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Smart Aquaponics Guide : Monitoring of parameters in aquaponics

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1 Introduction

1.1 Why monitoring crop and animal parameters?

Monitoring crops or animals are in the centre of human interests for millennia as human needs to fulfil his daily needs in terms of food mainly. The exponential growth of the world population increases the needs of higher knowledge about the crops and the animals themselves but also the needs of better monitoring methods or tools to satisfy the needs of about nine billion of people in 2050. Moreover, since the conclusions of different reports and congresses related to the environment and climate situations highlight urgent actions to better use limited resources in our planet, monitoring of several parameters with high impact on the environment and the climate becomes a huge domain especially with the emergence of technologies of information and communication.

1.1.1 (R)evolutions in plant and animal monitoring: from the Neolithic to the emergence of precision agriculture

History of plant and animal monitoring is important to know, from the beginning of the domestication until the recent development and democratization of technologies for monitoring. This history is highlighted by the three major revolutions (with technical and technological evolutions) occurred in agriculture. This part aims at explaining the origins of the type of monitoring adopted in aquaponics systems.

The monitoring of plants and animals is always the main concern of humans since the domestication of them, thousands of years before J.C., during what was considered as the "Neolithic revolution" or the first agricultural revolution (Strom, 2018). The Australian archaeologist Gordon Childe highlighted this term "Neolithic revolution" to define the drastic change in human behaviors as before that time humans lived by gathering and hunting, and during which they rapidly encountered many limits, as they did not have the control of plants nor animal growth. At this time, human started to make crop maintenance in order to obtain desired attributes as well as animal domestication for sale or for by-products use. Then, with only simple metallic tools, humans were able to start to grow plants and animals for their needs and more with the beginning of a form of exchange by barter or by progressively inducing monetary exchange.

The second agricultural revolution, which induced the industrial revolution, occurred in early nineteenth century was the second step of big changes in the monitoring of plants and animals. It concerned especially some European countries such as Great Britain, the Netherlands, Denmark and nearby. Several innovations occurred during that time, mainly to valorize the surplus generated by agriculture but also to generate enough products to nourish factories workers. Numerous advances were dedicated to improve seeds and seeding as well as the required fertilizers and the related machines. For animal husbandry, it was the period during which advances in livestock breeding were significant.

Then in the middle of the twentieth century, those advances were enlarged in order to produce more in the same piece of land. We are in the "third agricultural revolution" or "green revolution". High-yielding grains were used especially rice with the goal of hunger reduction. New varieties of wheat and corn also appeared. It was the period of biotechnology knowledge application, with the appearance of genetically modified organisms or GMOs. It was also increase of agribusiness with lot of exchanges as well as mechanization and fertilizers and pesticide uses increase. Consequences of this third agricultural revolution are still visible currently. If only fertilizers uses are considered, which greatly increased between the fifty's and 2000, their impact are highlighted by the amount of exceeding nitrogen in the soil (EEA, 2010). This situation led to the introduction of "nitrates directives" in the European Union in 1991. Even with that directive, the situation did not evaluate in the positive way, and in 2005 that amount of exceeding nitrogen in the soil was between 30 to 80 kg per hectare in 2005 for the North of France region and Belgium. In France, the SANDRE (Service d'Administration Nationale des Données et Référentiels sur l'Eau) defined vulnerable zone as "part of the territory where the pollution of water by direct or indirect discharge of nitrates from agriculture and other nitrogen compounds likely to be transformed into nitrates, short term threat for the quality of the aquatic environments and more particularly the supply of drinking water". In a map produced in 2014, practically all the North region of France is considered as vulnerable and needs a specific attention.
In order to increase the mastering of such situation, not only for the case of nitrogen and nitrate but to all the inputs used in agriculture as well as the crops and animals themselves, the concept of "precision agriculture" has evolved.

Figure 1: summary of the (r)evolutions occurred in the history of agriculture, leading to the use of precision agriculture technics in order to reach sustainable agriculture (Strom, 2018).

From that Figure 1, it is possible to consider the "precision agriculture" as a current solution to monitor efficiently crops and animals in order to reach sustainability goals of agriculture. It could be also considered as the fourth agricultural revolution as, besides knowledge improvement, it may offer an additional evolution in terms of use of technologies in agricultural practices.

1.2 The precision agriculture

1.2.1 Definition of precision agriculture

As defined by the International Society of Precision Agriculture (ISPA) in 2019, "precision agriculture is a management strategy that gathers, processes and analyses temporal, spatial and individual data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production”. In that definition, the principle (what?), the necessary tools (how?) and the objectives (for what?) could be raised as following:

- the principle: precision agriculture is a “management strategy” and it means that the users (the farmer, the technician, the advisors or all people involved in the works in an agricultural farm) have the choice to use or apply precision agriculture tools and methods or not, according to the objectives of the farm;
- the necessary tools: precision agriculture needs data to be efficient, and all sources of data are welcome. In particular, use of sensors could be important, and it will be the subject of the following part, in order to make continuous, real-time (even if it is not mandatory), and reliable data recording different parameters variability, for the monitoring of crops and animals, and their direct environment (the air or the atmosphere). In addition to that, the other source of data (such as the recordings of the interventions, the specific events, etc.) which may be recorded manually are also useful.
- the objectives: the first objective of precision agriculture is to improve resource use efficiency for better productivity and quality of the outputs leading to interesting profits and sustainability. In aquaponics systems, it is a question of good management of four compartments: water, crops (mainly vegetables), fishes and microorganisms as resources, in order to improve the quantity and quality of the produced vegetables and fishes, with a particular attention to the different nutrients allowed to be used in the four different above-mentioned compartments.

