a system that detects ammonia nitrogen or TAN with the range of 0.4–10 mg/L, for this reagents, hardware and sensors were used (Xu et al., 2022).

The preparation of the colorimetric chemicals and reagent for measuring the TAN is the first step. The creation of test papers happened. These were created since preparing these reagents would take a long time. It also requires accurate laboratory equipment, making them unsuitable for on-site detection. These test papers have the same purpose as a colorimetric test. The creation of a detection box eliminated the lack of stability in the results under different environmental conditions. Using a colorimetric sensor (TCS3200), a light source and a controlled environment, it was possible to detect the resulting color of the test papers. Thus detect the ammonia concentration in the water sample. The creation of these test papers requires laboratory grade material. This becomes an inconvenient approach for the user.

In order to monitor ammonia, nitrate, and nitrite levels without the use of expensive electronic sensors, Oommen et al. developed an automated concentration measurement system (Oommen et al., 2019). To replace manual testing of ammonia, nitrite, and nitrate concentrations, this research devised a system that looks at the color that develops when water reacts with various regularly used chemical reagents by farmers. When using the chemical reagents, different colors correspond to different concentrations. A comparison of the developed color provides the corresponding concentration. This was achieved using a *VEML6040* colour sensor and a microcontroller. The microcontroller used was the *ESP8266*. The *VEML6040* colour sensor senses red, green, blue, and white light. Along with measuring the concentration, the system also implements pumps to automatically recover the water samples and apply the reagents. The water quality is considered good for low concentrations (preferably 0 ppm), medium for medium concentrations (3 ppm), and bad for high concentrations (more than 3 ppm). Although there is a thorough control of the water quality, it only takes into consideration the concentration of each ion. As seen in Figure 1.4 it is necessary to cross-reference, for example, the ammonia concentration with the pH value of the system to assess the toxicity of the ammonia.

Wen et al. developed a system to measure ammonia nitrogen or TAN, with a range of 0.1–10 mg/L, in real time using an ammonium ISE, a glass electrode, a constant temperature magnetic stirrer, and a temperature sensor (Wen et al., 2019). Having the glass electrode to obtain the pH, the temperature sensor to obtain the temperature of the water and the ammonium ISE to detect the ammonium (NH_4^+) concentration, it is possible to detect the value of the TAN using some equations based on the water temperature, pH value and NH_4^+ concentration. The ammonium ISE is of high value in financial terms, so implementing it in an affordable solution is inconvenient.

As previously mentioned, Manoj et al. (Manoj et al., 2022), proposed to develop a system that analyses the water quality using a variety of sensor. One of those being an ammonia sensor that function on the ISE base. As explained thees sensors are of high financial cost making them unsuitable to implement in the present system.

Franco et al., developed a system that consisted on measuring the ammonia via a

ZnO (Zinc oxide) powder and analyzing a *Scanning electron microscope* (SEM) image (Franco et al., 2019). The *ZnO* powder reacts with water when the presence of ammonia is found. Surface morphology of *ZnO* film before and after the reaction is different. For that reason using a SEM image it is possible to identify the ammonia concentration. The present system for liquid NH_3 detection is highly sensitive (46.9 $\mu AmM^{-1}\ cm^{-2}$) and low NH_4^+ concentrations (0.39 to 10.9 mM). Although this approach is innovative, it is highly complex to implement in the described paper and not user convenient.

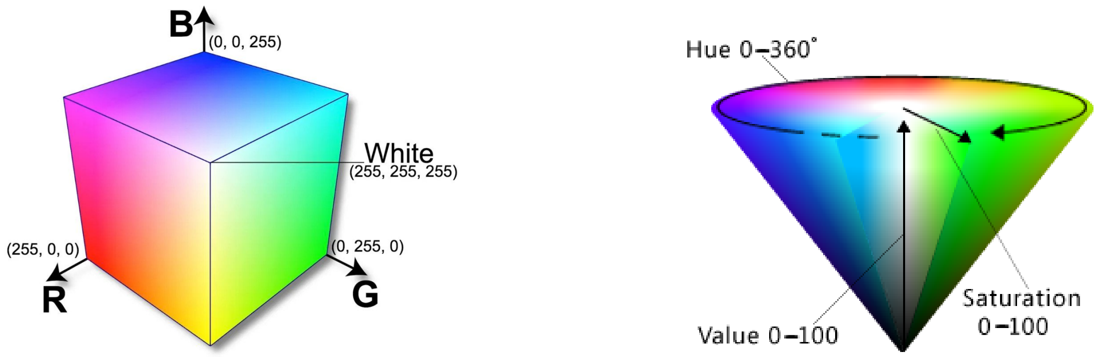
2.2.4 Ammonia measurement using computer vision

Red Green Blue (RGB) is not the only color space that exist. Other color spaces that exist are *CMY(K)*, *HSV*, *YCbCr*, *CIE L*a*b** or *LAB* and others. Nouha Khediri et al. go into detail on each color space mentioned and experiment with image segmentation with some of them (Khediri et al., 2021).

The acronym RGB stands for the three additive primary colors Red (R), Green (G), and Blue (B). The combination of these three primary colors creates the color white, while their absence creates the color black. These three primary colors are sufficient and suitable to match any other color through blending in numerous ways. Figure 2.3a illustrates the form of the RGB space as a cube with Red, Green, and Blue as its coordinate axes.

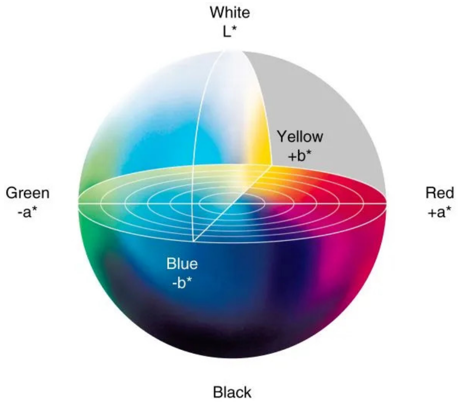
HSV is an acronym for "Hue Saturation Value," as shown in the model's name. The RGB color space is transformed nonlinearly to produce this color space. A separate coordinate system, specifically cylindrical coordinates that physically provide a hexagonal cone (See Figure 2.3b), is used by *HSV* to represent the RGB color space. When a color transitions from red to green, the hue component measures how pure the color is. The primary colors (red, green, and blue), secondary colors (cyan, yellow, and magenta), and linear mixtures between adjacent pairs are all represented in their true colors by this. The color purity is described by the saturation component. When a color changes from red to pink, the amount of white color that has been incorporated into that particular hue is measured. A saturation level of 100 indicates that a color is fully saturated. Value, also known as lightness, refers to the amount of light that illuminates a color. It measures how dark a color is represented by a percentage that ranges from 0 to 100. V = 0 and 100 respectively denote the colors black and white.

*CIE L*a*b**, also named *LAB*, is a uniform color space (See Figure 2.4). It is a three-dimensional model (See Figure 2.3c). L* symbolizes intensity, while a* and b*, which stand for red/green and blue/yellow coordinates, respectively, are the chromatic components. L*, which ranges from 0 (dark) to 100 (white), depicts color lightness. a* denotes the position of the color between red/magenta (+a) and green (-a). The value of b* indicates where it falls on the yellow (+b) and blue (-b) axes. It is significant to note that since the tonality changes are linear in this space (uniform color space), it is possible to calculate the chromaticity differences using the Euclidean distance.



(a) RGB color space

(b) HSV color space



(c) CIE L*a*b* color space

Figure 2.3: Different color spaces

The Euclidean distance represents the distance between two points in Euclidean space. The Euclidean space is the fundamental space of geometry, intended to represent physical space like the three-dimensional space. The Euclidean distance in a three-dimensional space can be calculated with the following mathematical expression:

$$d(a,b) = \sqrt{(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2} \tag{2.1}$$

In the mathematical expression 2.1 the Euclidean distance in a three-dimensional space between the point a and b is being calculated where a_1 and b_1 corresponds to the first variable, a_2 and b_2 to the second and a_3 and b_3 to the third.

The LAB color space is an international standard designed for perceptual uniformity (Schwarz et al., 1987), which means that the difference between two colors perceived by the human eye is proportional to the Euclidean distance within the given color space. On the opposite side, a non-uniform perceptual colormap can have stark contrasts when transitioning from one hue to another hue (see Figure 2.4).

Bao et al., using reagents, and knowing that different concentrations would have different color results, developed a system to detect the resulting color of the reagents and

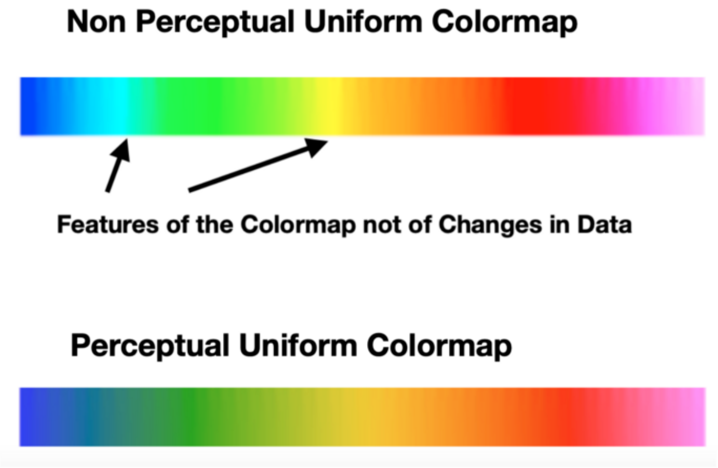


Figure 2.4: Comparison of Non-Perceptual Uniform and Perceptual Uniform Colormaps

thus detect the concentration (Bao et al., 2018). For this, a PC camera, reagents, a detection box, to obtain a controlled environment, and an LED were used. Having the result of the colorimetric test, a photograph is captured of the chromogenic solution using an ordinary PC camera and the average RGB value in the center region of the photograph, containing only the color that resulted from the colorimetric test, was obtained. Afterwards, the color space was converter from RGB to LAB. To determine the concentration based on the LAB value, the LAB values of each concentration were obtained, from which the color difference between each concentration and a blank sample solution, also called Euclidean distance, was calculated, and a curve was created. In this curve, the Y value represents the color difference and X the concentrations. With the curve, it was possible to recreate the process to detect the color difference, but this time between the sample and the blank sample solution. This way, it was possible to detect which concentration the sample corresponds to. Despite this, there is a lack of a user interface and the classification of ammonia toxicity is missing.

Zamora-Garcia et al., taking advantage of the camera present in cell phone's, developed a system based on a smartphone application that captures a photograph of the result of a colorimetric test (Zamora-Garcia et al., 2021). The steps involved in the computation of the ammonia concentration using the mobile application consist on: taking a sample of water, filtering it and applying the three reagents. In order too achieve the full reaction between the water sample and the reagents it is a necessity to wait fifteen minutes. The color of the liquid will change based on the TAN. Afterwards, the user needs to capture a photograph of a grey card. This serves the purpose as a reference color. The user then needs to take a photo of a Petri dish containing the result of the colorimetric test. Lastly the user obtains the result. The information displayed in the result are the concentration of ammonia in *Parts Per Million* (PPM) and the level of ammonia in the sample, which can be good, warning or danger. As seen in Figure 1.4, it is necessary to cross-reference the ammonia concentration with the pH value of the system to assess the toxicity of the ammonia as harmless, harmful, or toxic.

Jian-yu et al., analyzed the behavioral responses of a school of tilapia to different levels of unionized ammonia concentration, using CV (Jian-yu et al., 2005). Tilapia is the common name for nearly a hundred species of cichlid fish. The levels of unionized ammonia concentration that were monitored were: low (0.13 mg/L), moderate (0.79 mg/L), and high (2.65 mg/L). The conclusion reached was that the behavioral parameters of the school of tilapia reacted to the rise in unionized ammonia levels. Under typical conditions, the fish schools move around actively and uniformly. The typical stress signals of fish to high unionized ammonia concentration are an abrupt increase in swimming activity, and acute fluctuation of the fish school. Those being: remaining at the bottom or ascending to the water surface, obvious decrease in distribution, and darkening in body color.

2.3 Summary

In this chapter, previous works for the study of intelligent aquaponics systems and ammonia measuring were investigated and analyzed. Ammonia concentration measuring can be done using various techniques, sensors or reagents. The main test for detecting ammonia concentration is colorimetric tests. Although it is the most widely used, it requires human interaction, color comparison, and repeatedly performing the same action every time a reading was to be done. With technological advances, it is now possible to find robust solutions to measure ammonia concentration and toxicity without the use of expensive equipment and in a more autonomous way. These solutions can be through cell phone applications, CV, or sensors connected to an API.

All systems investigated for intelligent aquaponics systems use sensors, for obtaining information about the system, and actuators, for the ability to control the system variables without human interaction. This is a major advancement to develop a fully automated and autonomous system. But integrating water quality parameters like ammonia and ammonia toxicity measurement is lacking in most of the investigated systems.

Methods investigated for measuring ammonia also use sensors but focus mainly on CV, reagents and spectrophotometry. The use of CV comes with the use of reagents, as these are used to determine the TAN with a colorimetric response. CV is then used to capture a photograph containing the colorimetric response, detect the color present in the photograph, and further identify the ammonia concentration corresponding to the color analyzed. A mobile application has also been investigated. It uses the same principle as CV, but takes advantage of the fact that there is a camera in cell phones. This way, the user applies the reagents to the sample, but only needed his mobile phone to capture a photo of the colorimetric response. Then, the app would match the color present in the response with an ammonia concentration. Using the reagents, sensors can have the same principle as the CV, but instead of taking a photograph and analysing it to obtain the color represented in the colorimetric response, a colorimetric sensor is used. Other type of sensors also used are the ISE. These sensor are of high cost but they detect the levels of ammonium ions present in the sample and using some equations it is possible to detect the TAN present in the sample. Spectrophotometry is another way of measuring the ammonia concentration, these are usually used in a laboratory, and are of high financial cost. Despite the great results demonstrated, they are not suitable for use in an accessible and convenient approach.

After analyzing all the research articles, it was possible to make a comparison between the most opportune parameters when developing the project. Table 2.1 summarizes this analysis, showing for each work its response to each parameter. This table is intended to demonstrate whether the systems are user-convenient, meaning if it was thought of making the system easy and accessible for a user to use, if it measures the pH value of the system, if it measures the ammonia concentration and if the toxicity of the ammonia present in the system is available to the user.

Table 2.1: Comparative analysis between the systems analyzed

System	**User-convenient**	**Measure pH**	**Measure ammonia concentration**	**Measure ammonia toxicity**
(Vernandhes et al., 2017)	✓			
(Kyaw and Ng, 2017)	✓	✓		
(Jie Ong et al., 2019)	✓	✓		
(Dutta et al., 2018)	✓	✓		
(Haryanto et al., 2019)	✓	✓		
(Autos et al., 2020)	✓	✓		
(Menon, 2020)	✓	✓	✓	
(Manoj et al., 2022)	✓	✓	✓	
(Lin et al., 2019)			✓	
(Xu et al., 2022)	✓	✓	✓	
(Wen et al., 2019)	✓	✓	✓	
(Franco et al., 2019)			✓	
(Bao et al., 2018)			✓	
(Zamora-Garcia et al., 2021)	✓		✓	

Chapter 3

System Specification

The proposed system in this document aims to monitor the concentration and toxicity of ammonia in aquaponics systems. The system is intended to be user convenient, low cost, practical and contains some important features such as: i) Color detection; ii) pH measurement, and iii) Report the quality of the water of the aquaponics system with regard to the ammonia.

The goal of detecting the color were achieved using CV techniques, the *OpenCV* library[1], and the *NumPy* library[2].

The toxicity of ammonia can vary between harmless, harmful or toxic. It is possible to detect the toxicity of ammonia by cross-referencing the ammonia concentration with the pH present in the system (see Figure 1.4).

Measuring the pH was done with a pH sensor. Normally, the pH values are between 0 and 14. Under standard thermodynamic conditions, pH equal to 7 means that the solution is neutral, pH less than 7 means that the solution is acidic, and pH greater than 7 means that the solution is alkaline.

After the ammonia toxicity measurement, a report is issued with the pH value, the color resulting from the colorimetric test, the ammonia concentration, and the ammonia toxicity. This report allows the person to take into account the quality of the water in his system with regard to ammonia and, if necessary, to adopt the most appropriate methods to improve it.

3.1 System Requirements

The functional, non-functional, software and hardware requirements that the proposed system has met are identified and described in this section.

---

[1] OpenCV (2022). URL: `https://opencv.org/`

[2] NumPy (2022). URL: `https://numpy.org/`

3.1.1 Functional requirements

Functional requirements describe the features that the proposed system must be capable to perform. These requirements are the following:

- **FR001:** The system allows to measure the ammonia toxicity present in an aquaponics system through a camera and sensors.
- **FR002:** The system detects the ammonia concentration based on a photograph containing the color resulted from the colorimetric test.
- **FR003:** The system detects the pH value of the aquaponics system.
- **FR004:** The system detects the ammonia toxicity of the aquaponics system, by comparing the result of the colorimetric test and the pH value.
- **FR005:** Store the ammonia toxicity, pH value, captured photograph and ammonia concentration in the database.
- **FR006:** All the information about each reading can be accessed at any time by the user who took the reading.

3.1.2 Non-functional requirements

Non-functional requirements represent the requirements that establish how the system will behave in determined situations. These requirements are the following:

- **NFR001:** The system allows to measure the ammonia toxicity at any time of the day.
- **NFR002:** The system is composed of open-source software applications and libraries.
- **NFR003:** The proposed ammonia concentration detection algorithm is adapted for a Raspberry Pi camera.
- **NFR004:** The system should be low-cost and user convenient.

3.1.3 Software and hardware requirements

At last, the requirements that establish the software and hardware needs for the system to be implemented are enumerated. These requirements are the following:

- **SR001:** The system must employ a programming language supported by the device it operates in.

- **SR002:** The system must use a computer vision library.
- **SR003:** Use a low cost, single board and tiny computer, such as the Raspberry Pi Zero W.
- **SR003:** The system incorporates a camera.
- **SR004:** The system incorporates a pH sensor.
- **SR005:** The system incorporates an *Analog-to-Digital Conversion* (ADC).
- **SR006:** The system incorporates a 3D printed controlled environment.
- **SR007:** The system incorporates a light source.

3.2 System architecture

The system aims to measure the toxicity of the ammonia present in the aquaponics system by utilizing a color detection module and a pH measurement module. These two modules are deployed in a cloud and are responsible for analyzing the necessary parameters to determine the ammonia toxicity. The color detection module measures the ammonia concentration while the pH measurement module measures the pH levels in the system. Both modules communicate their findings to the main module, which aggregates the data and determines the overall toxicity of the ammonia. The main module then generates a report including the data from both individual modules and the overall ammonia toxicity level.

The overall architecture diagram of the system, including its hardware and software components, is shown in Figure 3.1. The system modules receive the necessary data from the Raspberry Pi, then each of these modules issues a response depending on the data it has received. The Cloud, with the response from each module, can calculate the toxicity of the ammonia. Finally, a report is issued with the response of each module and the toxicity of the ammonia.

It is also to note that the architecture used in the present system is an IoT Cloud Computing.

A shared pool of adjustable and adaptable computing resources, such as data storage and monitoring, device and system automation and integration, data mining, visualization, and analysis, etc., may be accessed anywhere, at any time, on-demand. This architecture model is called cloud computing. The key reason that cloud-based IoT systems were developed was to make it simpler to quickly offer and release solutions with little management work and contact with service providers. Additionally, for both vertical and transversal domains, IoT cloud systems offer essential application-specific capacities (Moreira et al., 2021).

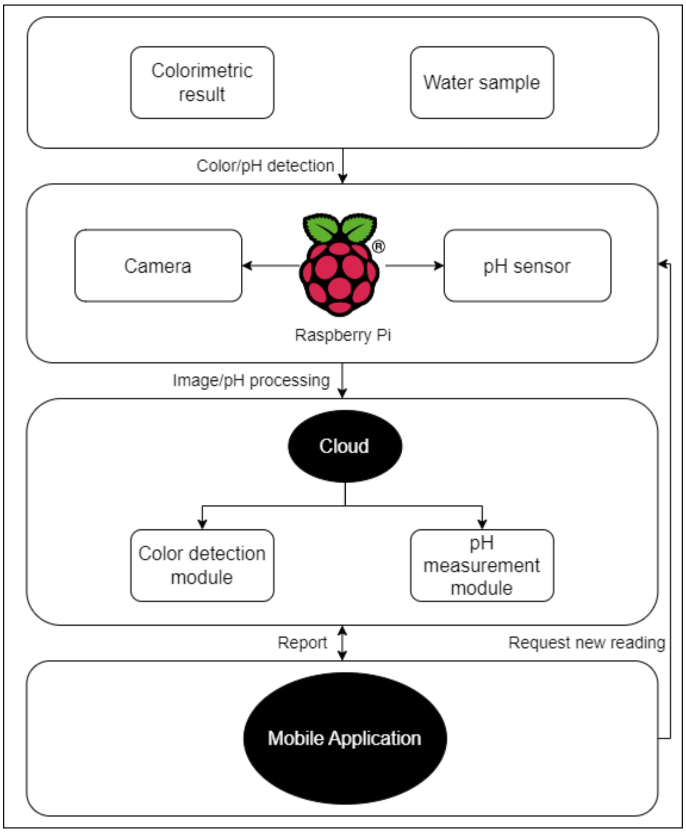


Figure 3.1: System architecture diagram

In the described work this is the architecture used meaning that multiple Raspberry Pi's can be used at the same time and connected to the same Cloud.

3.3 System workflow analysis

The general module's data flow is described in this subsection, along with the successive descriptions of the sub-modules for color detection and pH measurement.

The system's global flow represents all the processing that the data undergoes from the moment of its input, that is, from the moment the reagents are applied to the water sample, until the moment the ammonia toxicity is calculated.

It is first important to wait five minutes for the reagents to stabilize and give a colorimetric response. If the necessary waiting period has not been respected, the colorimetric response will not be accurate, and the result from the color detection will not be correct. It is also essential to wait for the camera to stabilize before beginning the photograph capture. This is necessary since the camera as to adapt to the ambient light conditions. If the camera as not been stabilized, the photograph will appear darker than what it is supposed to be, resulting in a wrong detection of the ammonia concentration. For this reason, there must be a three-second delay between initializing the camera and capturing the photograph.

With the camera ready and the colorimetric response stabilized the color and pH measurement modules can initiate sequentially, when finished the general module then takes the response of each sub-model and calculates the ammonia toxicity.

The overall program flow is described in the flowchart in Figure 3.2.

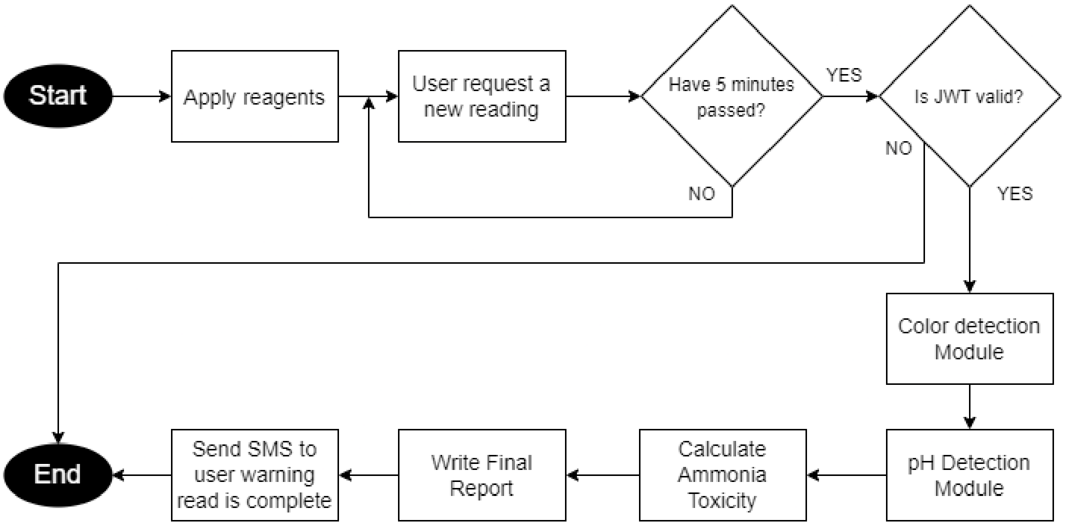


Figure 3.2: Ammonia Toxicity Measurement System Flowchart

3.3.1 Ammonia monitoring

3.3.1.1 Color Detection Flow

When applying specific reagents to a water sample containing ammonia, different concentrations will give different colorimetric results. So, to measure the ammonia concentration, it is necessary to take a water sample from the system, add reagents to the sample, wait for the reagents to act and produce a colorimetric response, capture a photograph of that response, and calculate the ammonia concentration by comparing it to different previously known ammonia concentrations. Knowing the colors of the predefined ammonia concentrations from the reagent test used in the developed system (see Figure 1.2), it is possible to know the RGB and LAB values of each of the concentration by preforming a pre-calibration on the controlled environment present in the developed system. By calculating the Euclidean distance between the colorimetric response of the reagent present in the water sample and the pre-calibrated LAB values of the ammonia concentration, it is possible to identify which concentration of ammonia is present in the water sample by comparing them. A smaller Euclidean distance represents the ammonia concentration present in the water sample, since it represents the smaller distance between them in the perception of the human eye.

The flow of the color detection process can be followed in the flowchart of figure 3.3.