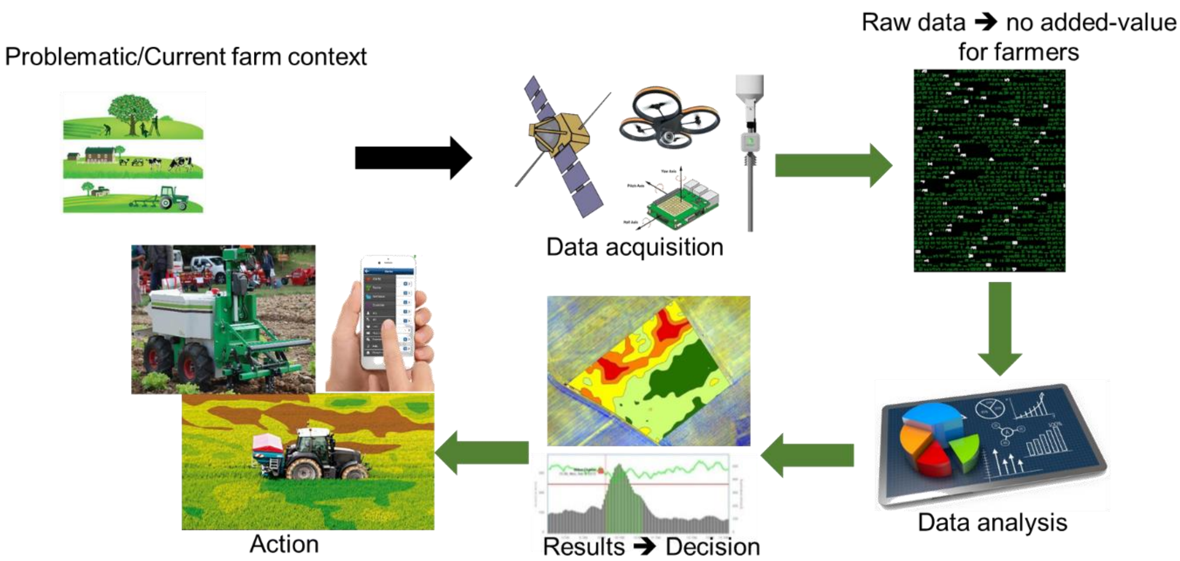


Figure 2: Main components of precision agriculture, from problematics to the decision support and the action to do in the farm.

The Figure 2 is summarizing the concept of precision agriculture. In order to assess the variability occurring in the exploitation (including aquaponics systems and their compartments: water, crops, fishes, microorganisms), data collection is necessary, using sensors or manual methods. The collected raw data could not provide any added value to the farmer or the end-user, as they need some analysis. Analysis could be as simple as descriptive statistics (calculation of mean, standard deviation, variance, minimum, maximum, etc.), or more analytical with inference statistics testing hypotheses (analysis of variance, mean comparison, correlation analysis, etc.). As data analysis, modelling and prediction could be also used in order to provide efficient data-based decision support to the end-users. The results of those analyses give decision support and inform the end-users about the action they need to perform on the crops or the animals to solve the initial problematics. The decision support or the needed action could be induced by different ways:

- alerts or warnings, when measured parameters are outside threshold values
- maps, for spatialized results
- advice of quantity, for inputs (could be coupled with maps)

In aquaponics systems, alerts or warnings are the most used decision support format in order to keep both crops and fishes under normal conditions of growth.

This figure xx is also summarizing the whole process behind what are called “decision support tools” available in the market for different users.

1.2.2 Precision agriculture vs smart-farming vs digital agriculture

With this definition of precision agriculture, it is normal that confusion with other concepts may be induced, especially when the question of use of technologies is raised.

Besides precision agriculture, which is based on the measurement of the variability, there are other concepts that are closely related to it: smart-farming and digital agriculture.

According to Schuttelaar (2017), smart-farming is “farming management concept using modern technology to increase the quantity and quality of agricultural products”. The Smart-AKIS network, an European network designed for farmers about technological innovations and practice changes linked to digital agriculture, definition is close to this first one as the use of modern information and communication technologies in agriculture is in the centre of the process. While variability was in the basis of precision agriculture, modern technologies are in the basis of smart-farming.

Then digital farming or digital agriculture creates added-value from data according to the definition given by the European Agricultural Machinery Association (CEMA, 2017). Digital is taken here as the way of showing information in a numeric format.

From those definitions, the purpose of the following parts concerns the use of digital technologies, or sensors, in aquaponics systems. There will be a focus on sensors used in such systems as they are the basis of the data valorisation process.

2 Sensors for a high level of monitoring frequency

2.1 Definition of a sensor

A sensor has multiple definitions, as given in the Cambridge dictionary. In one hand, it is "a device that is used to record that something is present or that there are changes in something". And in the other hand, it is "a device that discovers or reacts to changes in such things as movement, heat and light". Those are relatively general definition of sensors telling their role of detectors of what happening in their close environment. The definition of sensor could be summarized as "a device that receives a stimulus and responds with an electric signal" (Fraden, 2010).

Sensor has to be differentiated from transducer. While a sensor is transforming any type of input into an electric signal, a transducer is transforming any type of input into another without any specification in terms of output. But inside one sensor, it is possible to have several transducers: the initial stimulus (input) could be transformed into different non-electric signals before the final transformation into an electric signal.

In agriculture, sensors have a specific role as they monitor all measurable physical quantity or measurand. Agricultural sensors aim at transforming a physical measurand (mass, power, light, temperature, etc.) into electronic signals (figure 3).

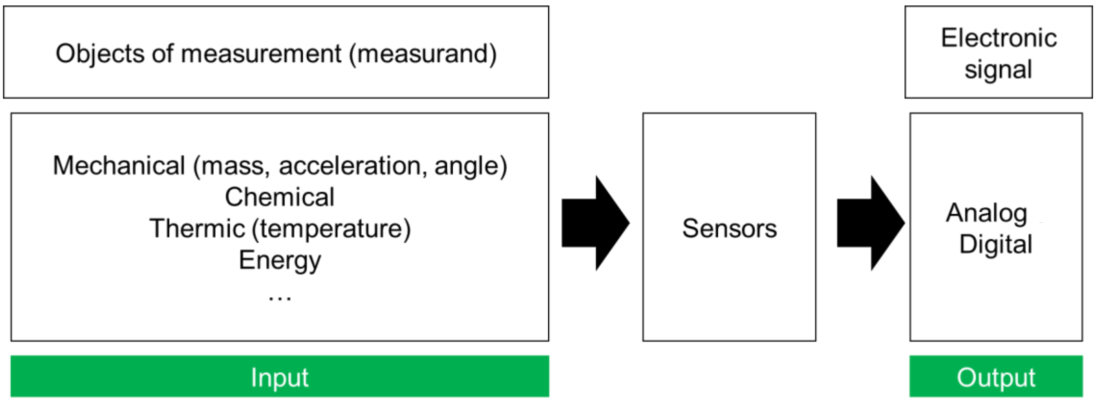


Figure 3: Functioning principle of sensors.

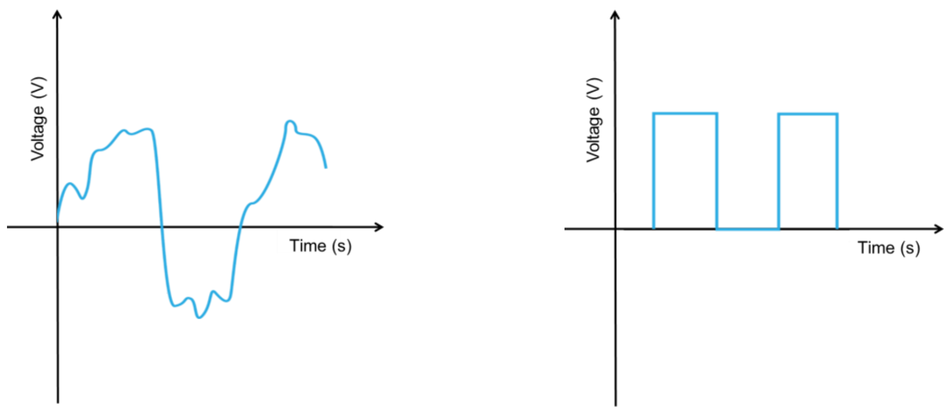
The information coming from the direct environment of sensors is transformed into an encoded information in the format of electronic message. Such electronic message is expressed as a voltage which is a difference in electric potential energy needed for electric current to flow. It is such voltage change that a sensor is continuously measuring and is calibrated to express the same variation as the input information.

There are two different kinds of electronic signals from sensors: analog and digital signals (Figure 3).

Analog signals are expressing continuous changes in voltage, resistance or electric intensity (Figure 3a). Even if those signals were used primarily in many devices, as they are subject to distortion and noise, they are not used as often anymore. Calibrations are needed when using sensors providing analog signals in order to retrieve concordant information compared to the reality.

Digital signals are the mostly used outputs of sensors nowadays. They consist of voltage pulses that repeatedly switch the off and on (Figure 3b), meaning that information are stored respectively as string of 0 and string of 1. Digital signals are also called binary code. They are present in most of modern tools as, compared to analog signals, they are more accurate and easier to transmit.

Both electronic signals, as outputs, are used as they are compatible with electronic circuits and the resulting data (combination of series of signals in function of data) could be, then, stored and analyzed by the users through a computer.



(a) Analog signal (b) Digital signal

Figure 4: Comparison between analog and digital signals as outputs of sensors

There are different uses of sensors (Figure 5), according to the domain or reason in which they are used, and different types of sensors (Figure 5), according to their working principles. Their classifications depend on these treats: the uses, the outputs (analog/digital sensors), which mainly depend on the providers, or on the physical properties they are measuring (temperature, conduction, motion, etc.).

Use of sensors	Name of the sensors	What do the sensor detect?
Occupancy and motion detectors	Air pressure sensors	Changes in air pressure
	Capacitive sensors	Body capacitance
	Acoustic sensors	Produced sounds
	Photoelectric	Light beams interruption
	Optoelectric	Illumination variation or optical contrast
	Pressure mat switch	Weight changes on floor
	Stress detectors	Strain gauges embedded into floor beams
	Switch sensors	Electrical contacts on doors and windows
	Magnetic switches	Noncontact version of switch sensors
	Vibration detectors	Walls or building structures vibration
	Glass breakage detectors	Specific vibration produced by glass