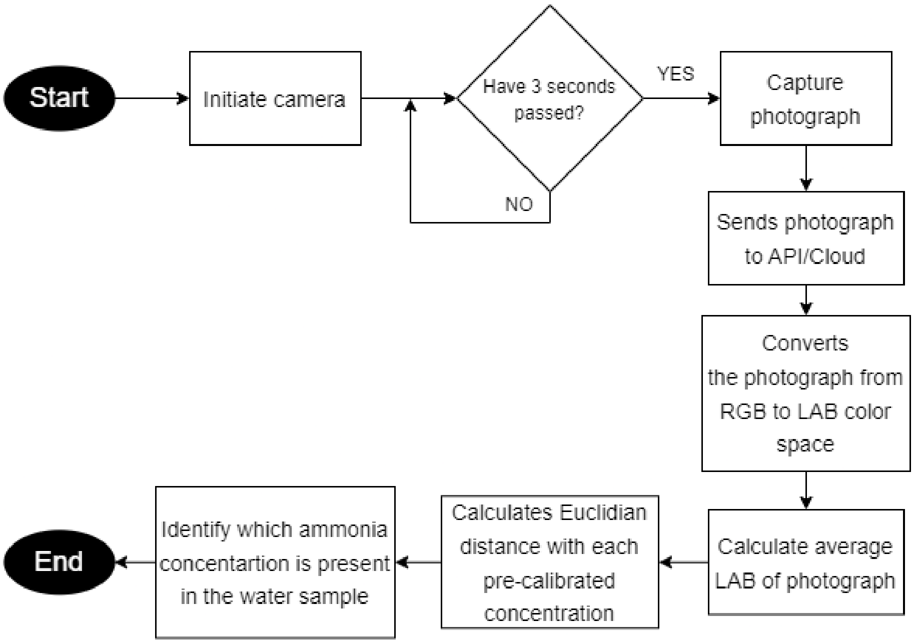


Figure 3.3: Color Detection Flowchart

3.3.1.2 pH Measurement Flow

To obtain the pH value of the system, a pH sensor is used on a water sample. The calibration of the pH sensor is essential and for this buffers solutions of pH 7.0 and 4.0 are needed. The buffer solutions are included with this pH sensor. After the calibration of the pH sensor, it is know to the system the analog value for both the pH 7.0 and the pH 4.0, with those values it is possible to create an linear function. In order to calculate any pH value based on the analog value returned from the pH sensor, the linear function created with the process of calibration is used.

The flow of the pH measurement process can be followed in the flowchart 3.4.

3.3.1.3 Authentication

The system is protected with authentication and *JSON Web Tokens* (JWT), meaning that an account needs to be registered and subsequently logged in and verified in order to use the system.

3.3.1.4 Account Registration Sequence

For a user to register in the system, a username, an e-mail address, phone number, and a password are required. The data is checked in order to verify the parameters, such verifications are confirming if the username, e-mail address and phone number are unique. If the verifications are a success, then the user is recorded in the database and an e-mail will be sent to the user in order to verify the account. In case that the verifications are

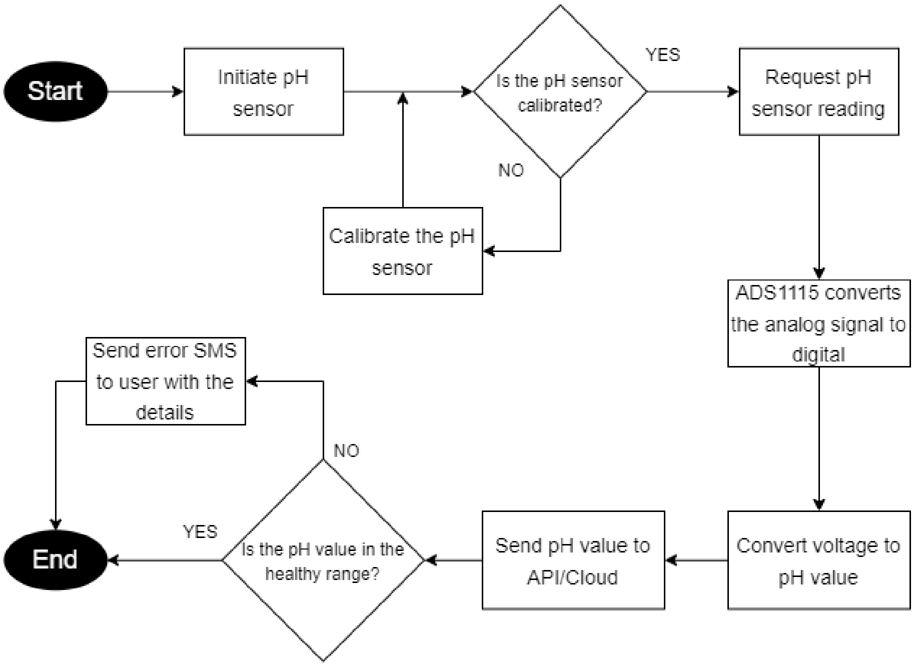


Figure 3.4: pH Measurement Flowchart

unsuccessful, an error will by triggered and the user will be notified. The user can only login if his account is confirmed.

The sequence of the account registration process can be followed in the sequence diagram 3.5.

3.3.1.5 Account Login Sequence

Every request in the system is protect with a JWT requirement, to obtain it the login must be effectuated. To perform the login the user must send the username and the respective password of the account desired to execute the login. The data is then verified in order to see if the username is present in the database and, if it is, if the password is the correct one. If the verification is successful, the JWT will be sent as a response of the request. In case that the verification turns out to be unsuccessful, an error will be triggered and sent to the user.

The sequence of the login process can be followed in the sequence diagram 3.6.

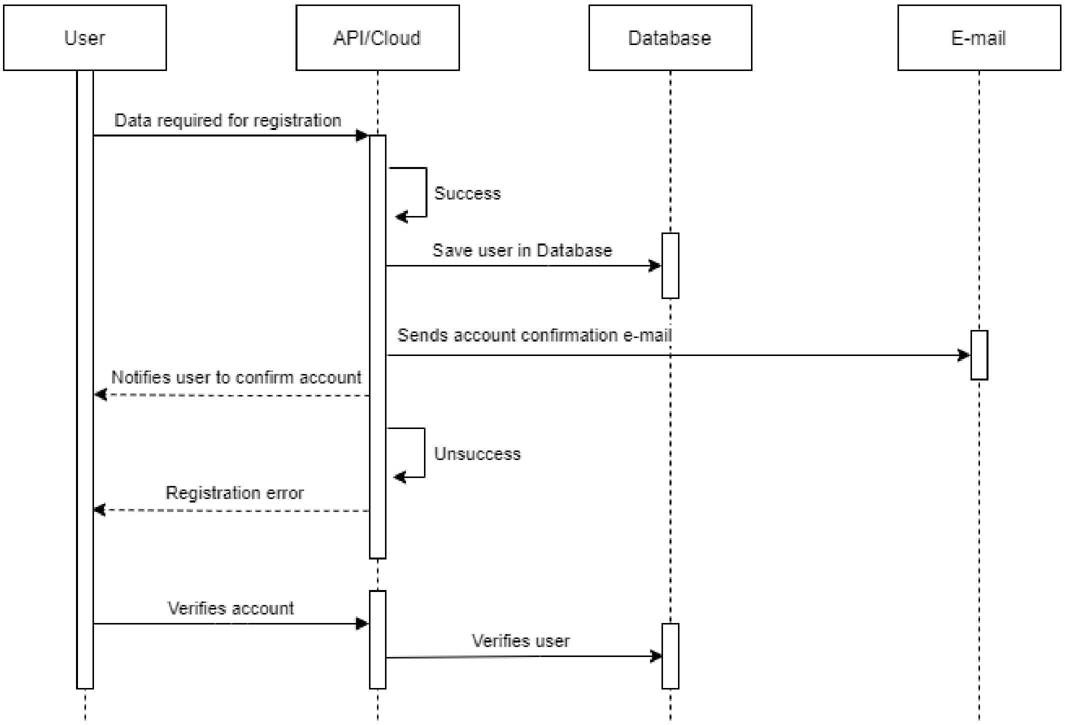


Figure 3.5: Account Registration Sequence

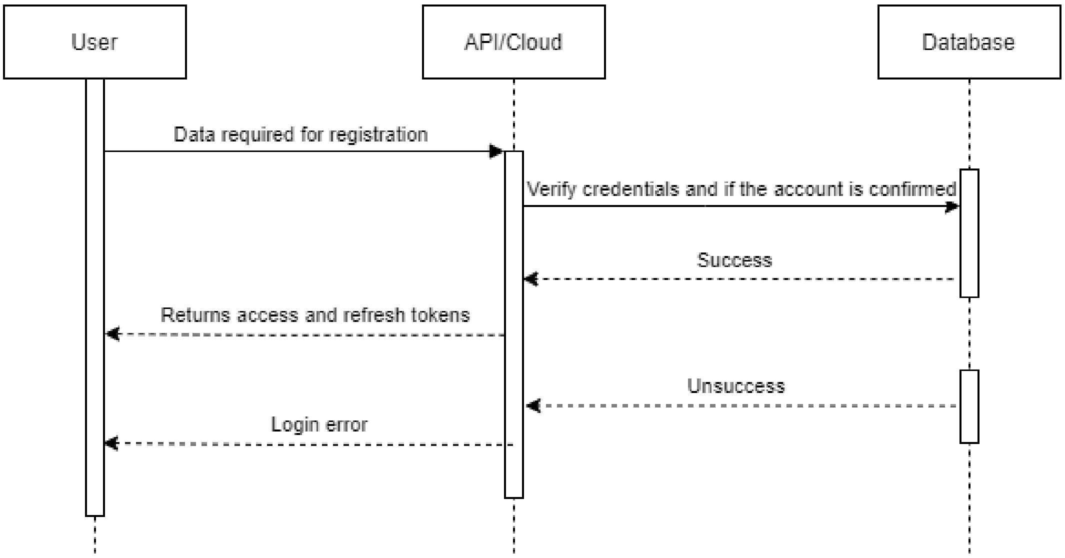


Figure 3.6: Login Sequence

Chapter 4

System Implementation

This chapter presents in detail the implementation of the project, using Python, a high-level, open-source, and multi-paradigm programming language. More precisely: the backend service and sub-modules (for color detection, pH measurement and ammonia toxicity detection), the mobile application and the hardware modules' procedures. This chapter's subsections describe the logic and implementation of all these components.

In particular, the color detection module aims to detect the predominant color present in the colorimetric test. The use of this module allows to determine the colorimetric result, and subsequently detect the ammonia concentration, using the *OpenCV* library[1] and *NumPy* library[2].

For determining the water pH we use a pH sensor and an external ADC module (I2C ADS1115 16-Bit ADC Module), since the Raspberry Pi *General Purpose Input/Output* (GPIO) pins can only read digital signals.

Additionally, the backend Cloud service was developed using the framework *Flask*[3].

Finally, the mobile application offers the user a management interface. This application was developed using *Flutter*[4].

4.1 Development Technologies

This subsection focuses on the technologies adopted to develop the system components. In particular, the backend support service and algorithms, the software running on the hardware components and the mobile app.

---

[1] OpenCV (2022). URL: `https://opencv.org/`

[2] NumPy (2022). URL: `https://numpy.org/`

[3] Flask (2022). URL: `https://flask.palletsprojects.com/`

[4] Flutter (2022). URL: `https://flutter.dev/`

4.1.1 Backend Cloud Components

The Cloud components offer an API developed using the framework *Flask*[1], and the algorithms for processing the received data, also developed in *Python*.

The API handles all communications between the Raspberry Pi and the backend, as well as between the backend and the mobile application. All requests are protected by JWT to identify the user and ensure system security. The available requests in the API can be viewed in Figure 4.1.

```
#Routes
#user
api.add_resource(UserRegistration, '/register')
api.add_resource(UserLogin, '/login')
api.add_resource(UserLogoutRefresh, '/logout/refresh')
api.add_resource(UpdateUserPassword, '/update-password')

# auth
api.add_resource(TokenRefresh, '/token/refresh')
api.add_resource(LoginWithToken, '/token/login')
api.add_resource(VerifyAccount, '/verify-account/<token>')
api.add_resource(ResendEmail, '/verify-account/resend')
api.add_resource(SendRecoveryPasswordEmail, '/reset-password')
api.add_resource(ResetPassword, '/recovery-password/<token>')

#read
api.add_resource(CreateResult, '/read')
api.add_resource(SeeResult, '/readuser')
```

Figure 4.1: Requests present in the API

The backend is divided into two modules: the Color Detection module and the pH Measurement module. The Color Detection module processes images using CV techniques and libraries such as OpenCV[2] and NumPy[3] to analyze and store the image data. The pH Measurement module receives data from the Raspberry Pi, analyzes it, and calculates the pH value. These modules are further discussed in chapters 4.2.3 and 4.2.4.

4.1.2 Client Onsite Hardware Components

For each client onsite system, we implemented a low-cost system by using a single-board computer (SBC), a camera, a pH sensor, a I2C ADS1115 16-Bit ADC Module, and LEDs. The Raspberry PI Zero W (Pi, 2022) was selected for its compact size and features (cf. processor, graphics processor, memory card slot, Micro USB interface, Mini HDMI, RAM memory, etc.). The Raspberry Pi operates on a Linux-based system and can operate as a typical computer when connected to a monitor.

The main characteristics of the Raspberry Pi used are as follows:

---

[1] Flask (2022). URL: `https://flask.palletsprojects.com/`

[2] OpenCV (2022). URL: `https://opencv.org/`

[3] NumPy (2022). URL: `https://numpy.org/`

- 1GHz, single-core CPU
- 512MB RAM
- 2 Micro USB ports
- CSI camera connector for connecting a Raspberry Pi camera
- Micro SD port for loading the operating system and storing data

The Raspberry Pi does not have a built-in camera. The camera used is a Raspberry Pi Zero 5MP (OV5647) of JOY-IT. The camera installation is represented in Figure 4.2.

Figure 4.2: Raspberry Pi Zero W with Camera Module 5MP (OV5647)

The pH measurement module utilizes a pH sensor, which is calibrated using a pH 7.0 and pH 4.0 buffer solution that comes with the sensor. Since the Raspberry Pi's GPIO pins can only read digital signals, an additional ADC module (I2C ADS1115 16-Bit ADC Module) is used (as shown in Figures 4.3 and 4.4). The programming for this module was done using the python DFRobot libraries (*DFRobot PH*, 2022).

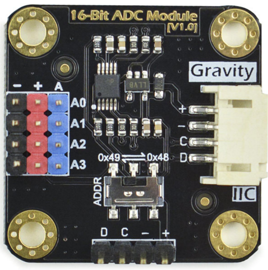


Figure 4.3: ADS1115 16-Bit ADC Module

Figure 4.4: pH sensor

The *picamera* package played a crucial role in the project, as it enabled capturing of images using the Raspberry Pi camera module, and further analysis of the captured images using CV algorithms.

4.1.3 Mobile Application

The mobile application was designed to be user-friendly, with a simple user interface for easy management of the system. The application was developed using the framework, Flutter[1]. As shown in Figure 4.5, six screens were created to assist the user in managing the system. The six screens, from left to right, line by line, respectively, are:

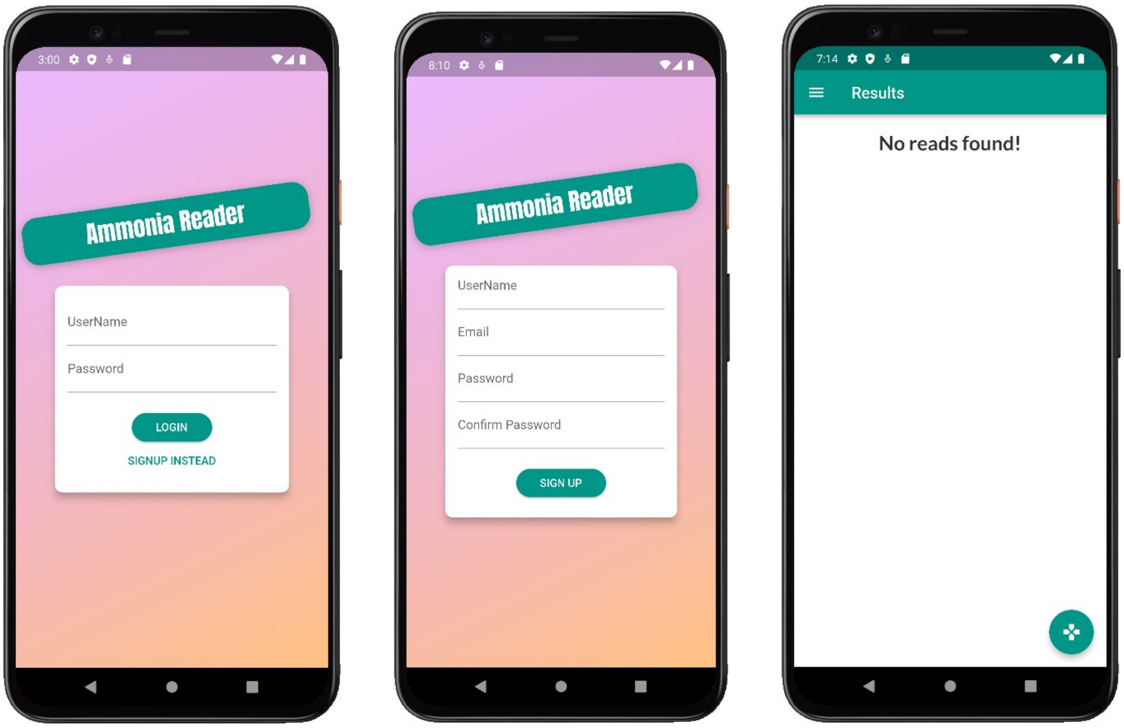
- A login screen ensures that the user needs to perform the authentication before using the mobile application. A username and password are necessary to login;
- A register screen allows the user to register in the system. He will have to insert the cell phone number, email, username, password, and confirmation of the same in the respective boxes belonging to the form;
- We redirected the user to the main screen after the log in. In the main screen, we show all the previously readings executed by the user. In this example, no readings from the desired user are found. In this case, we display a plain text reading "No readings found";
- By pressing the add button in the lower right corner of the main screen, the screen responsible for taking new readings will appear. To request a reading, in this screen,

---

[1] Flutter (2022). URL: `https://flutter.dev/`

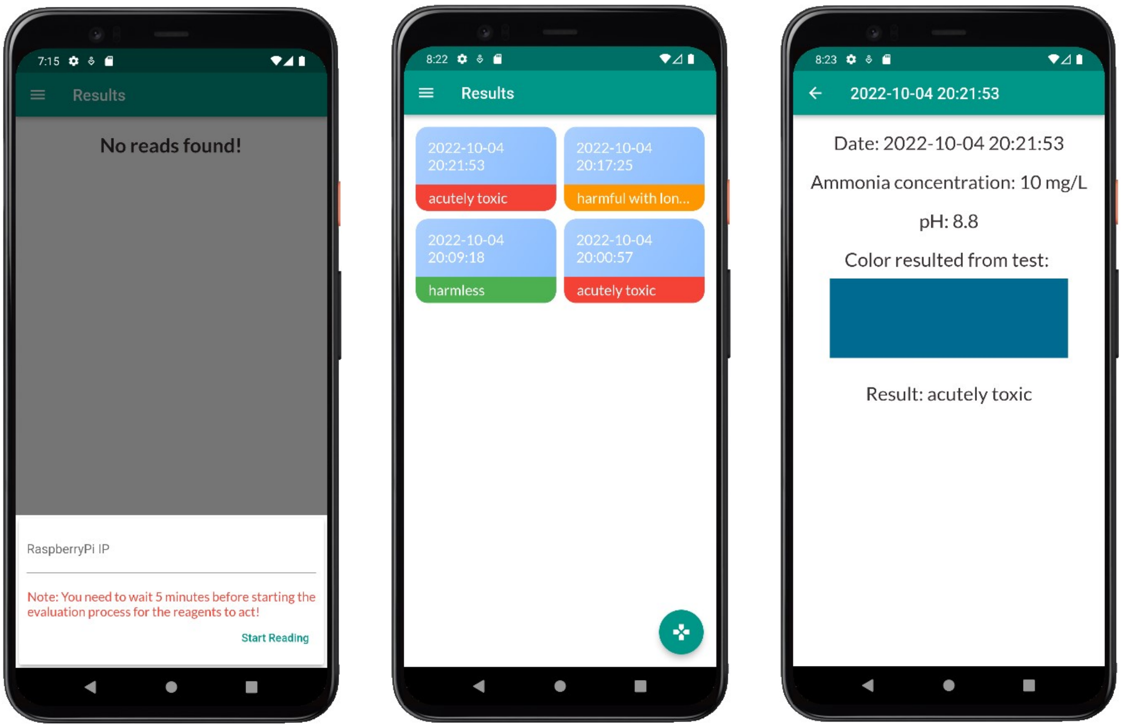
the user inserts the IP address of the Raspberry Pi. After entering the IP address and pressing the Start Reading button, the reading will start;

- In this screen, it is possible to see the main screen with different previous readings. In each reading, you can see the date when they took place and the respective toxicity of the ammonia. As shown, depending on the result of each reading, different colors would appear that match the severity of the ammonia toxicity;
- We redirect the user to a more detailed screen of the reading when the user presses on any reading. On this screen, the user can see the date when the reading occurred, the ammonia concentration, the pH of the water, a sample of the color perceived by the camera, and finally the toxicity that the ammonia presents to the system.



No reads found!

(a) Login screen (b) Register screen (c) Main screen, no reads



No reads found!

Note: You need to wait 5 minutes before starting the evaluation process for the reagents to act!

2022-10-04 20:21:53 acutely toxic

2022-10-04 20:17:25 harmful with lon...

2022-10-04 20:09:18 harmless

2022-10-04 20:00:57 acutely toxic

Date: 2022-10-04 20:21:53

Ammonia concentration: 10 mg/L

pH: 8.8

Color resulted from test:

Result: acutely toxic

(d) New Read screen (e) Main screen, with reads (f) Reads detail screen

Figure 4.5: Multiple screens from the mobile application

In order to enhance security, the mobile application has a built-in feature that periodically checks the validity of the JWT. If the token is found to be invalid, the system automatically logs the user out, ensuring the overall security of the system.

4.2 Backend and Onsite Components Implementation

The implementation of the system's onsite and backend components is the main topic of this section. It describes the technical details of how the Raspberry Pi communicates with the backend. Additionally, it discusses the exact parts that were employed, such as the pH sensor, camera, and I2C ADC module, as well as the libraries and software programs used for pH measurement analysis and computer vision. The Raspberry Pi's function as the primary Single Board Computer and its operating system are also highlighted in this section. Overall, this part gives a thorough overview of how the system's onsite and backend components were technically implemented.

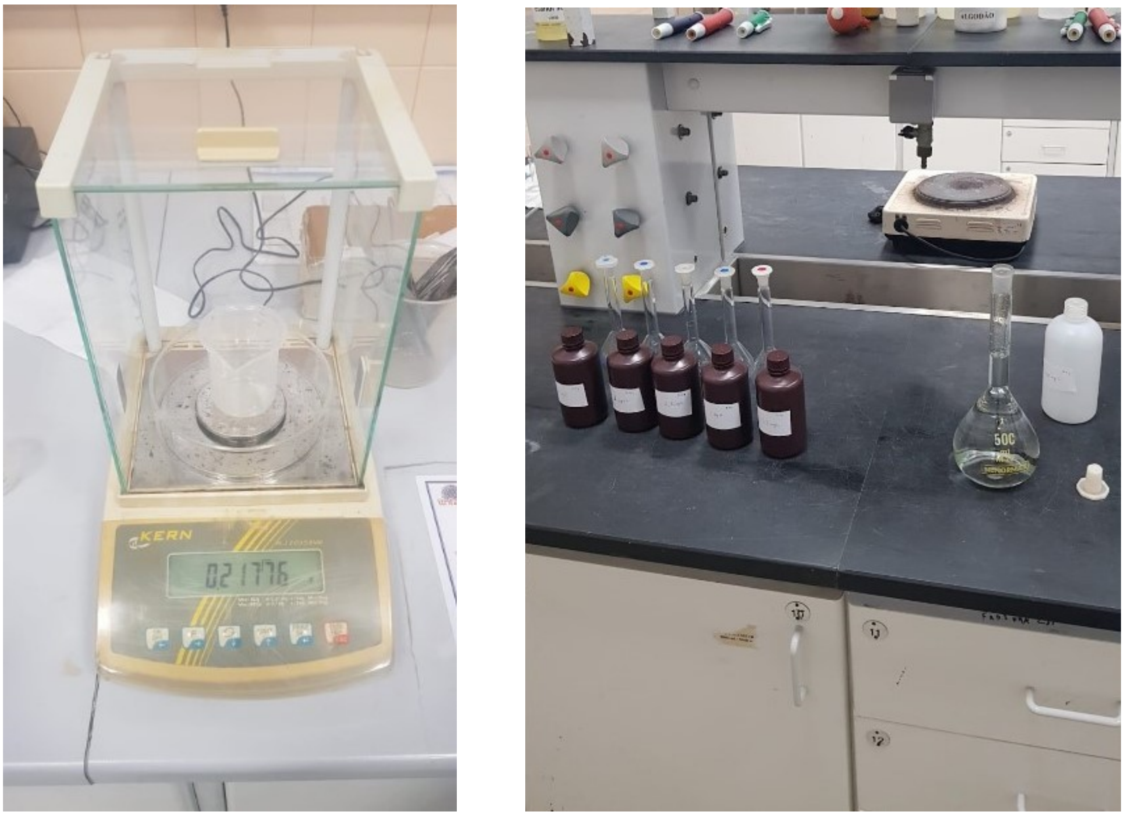
4.2.1 Ammonia concentrations preparation

We prepared aqueous solutions with different concentrations of ammonia nitrogen or TAN. We performed this in order to calibrate and test the system. We used ammonium bicarbonate (NH_4HCO_3) to create the different concentrations. One gram of ammonium bicarbonate is not the same as one gram of ammonium. It is important to know how much NH_4 is present in one gram of ammonium bicarbonate. It is also essential to take into account the purity grade of the used ammonium bicarbonate. This is 99.2%. So in one gram, only 0.992 grams are ammonium bicarbonate. The molar mass of NH_4HCO_3 is 79.05 g/mol, and the molar mass of NH_4 is 18.04 g/mol. With all these essential values considered, we can calculate how much ammonium bicarbonate (NH_4HCO_3) is needed to create a mother solution of 100 mg/L of ammonium (NH_4). The conclusion reach was that we need 0,44 grams of ammonium bicarbonate (NH_4HCO_3) in one liter to create a mother solution of 100 mg/L of NH_4.