	Infrared motion detectors	Heat waves emanated from moving objects
	Microwave detectors	Reflected electromagnetic signals from objects
	Ultrasonic detectors	Similar to microwave detectors but using ultrasonic waves
	Video motion detectors	Comparison of the actual position of an object from a previous position
	Video face recognition system	Facial features (to be compared with a database of facial features)
	Laser system detectors	Similar to photoelectric detectors but using narrow light beams
	Triboelectric detectors	Static electric charges carried by moving objects
Position, displacement and level	Potentiometric sensors	Wire length changes as displacement measurement
	Capacitive sensors (for gauge, proximity and position)	Changes of geometry (distance between the capacitor plates) or capacitance variations in the presence of conductive or dielectric materials
	Inductive and Magnetic sensors	Electromagnetic induction. It includes linear and rotary variable differential transformer (LVDT and RVDT), Eddy current sensors, Transverse inductive sensors, hall effect sensors, magnetoresistive sensors and magnetostrictive detectors.
	Optical sensors	Light direction changes, requiring a light source, a photodetector and light guidance devices (lenses, mirrors, optical fibers). It includes light bridge, proximity detector with polarized light, fiber-optic sensors, fabry-perot sensors, grating sensors and linear optical sensors.
	Ultrasonic sensors	Ultrasonic signals (over 20kHz) reflected from one object
	Radar (Radio Detection And Ranging) sensors	Radar waves signal reflected to the emitter after hitting an object allowing the position and the speed calculation of that object. It includes micropower impulse radars and ground penetrating radars.
	Thickness and level sensors	- ablation sensors: heat dissipation by removal or melting of protective layer (spacecraft) - thin film sensors: using optical, capacitive or electromagnetic sensors - liquid level sensors: using optical, resistive, magnetic or capacitive sensors

Velocity and acceleration	Accelerometers	Linear speed of an object moving on straight line or Angular speed of rotating object. It includes capacitive, piezoresistive, piezoelectric, or thermal accelerometers, gyroscopes and gravitational sensors
Force, strain and tactile sensors	Strain gauges	Deformation of an object under the action of applied forces
	Tactile sensors	- Touch sensors: contact forces at defined points - Spatial sensors: spatial distribution of forces perpendicular to a predetermined sensory area - Slip sensors: movement of an object relative to the sensor
Pressure sensors	Mercury pressure sensors	Resistance of an U-shaped wire immersed into mercury which is in proportion with the applied pressure
	Bellows, membranes and thin plates	- Bellows: pressure conversion into a linear displacement of a large surface area - Membrane: spherical shapes of a thin diaphragm under radial tension when a pressure is applied - Thin plate: similar principle as membrane but with a thicker material
	Piezoresistive sensors	
	Capacitive sensors	Pressure changes are indicated by the displacement of a diaphragm which modulates capacitance
	Variable-reluctance pressure sensor	Pressure changes using a magnetically conductive diaphragm modulating the magnetic resistance of a differential transformer.
	Optoelectronic pressure sensors	Sensors composed by a passive optical pressure chip, a LED and a detector chip. Principle is similar to a capacitive pressure sensor but the capacitor is replaced by an optical cavity
	Vacuum sensors	Extremely low pressures measurement using: - Pirani gauge: through thermal conductivity of gas - Ionization gauge - Gas drag gauge - Membrane vacuum sensors
Flow sensors	Thermal transport sensors or Thermoanemometers	Rate of heat dissipation in flowing media, to measure minute gas or liquid displacements or fast and strong currents

	Electromagnetic flow sensors	Movement of conductive liquids
	Breeze sensors	Change in the air or the gas movement
	Drag force sensors	Speeds of air or water flow and turbulence close to surface (in environmental monitoring, meteorology, hydrology or maritime application)
	Dust and smoke detectors	Presence of small airborne particles (smoke and air gas impurity)
Acoustic sensors	Resistive microphones	Use of resistive pressure converters (pressure to electricity) to detect the sound
	Condenser or capacitor microphones	Sound waves hitting the diaphragm changing the distance between the two capacitor plates of the device
	Fiber-optic microphones	Incident sound waves modulate the light guided in optical fibers without the help of electricity
	Piezoelectric microphones	Sense of audio vibrations through contact with solid objects
	Electret microphones	Type of electrostatic capacitor-based microphone, with permanently electrically polarize crystalline dielectric material.
	Dynamic microphones	Microphones that convert sound into an electrical signal by means of electromagnetism
Humidity and moisture sensors	Capacitive sensors	Measurement of relative humidity by placing a thin strip of metal oxide between two electrodes
	Electrical conductivity sensors	Measurement of relative humidity based on conductance changes measurement
	Thermal conductivity sensors	Measurement of absolute humidity based on the use of two thermistors
	Optical hygrometer	Measurement of the absorption of light by water in the air (at the dew point): humidity is indicated by a light attenuation
	Oscillating hygrometer	Similar measurement as the optical hygrometer but using the changing mass of a chilled plate as indicator of humidity
Light detectors	Photodiodes	
	Phototransistor	
	Photoresistors	
	Cooled detectors	Measurements of objects emanating photons on the range of 2 eV or higher
	Image sensors	Also named camera to capture images digitally. It includes charge-coupled device (CCD) and complementary metal oxide semiconductor (CMOS) image sensors.

	Thermal detectors	Detection of infrared radiation in mid- and far-infrared spectral ranges
	Gas flame detectors	Detection of the flame feature which the optical spectrum is located in the ultraviolet spectral range
Radiation detectors	Scintillating detectors	Based on the ability of certain materials to convert nuclear radiation into light
	Ionization detectors	Based on the ability of some gaseous and solid materials to produce ion pairs in response to the ionization radiation
Temperature sensors	Thermoresistive sensors	Variation of electrical resistances which are depending on temperature
	Thermoelectric contact or thermocouple sensors	Voltage created by the difference of temperature between hot and cold junctions formed by at least two dissimilar conductors.
	Semiconductor pn-junction sensors	Temperature variation exhibited in a diode and a bipolar transistor
	Optical temperature sensors	- Fluoroptic sensors: light excitation translated into a fluorescent signal - Interferometric sensors: light intensity measurement through two light beams interference (one light as reference and a second one related to the temperature measurement) - Thermochromic solution sensor: use of cobalt chloride solution, for biomedical application. Spectral absorption in the visible range is measured as it is function of the temperature
Chemical sensors	Electrical and electrochemical transducer	Direct measurement of the electrical properties of a target analyte. It includes potentiometric sensors, conductometric sensors and amperometric sensors
	Elastomer chemiresistors or polymer conductors	Adsorption of chemical species and swell, increasing resistance as a physical response to the presence of a chemical species. It includes chemicapacitive sensors, chemFET sensors and photoionization detector
	Physical transducer	- Acoustic wave device: detection of very small mass change from adsorbed chemical molecules altering mechanical properties of a system - Microcantilever: detection of various chemicals and biological materials - Ion mobility spectrometry: differential migration of ions under the influence of an electric field is

		used to detect and differentiate chemicals - Thermal sensors: detection of chemical reaction associated to evolution of heat (thermodynamics law) - Pellister catalytic sensors: similar to thermal sensors
	Optical sensors	- Infrared sensor: absorption level of infrared light (Lambert-Beer law) - Fiber-optic sensor: measurement of light wavelength reflected; absorbed or transmitted through a fiber waveguide and using a chemical reagent
	Biochemical sensors or biosensors	Combination of biologically active materials with physical sensing elements to respond to presence of few molecules. It includes enzyme sensors as example.

Figure 5: Different types of sensors based on their use (adapted from Fraden, 2010. This list is not exhaustive and refers to the most used sensors available in the market)

Behind these uses of sensors as classification criteria, sensors could be also grouped based on property, on application, on power or energy supply or on the technology in which they are built (Figure 6).

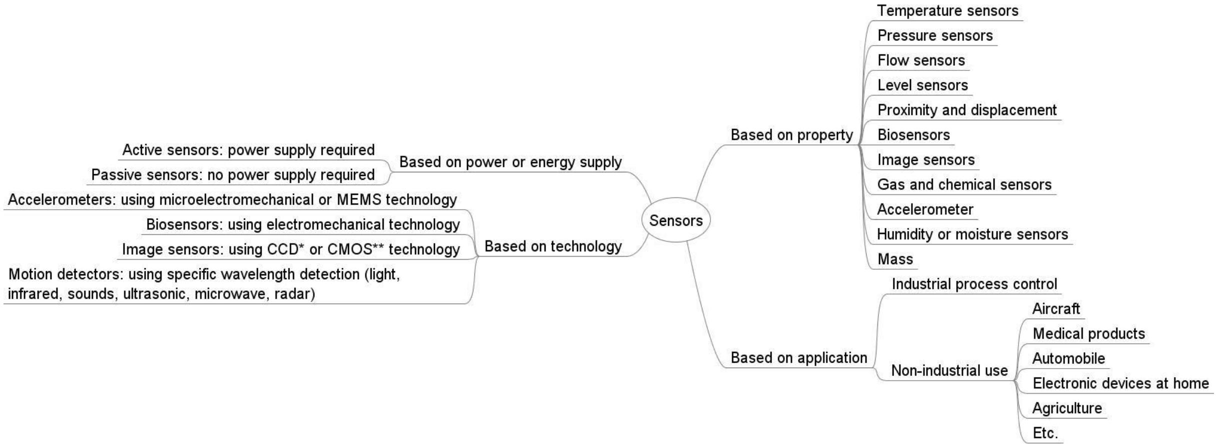


Figure 6: Classification of sensors based on property, on application, on power supply and on technology

In agriculture, sensors could be used to solve different problematics. According to Wang et al. (2006), a classification of agricultural sensors could be done based on their applications in agriculture and food production process (Figure 7).

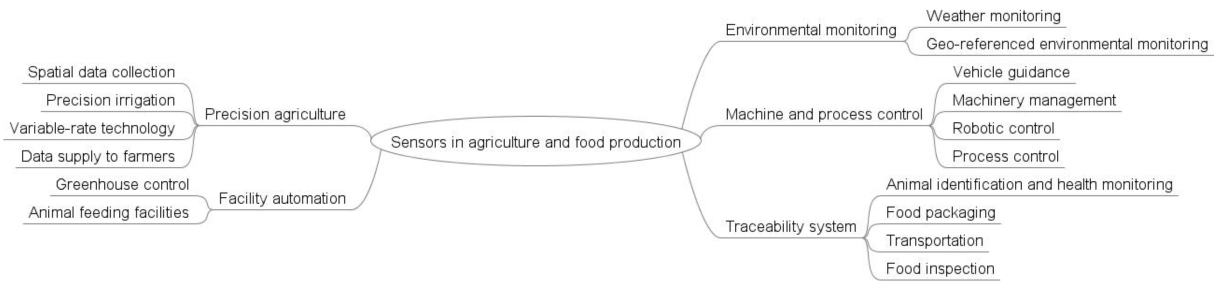


Figure 7: Use of sensors in agriculture and food production (based on Wang et al., 2006)