In order to create the ammonium concentrations, we used an analytical scale (see Figure 4.6a) since accuracy is fundamental, as a change of only 0.5 mg/L may affect the result of the colorimetric test.

We created a mother solution with a concentration of 100 mg/L of ammonium. With dilutions, we prepared concentrations of 0.5 mg/L, 1 mg/L, 5 mg/L, and 10 mg/L of NH_4 (see Figure 4.6b). A concentration of 0 mg/L, was also created but since this concentration contains no ammonia, it is pure water. These were the concentrations prepared since the colorimetric test used from Sera can only detect these, as seen in Figure 1.2 (sera GmbH, 2018).

We made all the concentrations and dilutions in a laboratory in order to eliminate any errors that might exist and to achieve the highest possible accuracy.



(a) Analytical scale used to prepare the concentrations

(b) Different concentrations of ammonium NH_4

Figure 4.6: Preparation process for the different concentrations

4.2.2 Creation of a controlled environment

As Lindsay W. MacDonald explains, the perception of color can vary based on many different factors (MacDonald, 1999) (see Figure 4.7). The Figure shows the colorimetric test results of the 10, 5, 1, 0.5 and 0 mg/L of NH_4 respectfully in different environments. For this reason, a controlled environment for the system is a necessity. With a controlled environment it is possible to handle all variables. These can be the light source or environment variables, that would otherwise affect the color perception. Since it is possible to restrict the light source to only one and remove all environment variables, the color represented in the colorimetric result, to a camera or a sensor, would always be perceived as the same. We sketched and 3D printed the controlled environment for the system (see Figure 4.8).

The original color of the 3D prints was black. Black absorbs light, and the color present in the colorimetric test captured by the camera was difficult to read. For this reason, later in development, we changed the color of the 3D prints to white, since white reflects the color.

The three sketches present in the Figure 4.8, respectively in order, are:

- A box, this serves the purpose of helping the color detection. A hole is present on

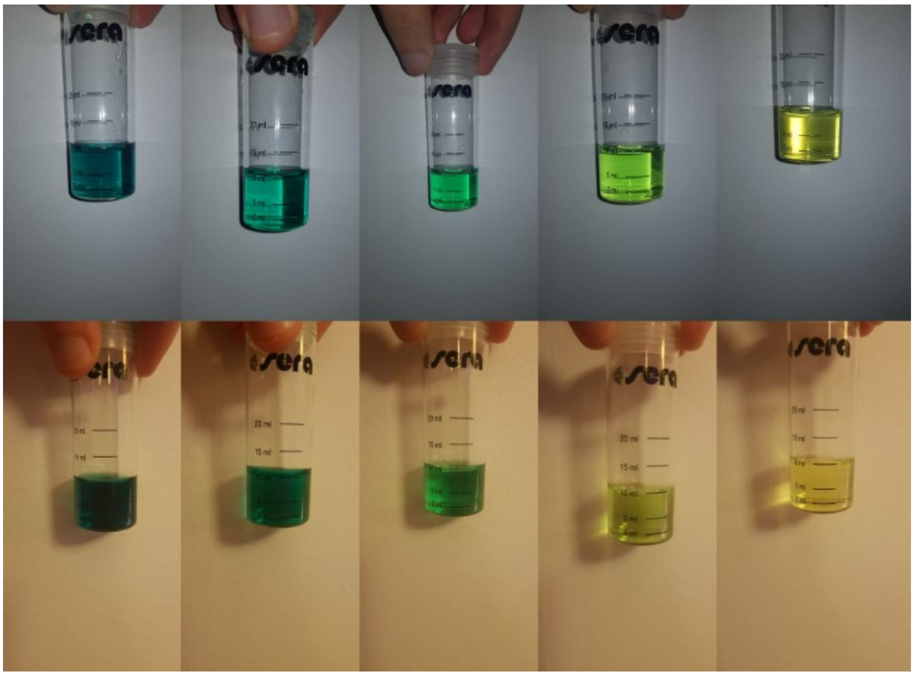


Figure 4.7: Different concentrations with distinct light sources and environment variables

Figure 4.8: 3D sketches of the controlled environment

the lateral of the box, more specifically at the end of the lateral in the center. This hole serves the purpose of placing the camera, sensor or light source inside the box;

- A lid, that has the intention of totally isolating the box from external light or environment variables;

- A glass holder, that has the purpose of holding a cylindrical glass where the colorimetric test happens. In this 3D print, there are two holes opposite to each other. One where we insert a light source. Another one, where we screw the AS7341 spectral sensor in order to read the light received from the light source filtered by the colorimetric result.

While performing tests, we also insert the glass holder 3D print inside the box. This occurs to eliminate all the external light sources and environment variables.

4.2.3 Color detection module

This module is responsible for detecting which color is represented in the colorimetric test and further on detect the ammonia concentration. This is possible by comparing the color present in the result with the colors of the previously known ammonia concentrations. In order to detect the color, we used two methods. i) a colorimetric sensor and, ii) CV. We implemented and tested both methods to detect which one would have a higher accuracy.

4.2.3.1 Color detection using colorimetric sensor

To detect the color of the colorimetric test using a sensor, we used the AS7341 Spectral Sensor (see Figure 4.9). This Spectral Sensor is an 11-channel multi-spectral that is used in applications for color detection and spectrum analysis. The wavelength range of the spectral response is between 350 nm to 1000 nm. The visible spectrum is covered by eight optical channels. Near-infrared light can be measured using a single channel. The "Flicker" channel is set up for flicker measurements, while the "Clear" channel is a photodiode without a filter (thus the name "clear") (*AS7341 – 11-Channel Spectral Color Sensor*, 2022).

Figure 4.9: AS7341 Spectral Sensor

Based on Frances experiment (Frances, 2020) and previously mentioned research (Xu et al., 2022), we developed a method to detect the color present in the colorimetric test result using a colorimetric sensor. The system would use the glass holder (See Figure 4.8) where in one of the holes we would insert a light source. On the other hole, we would screw the AS7341 spectral sensor (See Figure 4.10). Between the light source and the AS7341 spectral sensor is a cylindrical glass containing the colorimetric result. As explained previously, the colorimetric result has a coloration, so applying a white light source in front of it will cause the shadow to be the same color as the liquid (See Figure 4.11). The sensor would then capture the shadow and subsequently it would be possible to identify the color present in the liquid. When we know the color, it would be possible to identify the ammonia concentration. This would also be possible because different concentrations result in different colors. Then, by comparing the color of the colorimetric test, and the previously know colors of the different ammonia concentrations, it would be possible to identify which concentration is present in the water sample.

Figure 4.10: Assembly of the sensor in the system

As shown in the Figure 4.10, we screwed the AS7341 spectral sensor in one side of the 3D printed glass holder. On the opposite side we attached the light source, Bright LED Module. Finally, we placed the cylindrical glass where the colorimetric test will take place between the colorimetric sensor and the light source. It is important to note that the sensor also includes an LED, which can be turned on or off. It is possible to regulate the intensity of it with a range from 0 to 10.

In order to apply the AS7341 spectral sensor to the system, we used a microcontroller with the ESP32 module connected via the SCL and SDA pins. The light source used was the Bright LED Module (*Gravity: Bright LED Module*, 2022) also connected to the microcontroller.

The coding language to develop this approach was C++ using the Visual Studio Code plus the platformIO extension. This way it was possible to upload and run code into the microcontroller with the ESP32 module. The algorithm developed used the DFRobot_AS7341 library (*DFRobot_AS7341 Library*, 2022). Using this library it was feasible to retrieve from the sensor the intensity ranging from 0 to 1000 of the following sections of the visible spectrum: 405-425nm, 435-455nm, 470-490nm, 505-525nm, 545-565nm,

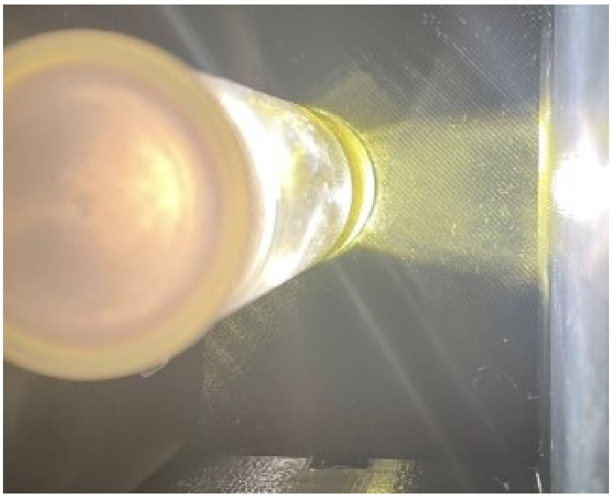


Figure 4.11: Filtration of light based on the color of the liquid

580-600nm, 620-640nm, and 670-690nm. To obtain such values the following code 4.1 can be executed.

Listing 4.1: Obtain the values from the AS7341 spectral sensor

```
#include <Arduino.h>
#include "DFRobot_AS7341.h"

void read_from_sensor(){
    DFRobot_AS7341::sModeOneData_t data1;
    DFRobot_AS7341::sModeTwoData_t data2;

    //Start spectrum measurement of the first four sections
    as7341.startMeasure(as7341.eF1F4ClearNIR);
    //Read the value of sensor data channel
    data1 = as7341.readSpectralDataOne();

    Serial.print("F1(405-425nm):");
    Serial.println(data1.ADF1);
    Serial.print("F2(435-455nm):");
    Serial.println(data1.ADF2);
    Serial.print("F3(470-490nm):");
    Serial.println(data1.ADF3);
    Serial.print("F4(505-525nm):");
    Serial.println(data1.ADF4);

    //Start spectrum measurement of the last four sections
    as7341.startMeasure(as7341.eF5F8ClearNIR);
```

```
    //Read the value of sensor data channel
    data2 = as7341.readSpectralDataTwo();

    Serial.print("F5(545-565nm):");
    Serial.println(data2.ADF5);
    Serial.print("F6(580-600nm):");
    Serial.println(data2.ADF6);
    Serial.print("F7(620-640nm):");
    Serial.println(data2.ADF7);
    Serial.print("F8(670-690nm):");
    Serial.println(data2.ADF8);
}
```

To prove the concept of the sensor, we executed a simple test where the sensor would be exposed to a white light and the absence of light. The results were the expected: the sensor returned the maximum intensity (1000) on all sections of the visible spectrum when exposed to the white light, and the minimum intensity (0) without any light. Thus, it was possible to conclude that the sensor was performing as expected.

To detect the color of a liquid using the spectral sensor, we executed a straightforward test. The test consisted in testing the different ammonia concentrations, as seen in the Figure 4.7, and comparing the actual color of the colorimetric test result with the color perceived by the sensor. First, it was necessary to determine the colors of the colorimetric result to know ammonia concentrations. Those are, as seen in the Figure 4.7, yellow for 0 mg/L, light green for 0.5 mg/L, green for 1 mg/L, light blue for 5 mg/L and finally dark blue for 10 mg/L. In the test, we made 500 reads with a spacing of 500 milliseconds between each reading. After obtaining the readings, we calculated the average of the 500 measures. The sensor light was off and the only light source that illuminated the system was the Bright LED Module. The test used the 3D printed glass holder inside the box covered with the lid with the purpose of restricting any external variable. The results can be seen at the Table 4.1.

In the Table 4.1 it is possible to observe the intensity of light in each section of the visible spectrum. The 5 mg/L concentration was not included in this test. This happened because, at the time, there was a dilution error at such concentration. Observing the Table in question it is conceivable to conclude that the predominant section of the visible spectrum in the concentrations of 0 mg/L, 0.5 mg/L and 1 mg/L is the 545-565nm. By observing such section in the Figure 4.12, we conclude that it indicates the green color. In the concentration of 10 mg/L the predominant section of the visible spectrum is the 505-525nm. This section corresponding to the color light green. From the results it is difficult to distinguish the concentrations. The predominant section of the visible spectrum is mainly the same and not the correct in most cases. The only difference is the total amount

Table 4.1: Intensity of light in each section of the visible spectrum with the LED of the sensor off

Concentration	405-425nm	435-455nm	470-490nm	505-525nm	545-565nm	580-600nm	620-640nm	670-690nm
0 mg/L	12	39	55	131	252	172	138	42
0.5 mg/L	8	29	46	120	187	104	57	17
1 mg/L	5	31	38	117	124	60	19	7
10 mg/L	2	31	27	52	23	3	2	2

of light that passes through the liquid and captured by the sensor. This can be calculated by summing the light intensity of all sections of the visible spectrum. The total amount of light is less as the concentrations get higher as seen in the Table 4.2.

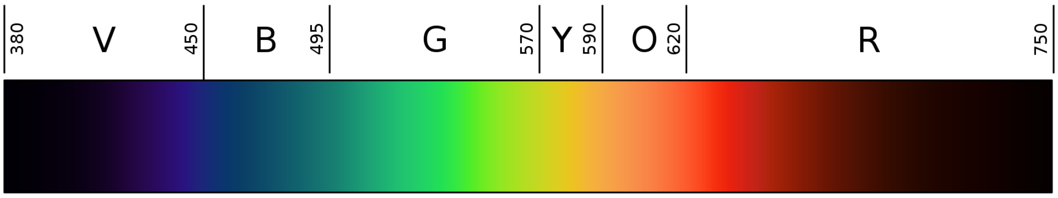


Figure 4.12: Visible spectrum divided into sections

Table 4.2: Total light filtration of each concentration from Table 4.1

Concentration	Total sum of light
0 mg/L	790
0.5 mg/L	531
1 mg/L	365
10 mg/L	109

It's also possible to note that the values present in the 10 mg/L concentration are too low. The higher value is 52 but the range of the sensor is from 0 to 1000. For this reason we performed a test with the AS7341 spectral sensor LED on. The test consisted on 500 reads with a spacing between them of 500 milliseconds with the sensor LED on at the intensity of 7, for each concentration. The test was executed with the sensor LED on to see if the value would become higher and more distant. As explained before the sensor light was on, so there were two light source that illuminated the system, the Bright LED Module, and the LED from the sensor. The test was done with the 3D printed glass holder inside the box covered with the lid to restrict any external variable. It is possible to observe the results at the Table 4.3.

Table 4.3: Intensity of light in each section of the visible spectrum with the LED of the sensor on

Concentration	405-425nm	435-455nm	470-490nm	505-525nm
0 mg/L	13	67	31	70
0.5 mg/L	17	122	51	115
1 mg/L	13	78	32	73
5 mg/L	16	113	42	101
10 mg/L	17	139	55	114

Concentration	545-565nm	580-600nm	620-640nm	670-690nm
0 mg/L	112	100	79	54
0.5 mg/L	190	162	123	77
1 mg/L	115	101	79	53
5 mg/L	162	148	115	69
10 mg/L	199	161	125	83

As it is possible to conclude by observing the Table 4.3, the results were not the expected. The predominant section on the visible spectrum in every concentration tested was the 545-565nm. When comparing to the Figure 4.12, corresponds to the color green.The total sum of light increased in every concentration as the exception of the 0 mg/L. It also was no longer possible to observe its decrease as the concentrations got higher. It became an irregular value, as seen in the Table 4.4.

Table 4.4: Total light filtration of each concentration from Table 4.3

Concentration	Total sum of light
0 mg/L	526
0.5 mg/L	857
1 mg/L	544
5 mg/L	766
10 mg/L	793

We have to consider different variables that may be influencing the outcomes from the unexpected results. One of the conclusions reached was that many light sources would only interfere and not help with the process of detecting color. For that reason for the following tests, we only use the Bright LED Module. Until now, all the test, were inside the controlled environment which was of a black color. This could be interfering with the results since black absorbs light. That would only lead to the AS7341 spectral sensor detecting less light and less color. Consequently, we changed of the color of the controlled environment to the white. The white coloration restrict light absorption and promote light reflection.

In conclusion, the system in order to detect color using the AS7341 spectral sensor consisted on the sensor it self, a Bright LED Module, a microcontroller with the ESP32 module, and the 3D printed controlled environment of white color (see Figure 4.8). The 3D prints include the glass holder, the box, and the lid with the purpose of restraining all external variables.

4.2.3.2 Color detection using computer vision

In the early stages of the development of the system, in terms of computer vision, a black box and lid where 3D printed (See Figure 4.8). This was carried out to to control external variables like changes in the light source. The camera was places inside the box using the hole present in it, along with the light source Bright LED Module (*Gravity: Bright LED Module*, 2022). Using this technique by placing the result of the colorimetric test inside the controlled environment, that was lighted up with the LED, the results were hard to distinguish and to identify (See Figure 4.13). This happened because the 3D prints were black and for that reason the light emitted by the LED was getting absorbed. The concentrations shown in the Figure 4.13 are respectively in order 0 mg/L, 1 mg/L and 10 mg /L.

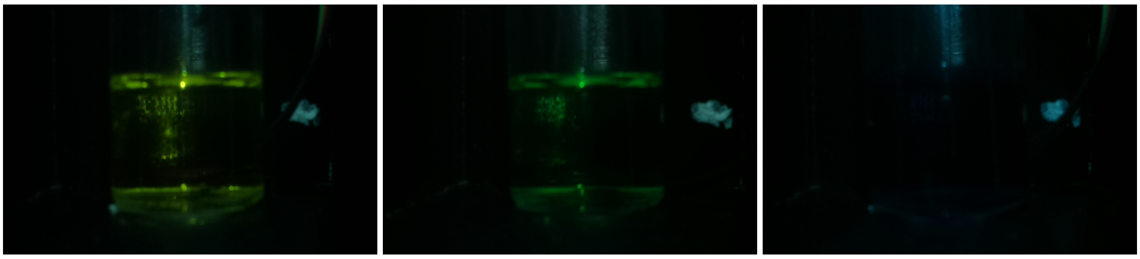


Figure 4.13: Different concentrations inside the controlled environment of black color

For this reason we made a temporary change to the controlled environment. We covered the walls of the box with a white sheet of paper in order to prove the concept. The results conclude that the problem was indeed the color of the controlled environment being black as shown in the Figure 4.14. The concentrations shown in the Figure 4.14 are respectively in order 0 mg/L, 1 mg/L and 10 mg /L.

With improvement of the results we decided to change the color of the controlled environment to white. Every wall and ground of the box where spray painted into white, along side with the lid which also suffered such alterations. The concentrations shown in the Figure 4.14 are respectively in order 0 mg/L, 1 mg/L and 10 mg /L in the described controlled environment.

As seen in the Figure 4.14 and Figure 4.15, the perception of the background color concerning the controlled environment changes based on the color present on the colori-

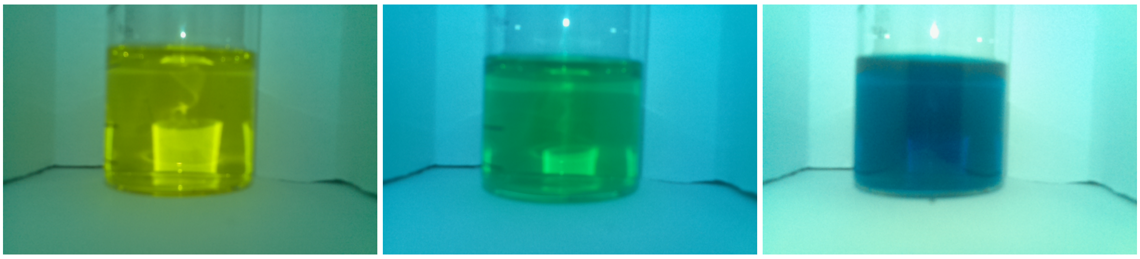


Figure 4.14: Different concentrations inside the temporary changed controlled environment

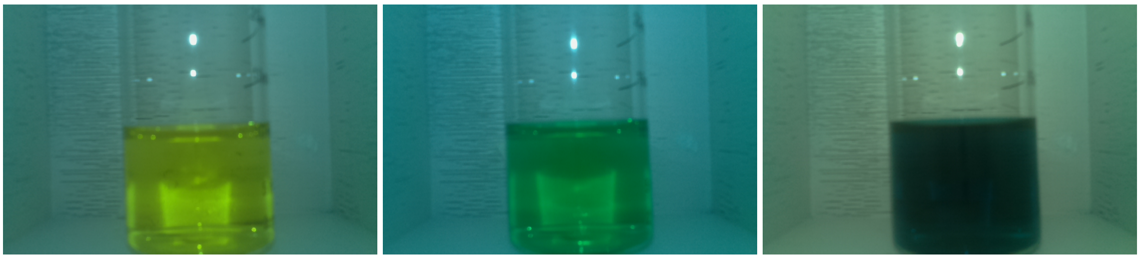


Figure 4.15: Different concentrations inside the controlled environment of white color

metric test result and the color of the controlled environment itself. In order to attempt to remove this, we tested a different light source. Until now all tests were done using the Bright LED Module, but a different light source was tested, the WS2812-12 RGB LED Ring Lamp.

The WS2812-12 RGB LED Ring Lamp consists on a full-color RGB LED Ring that gives the possibility to control the color of each 12 LED's present in the ring (*WS2812-12 RGB LED Ring Lamp*, 2022). Since it is possible to control every LED individually two tests were preformed with the described light source. One where all LED's were illuminating with the color white, which corresponds to the value (255,255,255) in RGB. Another test with each third of the LED Ring illuminating one of the primary colors. One third would display only red (255,0,0), another with green (0,255,0), and the final third with blue (0,0,255). In the Figure 4.16, it is possible to compare the color perception by the camera when illuminated with: the Bright LED Module, the WS2812-12 RGB LED Ring Lamp with all LED's emitting white color, and the WS2812-12 RGB LED Ring Lamp with each third displaying each primary color, respectively. All images exhibit the colorimetric result of 0 mg/L.

Figure 4.16: Difference between the Bright LED Module an the WS2812-12 RGB LED Ring Lamp with difrent configurations

By analyzing the different images it is possible to conclude that using the WS2812-12 RGB LED Ring Lamp impede the camera from examining the true color of the colorimetric response. Due to this reason the light source used in the system was the Bright LED Module.

The camera instability over the background color still remained a problem, since changing the light source would only make it worse. Due to this reason a different technique was conceived. Using the same principle as the AS7341 Spectral Sensor, an approach where the distance between the camera and the cylindrical glass was shortened. This way the only color present in the image captured by the camera was the color of the colorimetric result. With this technique, the results were faultless as seen in the Figure 4.17. The Figure shows the concentrations of 0 mg/L, 0.5 mg/L, 1 mg/L, 5 mg/L, and 10 mg/L, respectively.

(a) 0 mg/L (b) 0.5 mg/L (c) 1 mg/L (d) 5 mg/L (e) 10 mg/L

Figure 4.17: Different concentrations inside the controlled environment

In order to detect the color present in the colorimetric test result, we made a change of color space. The captured photograph are represented in the RGB space and in order to analyse and detect the colors, the color space of the image was changed to the CIE L*a*b* (See Figure 4.18). To alter the color space represented in an image is it a necessity to use the *OpenCV* library specifically the *cv2.cvtColor()* function. The function requires two parameters, the src, which indicates the image whose color space is to be changed, and the code, which requests for the color space conversion code. After the execution, the function will return an image with the color space changed from the image selected to the code inserted. An image is captures by the Raspberry Pi camera module and opened in the algorithm using the *OpenCV* function *cv2.imdecode()*. The requested parameter of this function is only the image bytes in base64 and a flag. The function, using the flag read, returns an image that is loaded from those specified bytes. The color space predefined is *BGR* which is a modified RGB being the only difference the sub-pixel layout. So when it is intended to change the color space to, for example, the *LAB* color space, the structure used, considering that an image was opened and saved in a variable called *img*, is *imglab = cv2.cvtColor(img, cv2.COLOR_BGR2LAB)*. An example of this code can be executed as follows (See 4.2).

Listing 4.2: Obtain image from base64 and convert it to the color space LAB

```
import cv2
```

```
img_BGR = cv2.imdecode(img_bytes, cv2.IMREAD_COLOR)
img_LAB = cv2.cvtColor(img_BGR, cv2.COLOR_BGR2LAB)
```


(a) 0 mg/L (b) 0.5 mg/L (c) 1 mg/L (d) 5 mg/L (e) 10 mg/L

Figure 4.18: Different concentrations inside the controlled environment, LAB color space

First it was a necessity to determine the RGB and LAB values of each concentration. Ten readings of each concentration were done and the average result is displayed in the Table 4.5. To determine the average RGB and LAB values of a picture, the following code can be executed (See 4.3).