Specific agricultural problematics could be solved using sensors and could be highlighted from the previous list:

- Soil analysis and characteristics: soil content (nitrogen, carbon, organic matter), soil salinity, soil moisture, soil temperature, soil electrical conductivity
- Yield estimation or measurement
- Detection and classification of crops, weeds and fruits: to follow their growth, to eliminate non-desirable plants (weeds) and to detect the presence of products (fruits, grains)
- Weed control
- Positioning, navigation and safety: in agricultural machinery or robots
- Seeds, seedling, breeding, growing and health status
- Microorganisms and pest control

In aquaponics, the most important parameters that should be followed are linked to the two main compartments of an aquaponic system: the water and the air (or the direct environment of the system) (Figure 8). The following section will focus only on the sensors used to carefully monitor those parameters.

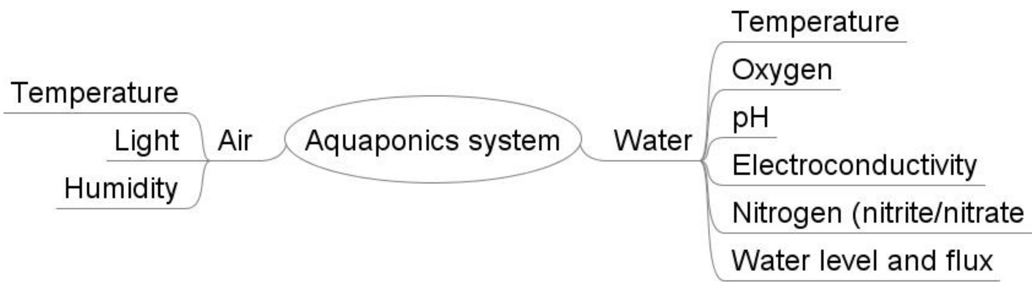


Figure 8: Aquaponics system compartments in which sensors are useful and related list of parameters

Finally in this chapter, when talking about sensors used for aquaponics system monitoring, it means sensors which are continuously measuring the parameters (temperature, light humidity, oxygen, pH, electroconductivity, nitrogen, water level and flux) at a fixed frequency and not those which can achieve punctual measurement. This is to rely with the definition of sensors which the output is to get data from those tools and to be able to directly analyze those data afterwards.

2.2 Why do we use sensors?

Use of sensors have multiple advantages related to the characterization of a specific process.

Before telling the importance of sensor, in agriculture, including aquaponics systems, it is important to put the human at the center of the management of any systems. The human has different sensors, with the five senses: sight (sensor = the eyes), smell (sensor = the nose), taste (sensor = tongue), hearing (sensor = ears), touch (sensor = the skin). In the specific domain of agriculture, those senses are trained to notify all things happening to the system. One example is the recognition of plant species, to differentiate the main crop from the weeds for example, or of diseases symptoms. Using those senses, farmers are building a certain experience to greatly manage their systems. However, humans are limited in terms of time, in terms of memory and in terms of objectiveness.

By definition, a sensor is transforming a physical into an electrical variable which is highly correlated to the initial stimulus. In terms of usefulness, this new variable gives a quantification of this initial stimuli. This quantity or this data is, then, easier to store, to analyze (in real-time or in a post-processing), and easier to exchange. A great example concerns the temperature that anyone can feel by telling if the environment is hot or cold, but to give a concrete value of such statement, sensors are necessary to transform this heat/cold sensation into values of temperature. It is the same for the light, the humidity, the acidity/basicity which are essential for the development of the quadriptych water/fish/plant/microorganism in an aquaponics system. The values given by sensors are also objective, when sensors are correctly calibrated, and in opposite to the human experience, there is not any influence of certain perception.

In addition to that quantification, sensors are also important tools for a continuous monitoring of one of the elements of this quadriptych. Even if the presence of a human close to the system could be recurrent, to make different interventions, it is not possible to stay there permanently. Thanks to sensors, a continuous monitoring is possible. By collecting data continuously, sensors are also the key element that are on the basis of alerting systems announcing to the users that something is going wrong, so, interventions are necessary. Within the data analysis, after data collection, it is possible to fix some thresholds where a system is functioning normally and once the data is going out of those thresholds, alerts are sent to the users

<u>Remark:</u>

Some sensors are not able to record or to send data to the users for real-time or posterior processing, but able to indicate punctually the status of the measured object or environment. Those sensors are also useful in order to have an idea of the status of an object or an environment, but it is not possible to make a continuous measurement nor to define alerting systems. Also, for sensors having the ability to make a continuous measurement, it is possible to define the frequency of the measurement. This measurement frequency, defined in Hertz (Hz, 1 Hz corresponds to 1 data collected each second), is important as it conditions the available data to be furtherly analyzed. But the frequency also conditions the memory size and the battery life needed for the system to be monitored using sensors.

2.3 Limits of sensors

The main limits of sensors concern the life duration and the measurements' ability themselves.