Listing 4.3: Calculate average RGB and LAB values of a photograph

```
import numpy as np
import cv2

img_BGR = cv2.imdecode(img_bytes, cv2.IMREAD_COLOR)

#Calculates the average RGB values of a photograph
avg_color_per_row = np.average(img_BGR, axis=0)
avg_color = np.average(avg_color_per_row, axis=0)
avg_color = [int(arrayint) for arrayint in avg_color]
average_R = avg_color[2]
average_G = avg_color[1]
average_B = avg_color[0]

#Changes color space of image from BGR to LAB
img_LAB = cv2.cvtColor(img_BGR, cv2.COLOR_BGR2LAB)

#Calculates the average LAB values of a photograph
avg_color_per_row = np.average(img_LAB, axis=0)
avg_color = np.average(avg_color_per_row, axis=0)
avg_color = [int(arrayint) for arrayint in avg_color]
average_L = avg_color[0]*100/255
average_A = avg_color[1]-128
average_B = avg_color[2]-128
```

As explained before, the values in the RGB color space vary form 0 to 255, but the values of the color space LAB do not have the same range. The ranges in the LAB color

Table 4.5: Values of the different concentrations in RGB and LAB values

Concentration	Average RGB	Average LAB
0 mg/L	[84,132,41]	[128,96,170]
0.5 mg/L	[27,149,63]	[133,83,160]
1 mg/L	[0,160,98]	[148,77,150]
5 mg/L	[0,149,106]	[140,83,141]
10 mg/L	[0,113,139]	[112,110,106]

space are, the L varies from 0% to 100%, the a and b have the same ranges those being from -128 to 128.

In the Table 4.5 the values of the LAB color space are not in the correct ranges. This happens when *OpenCV* converts an image from RGB to LAB the following changes to obtain the final values happen. $L = L \times 255/100,\ a = a+128,\ b = b+128$[1]. To obtain the real LAB values in the right format it is a necessity to convert the modified values into the original ones. This conversion can be done by multiplying the *L* value with 100 and then divide it by 255 and subtracting 128 to both the *a* and *b* values. This changes can be viewed at the Table 4.6.

Table 4.6: Values of the different concentrations in Original LAB average

Concentration	OpenCV LAB average	Original LAB average
0 mg/L	[128,96,170]	[50.196%, -33, 42]
0.5 mg/L	[133,83,160]	[52.157%, -45, 32]
1 mg/L	[148,77,150]	[58.039%, -51, 22]
5 mg/L	[140,83,141]	[54.902%, -45, 13]
10 mg/L	[112,110,106]	[43.922%, -18, -22]

With the right LAB values it was now possible to detect the result of the colorimetric test. With the following algorithm, the system captures a photograph of the colorimetric test result, and converts the captured image from the color space RGB to the LAB color space. It then calculates the average LAB values of the image captured, that represent the color of the colorimetric test result. It is possible to discover the ammonia concentration by calculating the Euclidean distance between the average of the captured image with the previously known LAB averages of the different concentrations. The smaller the Euclidean distance between two colors the less the difference between them. This method of color detection can be used in the LAB color space since it is perceptually uniform. This way it it possible to identify the concentration present in the water sample by comparing the distances between the color present in the colorimetric test result with the colors of the known ammonia concentrations. This can be executed in python with the following

---

[1] OpenCV: Color conversions(2015). URL: `https://docs.opencv.org/3.4/de/d25/imgproc_color_conversions.html`

code (See 4.4).

Listing 4.4: Calculate the Euclidean distance, and identify the smallest one.

```
#Known LAB averages of the different concentrations
lab_concentrations = {
    0:[50.19607843137255, -33, 42],
    0.5:[52.15686274509804, -45, 32],
    1:[58.03921568627451, -51, 22],
    5:[54.90196078431372, -45, 13],
    10:[43.92156862745098, -18, -22],
}

#Detects concentration present in photograph
#Receives the average L, A, and B values of a photograph
def detect_concentration(average_L, average_A, average_B):
    #0 mg/L
    dl = (lab_concentrations[0][0] - average_L) ** 2
    da = (lab_concentrations[0][1] - average_A) ** 2
    db = (lab_concentrations[0][2] - average_B) ** 2
    zero = math.sqrt(dl+da+db)

    #Repeat the same process for all five concentrations
    ...

    #10mg/L
    dl = (lab_concentrations[10][0] - average_L) ** 2
    da = (lab_concentrations[10][1] - average_A) ** 2
    db = (lab_concentrations[10][2] - average_B) ** 2
    ten = math.sqrt(dl+da+db)

    #Create a list with the five Euclidean Distances
    list = [zero, zerodotfive, one, five, ten]
    #Sorts the list from smallest to biggest
    list.sort()

    #Shortest distance represents the concentration
    #present in the tested water sample
    if list[0] == zero:
        return("0")
    elif list[0] == zerodotfive:
        return("0.5")
    elif list[0] == one:
```

```
        return("1")
    elif list[0] == five:
        return("5")
    elif list[0] == ten:
        return("10")
```

4.2.4 pH Measurement module

To detect the ammonia toxicity in the system it is a necessity to cross-reference the ammonia concentration with the pH as seen in the Figure 1.4. The pH sensor Analog pH Sensor/Meter Kit V2 from *DFRobot* was used (see Figure 4.4). The pH is a number that indicates how acidic or alkaline a solution is. The hydrogen ion concentration index is another name for it, and it is measured using the pH scale. The pH is commonly used in aquaponics, aquaculture, and environmental water testing in a variety of ways. The pH typically ranges from 0 to 14. When a solution has a pH of 7, it is considered to be neutral, if it has a pH below 7, it is acidic and if it has a pH beyond 7, it is alkaline. Since we connect the pH sensor to the Raspberry Pi and the GPIO of this SBC can only read digital signals, it is a necessity to use an external ADC module (I2C ADS1115 16-Bit ADC Module) (see Figure 4.3). The *DFRobot* I2C ADS1115 16-bit ADC module is especially made for the Raspberry Pi and uses 16-bit ADC chip ADS1115 that supports 3.3 to 5V wide voltage power supply. Accurate capture and conversion can be carried out for both weak and highly fluctuating signals. This is possible thanks to the programmable gain adjustment (PGA). As a result, it can be used for any application where the primary control board has to precisely capture analog signals such as the pH sensor.

We developed the detection of the pH in python and used the *DFRobotPH library* (*DFRobot PH*, 2022). This library already takes into consideration the necessity to use the ADC module (I2C ADS1115 16-Bit ADC Module).

A calibration must be performed with the purpose of using the pH sensor. It comes with four buffer solutions two of pH value 4.0 and two with a pH value of 7.0. In order to calibrate the sensor it is necessary to record the analog values of both pH 4.0 and 7.0 into a text file. This would operate as the ground truth of the sensor, meaning that each measurement will take these values into account. The calibration process consists of creating a linear function based on two points: the pH 4.0 and 7.0 values and their respective analog values. With the created linear function each analog value will result in a pH value.

In the system, we used the pH sensor as follows. The user takes a water sample from the aquaponics system and submerge the sensor inside it. The sensor returns the analog value by reading the hydrogen ion concentration index. This value is then inserted into the linear function, resulted from the calibration process, returning a pH value. This value depict the pH that is in the water sample, thus the value present in the aquaponics system.

4.2.5 Ammonia toxicity detection

To determine the toxicity of the ammonia present in the aquaponics system we must use two values: pH and ammonia concentration (see Figure 1.4).

There are two types of ammonia in water: ionized (NH_4^+), and unionized (NH_3) ammonia. The pH of the water is the main determinant of the relative content of the two types of ammonia (see Figure 1.1). Total ammonia nitrogen, abbreviated as TAN, is the sum of NH_4^+ and NH_3 ions.

For this reason, a colorimetric test needs to be used to develop the system to detect the total ammonia nitrogen. The sera NH_4/NH_3-Test, colorimetric test used, enables the monitoring of both ions total concentration (sera GmbH, 2018). The actual ammonia level or TAN can be calculated according to the pH value using the included chart 1.4. The test includes three reagents, numbered from 1 to 3, a cylindrical glass, where the water sample will take place and an instruction guide. The instruction guide includes a palette and a chart. The pallete is used to compare the result of the colorimetric test with the colors to obtain the ammonia concentration (see Figure 1.2). The chart is used with the purpose of cross-referencing the ammonia concentration and the pH value to obtain the TAN (see Figure 1.4).

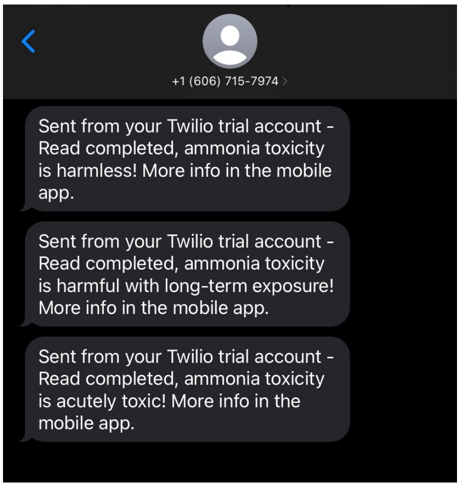
The color detection module returns the ammonia concentration present in the water sample, and the pH detection module is responsible for determining the pH value present on the system. We imported the table provided by the colorimetric test into the code, in order to cross-reference the two values returned by both models. This way, we can obtain the toxicity of the ammonia present in the system which is later return to the user.

4.3 Summary

In the system everything beyond applying the reagents will be executed autonomously. The color detection module handles the identification of the color present in the colorimetric test result and determining which ammonia concentration is present in the sample. The pH detection module handles detecting the pH present in the system, using the pH sensor. Finally, the ammonia toxicity can be establish by cross-referencing the ammonia concentration and the pH of the system concluding if the ammonia present is harmless, harmful with long-term exposure or acutely toxic.

A mobile application was also created to make this steps as autonomous and as simple to the user as possible. Making it convenient and elementary to use, information like the date of each reading and the ammonia toxicity resulted from that reading can be seen in the main screen. When pressing in one reading we redirected the user to a screen showing every detail about the select reading. In this screen, the ammonia concentration, pH value, color resulted from the colorimetric test, the date, and the ammonia toxicity are shown.

We also send warnings via SMS to the user (see Figure 4.19). When the pH values are unhealthy or unacquainted to an aquaponics system and when the reading is completed. The information shown on the SMS varies depending on the reason it was sent. The two reasons why the SMS was sent are: i) The pH value is too low or too high for the system, or ii) The reading is complete. The information shown in the SMS respectively are: i) the pH value and whether it is too low or too high, or ii) the ammonia toxicity. To obtain more details about any reading, the user can press in the desired read in the mobile app.



Sent from your Twilio trial account - Read completed, ammonia toxicity is harmless! More info in the mobile app.

Sent from your Twilio trial account - Read completed, ammonia toxicity is harmful with long-term exposure! More info in the mobile app.

Sent from your Twilio trial account - Read completed, ammonia toxicity is acutely toxic! More info in the mobile app.

Figure 4.19: SMS warnings sent to the user

Chapter 5

Evaluation Experiments and Analysis of Results

After examining the flow, the system's implementation, and its evaluation, this chapter will assess the outcomes of the tests conducted with each system module. This chapter describes in detail the evaluation metrics used for each module, and discusses the results obtained.

In order to detect the color resulted from the colorimetric test, two approaches were studied: i) using a microcontroller and a colorimetric sensor; ii) using CV algorithms with the help of an SBC and a camera module. These two components allow the system to obtain the ammonia concentration depending on the color present in the colorimetric test result. With the purpose of detecting the pH present in the system, we used a pH sensor connect to the SBC via an ADC.

5.1 Evaluation and results

The metrics and implementation formulas used to evaluate the system are described in this section. A description of every test that was conducted is also provided.

5.1.1 Evaluation metrics

Evaluation metrics are used to quantify the performance and accuracy of a system. The evaluation metrics used in this system were the following:

- Euclidean distance
- Percentage error
- Absolute error

In terms of CV, the Euclidean distance (See figure 5.1) is an evaluation metric that measures the distance between two points in an Euclidean space. Euclidean space is the fundamental space of geometry, intended to represent physical space. Specified that the *CIE L*a*b** is a global standard for perceptual uniformity, the difference between any two colors that the human eye can distinguish is proportional to their Euclidean distance inside the given color space. Meaning that it is possible to know the distance between two colors in the *CIE L*a*b** color space by calculating the Euclidean distance between them.

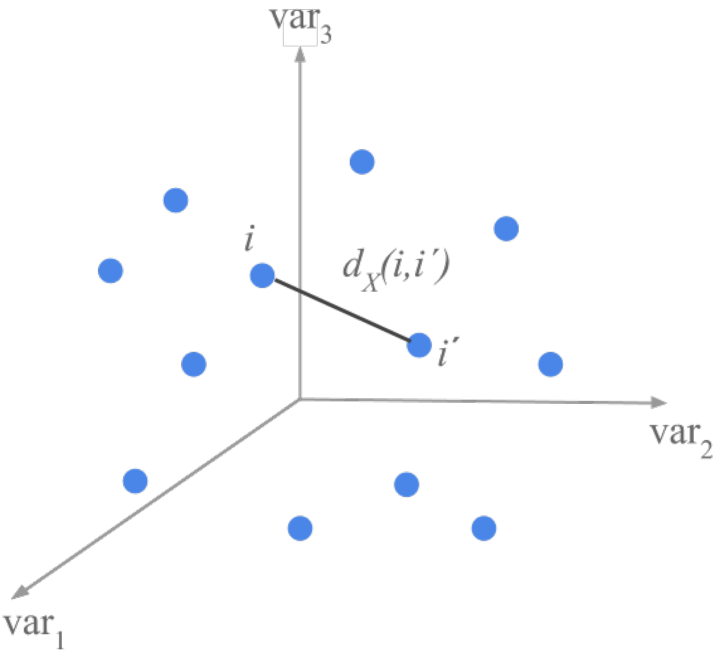


Figure 5.1: Euclidean distance in three-dimensional space

To calculate the Euclidean distance in the *CIE L*a*b** or *LAB* color space between point a and b, the following mathematical expression is used 5.1.

$$d(a,b) = \sqrt{(a_L - b_L)^2 + (a_a - b_a)^2 + (a_b - b_b)^2} \tag{5.1}$$

Points a and b are present in the *CIE L*a*b** color space, meaning that these points represent colors. Knowing the distance between the colors that correspond to points a and b allows one to determine whether those colors are far away or close to one another in terms of how the human eye perceives them.

Another evaluation metric used was the percentage error. This is used in order to ensure that the values returned from a sensor are viable and calibrated. This can be calculated by reading the value of a sensor and comparing it to a values measured with other form of measurement. A percentage error can be calculated using the following mathematical equation 5.2.

$$PercentageError = \frac{ValueFromSensor - RealValue}{RealValue} \times 100 \tag{5.2}$$

Additionally, another evaluation metric used was the absolute error. This is carried out in order to make sure that a sensor's values are accurate and valid. This can be determined by reading the sensor's value and comparing it to readings obtained using other feasible measuring methods. The absolute error can be calculated using the following mathematical equation 5.3.

$$\Delta_{value} = |RealValue - ValueFromSensor| \tag{5.3}$$

5.1.2 Results obtained

This subsection describes the results obtained from implementing the metrics presented for the evaluation of each modules. These metrics vary from module to module.

These results, which are an average of the outcomes of all the tests carried out on each module, will be presented in properly annotated tables. The outcomes of the various system modules can then be analyzed in accordance with various evaluation criteria.

To determine the efficacy of the absolute system, the mean of all the modules will be assessed at the conclusion.

5.1.2.1 Color detection module using colorimetric sensor

To test the colorimetric sensor AS7341 spectral sensor, we used a microcontroller with the ESP32 module, a Bright LED Module, and the controlled environment with the white color (See Figure 4.8). The test was executed with the 3D printed glass holder inside the box covered with the lid to restrict any external variable. The test consists on 500 reads with a spacing of 500 milliseconds between each reading. After obtaining the readings, the average of the 500 measures was calculated. With this into consideration, we performed tests where the sensor LED was off.

Looking at the previous tests where the controlled environment was black, it was expected that the sensor would capture more light by changing the color of the controlled environment to white. However, this is not what happened. Table 5.1 displays the comparison between the concentration of 10 mg/L. The only variable that changes is the color of the controlled environment, those being black or white. By analyzing the results it is clear to say that it gets worse. The results became lower and hardest to identify the color.

We ordered different sensors and tested in the same environment and test conditions. This was carried out in order to make sure that the unexpected results were not due to a faulty sensor. Nevertheless, the results remained the same. Reaching the conclusion that the approach of detecting the color present in the colorimetric test result and identify the

Table 5.1: Intensity of light in each section of the visible spectrum with the LED of the sensor off when analyzing the concentration 10 mg/L

Controlled environment	405-425nm	435-455nm	470-490nm	505-525nm	545-565nm	580-600nm	620-640nm	670-690nm
Black	2	31	27	52	23	3	2	2
White	0	14	10	13	0	1	1	1

concentration present in the water sample with the colorimetric sensor was not suitable for use in the present system. Other approaches like using CV were analyzed and tested.

5.1.2.2 Color detection module using computer vision

To remove specific details and to obtain a more uniform color, without altering the color present in the captured image the Gaussian blur was tested in all concentrations. The Gaussian blur did not changed any values in the LAB or RGB color spaces. For that reason, the Gaussian blur was not used.

We performed a test using five readings of each concentration. The Euclidean distance between every calibrated color of each concentration and the tested one was calculated (See 4.4). The average of the Euclidean distance of those five tests is displayed in the Table 5.2. The first row displays the concentrations where the colors is known i.e., calibrated colors. In the first column the concentration being tested. The smaller Euclidean distance for each sample of tests is highlighted using bold. This represents the concentration that the algorithm would identify. All the tests were done in the *CIE L*a*b** or *LAB* color space with the real range of values.

The tests displayed in the Table 5.2 had a 100% accuracy in detecting the ammonia concentration. The Euclidean distance between the 0 mg/L varied between 1.271 and 3.374. The 0.5 mg/L varies between 0.0 and 1.271. In the concentration 1 mg/L the variation was from 3.246 to 3.853. When testing the 5 mg/L concentration the values varied from 3.721 to 4.178. Finally, in the 10 mg/L concentration the variation was between 5.987 and 8.739.

In order to test different concentrations and to obverse how the colorimetric test and the developed algorithm used would perform under various concentrations, we tested concentrations with the values of 0.25 mg/L, 0.75 mg/L, 3 mg/L and 7.5 mg/L. These concentrations represent the medium point of the concentrations detected by the colorimetric test.

As seen in the Table 5.3 the concentration under test are shown in the first column, along with the calibrated colors representing the respective concentrations present in the

Table 5.2: Average Euclidean distance between readings and calibrated colors of each concentration in the LAB color space

	0 mg/L	**0.5 mg/L**	**1 mg/L**	**5 mg/L**	**10 mg/L**
0 mg/L	**2.593**	14.122	26.063	29.392	63.826
0.5 mg/L	15.248	**0.899**	13.726	20.005	61.635
1 mg/L	25.884	10.757	**3.560**	10.835	55.961
5 mg/L	32.525	19.332	9.132	**4.087**	48.280
10 mg/L	72.381	68.096	64.452	53.230	**7.890**

Table 5.3: Average Euclidean distance between readings and calibrated colors of each concentration in the LAB color space

	0 mg/L	**0.5 mg/L**	**1 mg/L**	**5 mg/L**	**10 mg/L**
0.25 mg/L	8.766	**8.062**	20.582	26.449	65.710
0.75 mg/L	22.103	**6.754**	7.141	13.485	57.318
3 mg/L	27.108	11.958	**1.270**	11.897	57.374
7.5 mg/L	68.465	62.749	57.633	46.469	**5.670**

first row. Each test sample's with the shortest Euclidean distance is highlighted in bold. This represents the concentration that the algorithm would assign to the sample. The *CIE L*a*b** or *LAB* color space was used for all testing. Analysing the Table 5.3, it is possible to assume that the concentration of 0.25 mg/L will be detected as 0.5 mg/L. The 0.75 mg/L would be detected as 0.5 mg/L. The 3 mg/L would be identified as 1 mg/L. The 7.5 mg/L as 10 mg/L.

5.1.2.3 pH Measurement

With the aim of using the pH sensor to measure the pH of the system, the calibration process is the first necessary procedure to be performed. In the calibration process, the analog result return from the sensor on the buffer solutions which have the pH value of 4.0 and 7.0 are saved. With these values a linear function is created. This linear function will return a pH value for every analog sensor. The analog values of each buffer solution in the calibration process is 1353 for the pH 7.0 and 1862 for the 4.0 pH.

After the sensor calibrated, tests were executed which use the pH sensor and a Digital pH Meter. Using the mathematical equations 5.2 and 5.3 it is possible to know the percentage error and the absolute error present in the pH sensor used in the system.

Table 5.4: Percentage error present in the pH sensor

Digital pH Meter	pH sensor	Percentage error	Absolute error
7.0	6.81	-2.714%	0.19
7.0	6.93	-1.0%	0.07
7.0	7.31	4.429%	0.31
4.0	4.31	7.75%	0.31
4.0	4.09	2.25%	0.09
4.0	3.83	-4.25%	0.62
8.5	8.47	-0.353%	0.03
8.5	8.34	-1.882%	0.16
8.5	9.06	6.588%	0.56

The test in the Table 5.4 represent an average of 10 readings with a spacing of 1 seconds between each reading resulted from the pH sensor in a water sample. The average absolute percentage error represented in the Table 5.4 is 3.468% and an average absolute error of 0.26. Meaning that it can be expected for the pH sensor to give an error of 0.26 or 3.468%.

5.2 Summary

This chapter analyzed the results for the evaluation metrics for each of the modules of the ammonia toxicity measurement system.

In the color detection modules, we performed tests with two different approaches. This module has the purpose of detecting the color present in the colorimetric test result. It also has the responsibility to correspond such to an ammonia concentration. The two approaches tested were: i) using the colorimetric sensor AS7341 spectral sensor, and ii) using CV through the use of a SBC and a camera.

As shown in the previous chapters using the AS7341 spectral sensor is not a viable option for the system. The results were not as expected. The tests performed on this sensor resulted in values that did not differ between the different concentrations. They had the same predominance in one section of the visible spectrum. It also showed low values that make it impossible to perform an evaluation on them or be considered as errors.

When using CV algorithms the results were flawless, as shown in the Tables 5.2 and 5.3. With this results, regarding our experiments, we can detect with an 100% accuracy the color present in the colorimetric test. Also it is possible to identify the ammonia concentration present in the water sample examined. Meaning that this approach was the one used to detect the color and the ammonia concentration present in the system.

In the pH detection, the only approach tested was using an pH sensor connected to an SBC. In this case the chosen SBC is a Raspberry Pi Zero W. To use an analog sensor with the Raspberry Pi, we add an ADC. The test preformed in the pH sensor show that we have a small error that consists in average of 0.26 in the pH value or 3.468% as shown at the Table 5.4. Reaching the conclusion that using this method it is possible to detect the pH value of the aquaponics system with a high accuracy and low error.

Finally, in order to detect the ammonia toxicity and the TAN present in the system we need two parameters. The ammonia concentration and the pH value of the aquaponics system. Both can be achieved with an accuracy of 100% and 96.532%, respectively, on average. Meaning that, regarding our experiments, it is possible to detect the ammonia toxicity present in the aquaponics system with a very high accuracy using the methods presented in the described system.

Chapter 6

Conclusions

This thesis describes the system developed to perform an ammonia toxicity monitoring of an aquaponics system. This system was developed to be used at home, in a practical and convenient way for the user. The system was developed for a computer to process a picture of the colorimetric test result, and measure the pH value of the aquaponics system. We adapted it for operation on a SBC, a Raspberry Pi Zero W. This system incorporates two modules to fulfill its objectives: i) color detection module, and ii) pH measurement module.

The color detection module allows us to detect the colorimetric test result. This can be achieved by capturing a picture using an SBC, a Raspberry Pi Zero W, and an attached camera. All tests and readings must be performed inside a controlled environment. This environment serves the purpose of isolating and restricting any external variables as external light sources. The picture captured contains the color present in the colorimetric test result. By converting the original picture to the color space *LAB* from the color space RGB, it is possible to calculate the Euclidean distance between the pictures and the *LAB* values of the known ammonia concentrations. Comparing each Euclidean distance, the smallest one represents the smaller distance between the colors, as perceived by the human eye, meaning that it is possible to identify the ammonia concentration present in the water sample tested by identifying the smallest Euclidean distance. In its final evaluation, regarding our experiments, the color detection module using CV achieved a precision of 100%.

The pH measurement module enables the system to measure the pH value of the aquaponics system. It can be achieved by taking a sample of water and inserting the pH sensor inside. To read the pH value of the system, we connect the pH sensor to the Raspberry Pi Zero W. It is a necessity to use the ADC since the Raspberry Pi GPIO's alone cannot read analog values from the sensor. With the pH sensor measuring the pH value of a water sample from the aquaponics system, it is possible to know the pH value present in the system. In its final evaluation, the pH measurement module achieved a precision of about 96.532%.

With the pH value and the ammonia concentration, it is possible to calculate the TAN. This can be achieved by using the table shown at the Figure 1.4. With this table, we can also evaluate the ammonia toxicity.

The set of these two modules made it possible to achieve the system's objective of ammonia toxicity monitoring. The hardware used was, an SBC, a camera module for the Raspberry Pi Zero W, a pH sensor, an ADC, and a 3D printed controlled environment.

As future work it is possible to automate the processes of withdrawing a water sample from the aquaponics system, applying the reagents, and mixing them with said water sample. This would make the process of obtaining the colorimetric test result independent of an human interaction. It is also important to note that after obtaining the ammonia toxicity, if the results are of concern, the water needs to be treated. Combining said future work with the work presented in this thesis would result in an autonomous system, leaving the user to only press a button to obtain the TAN, and the ammonia toxicity present in the system.

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