The battery life of sensors is one the most important limiting factor by using those tools. This battery life is expressed in milli-Ampere (mA) x hours or mAh. It is visible in all tools, including sensors, using a battery. As example, in theory, a sensor having a battery of 100mAh could provide 2mA of intensity during 50 hours. In practical, depending on the way the tool is used, the battery could last less than its indicated (or nominal) capacity. A usual way on how sensors are collecting data to optimize the battery life is to let them sleep when measurements are not required. During that sleeping time, the device has a very low battery consumption. The consumption peak arrives during the measurement, knowing that, as reminder, a sensor is transforming one physical measurand into an electrical signal. This active period is limited in time (in millisecond), and with a defined frequency (1 Hz or less). If the device has a capacitor, which is charged by the battery during the sleeping mode, it is possible to use the energy stored in this capacitor during the active mode. In addition to that, even if the device is not used, a battery continues to lose its capacity over time: it is named self-discharge per month (Farahani, 2008). The providers normally indicate that internal leakage in percentage: as example, a device with a battery of 100mAh having a self-discharge per month of 0.5% loses 0.5mAh of its capacity after one month. Farahani (2008) suggested estimated the total energy required for one measurement including the device in sleep (for 1 hour), the transition to active mode, the measurement itself, the data transmission and the transition to sleeping mode (during 13 milliseconds), to 0.001 mAh. A sensor with 100mAh of capacity, in this situation, will be able to make about 100.000 measurements with a frequency of 1 measurement each hour. Then, if this frequency is too low, it is easy to make a calculation including a higher measurement frequency. The figure xxx (Farahani, 2008) shows how battery is behaving according to a simple use-case scenario.

However, for the devices used to monitor systems such as aquaponics, manufacturers often sized the battery to last for long period (several months and several years). In the case of greenhouses, which is possible to have access to the mains power, this limitation could be neglectable.

2.4 Sensors used in aquaponics

2.4.1 Temperature measurement

Temperature is the first parameter to be considered in aquaponics system. It has to be measured both in the air and in the water.

2.4.1.1 A small history: the temperature measurement and the different scales

Even before the Neolithic revolution (first agricultural revolution), humans were confronted to different temperature variation in their direct environment, across the seasons, and tried to assess its intensity through different mechanisms. The first thermometer was apparently invented by Galileo Galilei in the 16^{th} century. His principle was to suspend a long narrow throated glass tube within an open container filled with colored alcohol. Hollow spheres are placed at the upper end of the glass tube (Figure 9). Alcohol was chosen as this liquid is more sensitive to temperature variation and leaves less residue or scum on the hollow spheres. Within a temperature ranging between 15°C to 30°C, ethanol density changes 3.7 times more than water (Loyson, 2012). The variation of temperature could be observed through the movement of the hollow sphere: if the temperature increases, the sphere expanded and bubbled through the liquid, but if the temperature decreases, the liquid is moving up the tube.

The principle is based on the physical property of temperature which is dependent to the density of a liquid (here the liquid is inside the container). When the temperature of the liquid is changing, inducing also a change in its density, and when this density corresponds to the density of one of the floating sphere, the floater is rising and suspending in the liquid (Loyson, 2012). Even if this first version of a temperature measurement device, called also thermoscope, could be useful to see the temperature variation, it did not indicate clearly a temperature value (no scale) and barometric pressure could influence the measurement.

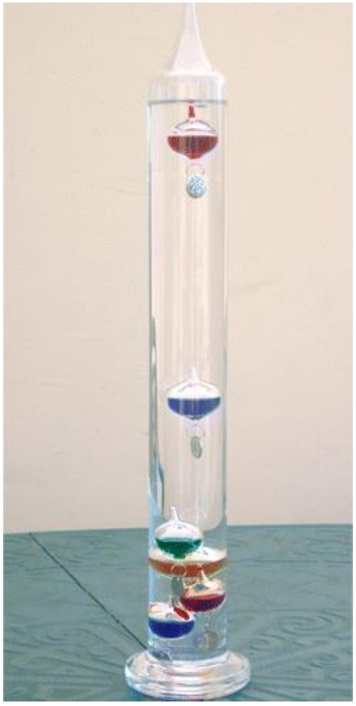


Figure 9: example of a Galilean thermometer (Loyson, 2012)

Other articles attributed the invention of the earliest thermometer to Cornelis Drebbel during that same century as Galileo Galilei. In order to give this notion of scale in the measurement, a first attempt was done by Guiseppe Biancani and afterwards by Sanctorius in the 17th century. The format of the device was a vertical tube closed by an air bulb at the top and with the lower end opening into a vessel of water.

The word "thermometer" was firstly described by Leurechon with a measurement scale of 8 degrees. Main advances were made in the 18th and 19th century and have led to the creation of nowadays temperature scales still in us: the Fahrenheit scale, the Celsius scale and the Kelvin scale.

Daniel Gabriel Fahrenheit, a Dutch physicist, invented the "mercury-in-glass" or mercury thermometer in early 18th century. The mercury was used, and still used nowadays, as it has a high coefficient expansion. The lowest reference (the zero-degree Fahrenheit or 0°F) was equivalent to the freezing temperature of a solution composed with water, ice and ammonium chloride or a salt as it provides an eutectic system stabilizing its temperature automatically. And the highest reference, also called "the 96 degrees Fahrenheit or 96°F), was equivalent to the human blood temperature. The temperature of ice water was noted at 32°F and used as middle point. Afterwards, the boiling water was measured at a temperature of 212°F using this Fahrenheit scale. And more recently, that scale was refined using the water freezing point of 32°F and the boiling water point of 212°F, so 180°F higher.

Anders Celcius, a Dutch scientist, decided to have his own scale, with the same mercury-based device, using similar reference temperature: the lowest at the freezing point of pure water (the zero degree Celcius or 0°C, equivalent to the 32°F) and the highest at the boiling point of pure water (the hundred degree Celcius or 100°Cn equivalent to the 212°F). The Celcius scale was also given to ease the calibration method of a thermometer by marking the stabilized lowest (in melting ice of pure water) and highest (in a boiling water) level of the fluid and divide such length into 100 equal parts.

Knowing the two fixed temperature points, which are the same, the Fahrenheit and Celcius scales are comparable in terms of temperature measurement (Figure 10).

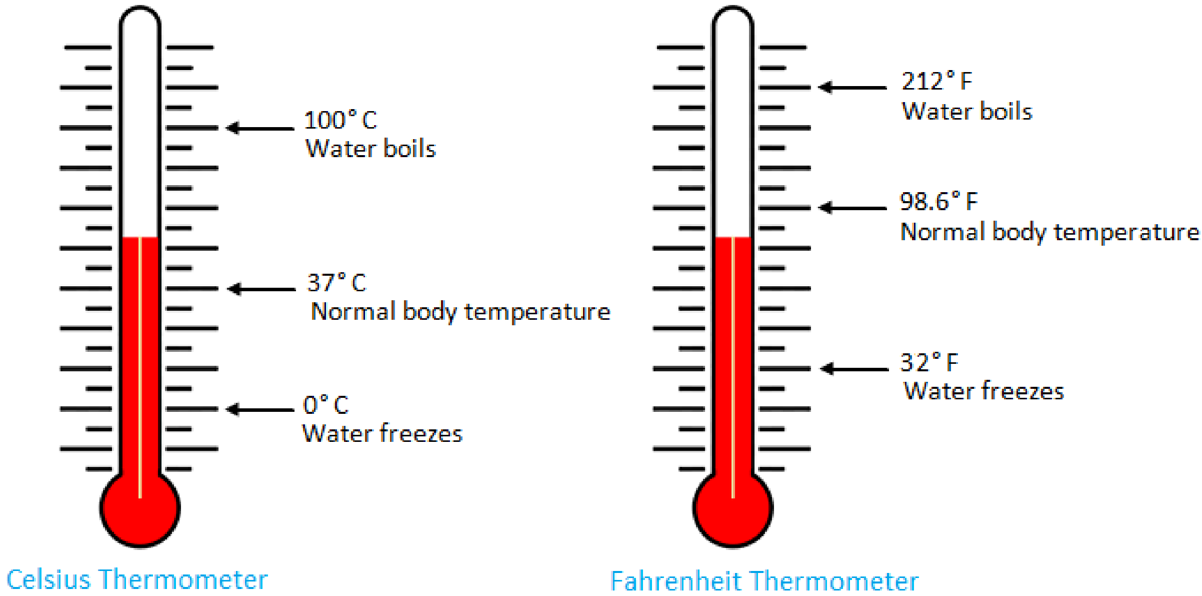


Figure 10: comparison between Fahrenheit and Celsius scales for temperature measurement.

The last temperature scale named Kelvin scale is the international system of units reference for temperature or precisely for thermodynamic temperature (until May 2019 in which the Boltzmann constant value was introduced to define the value of 1 Kelvin). The Kelvin scale was developed by William Thomson, also called Lord Kelvin, and based upon the coefficient of expansion of an ideal gas. The advantage of that scale is that, compared to the Fahrenheit and Celsius scale, there is only one reference point which is the water triple point meaning the status where the three phases coexist (liquid, solid and gas) and where the temperature and the pressure do not vary. This reference, called absolute zero or 0 K, corresponds to the third principle of thermodynamic (Nernst principle), and equivalents to -273.15 °C.

Besides those three scales, which are the most used in the world, there are other scales existing such as Rankine scale, Delisle scale, Newton scale, Réaumur scale or Romer scale (Figure 11). It is possible to see the different relationships between the scales (Equation 1).

References	Kelvin (K)	°Fahrenheit (°F)	°Celsius (°C)
Absolute zero	0	-459.67	-273.15
Melting temperature of pure water (at standard pressure condition)	273.15	32	0
Vaporization temperature of pure water (at standard pressure condition)	373.13	211.97	100
Water triple point temperature	273.16		32.02
Mean temperature of human body	309.95	98.24	36.80
Mean temperature at Earth surface	288	59.00	15.00

Figure 11: Comparison between the three most-used temperature scales with different references

Equation 1: relationships between the three most-used temperature scales (Fahrenheit, Celsius and Kelvin).

$$°C = 5/9\ (°F-32)$$

$$°F = 9/5\ °C+32$$

$$K = °C + 273.15$$

2.4.1.2 Current standards in temperature measurement

Two standards exist in temperature measurement: ISO 17714:2007 and ITS-90.

The ISO 17714:2007 defines characteristics of a thermometer shield and screen and defines test methods to inter-compare the behaviour of different screen designs.

The ITS-90 or International Temperature Scale of 1990 aims at standardizing the calibration of equipment measuring temperature at Kelvin and Celsius scales. It is specified by the International Committee of Weights and Measures ("Bureau International des Poids et des Mesures" or BIPM). The ITS-90 has its own guide describing methods to realize it successfully (BIPM, 2018). This standard fixed different reference points for specific materials (Figure 12).

Symbols	Element	Type	K (Kelvin scale)	°C (Celcius scale)
H_2	Hydrogen	Triple point	13.8033	-259.3467
Ne	Neon	Triple point	24.5561	-248.5939
O_2	Oxygen	Triple point	54.3584	-218.7916
Ar	Argon	Triple point	83.8058	-189.3442
Hg	Mercury	Triple point	234.315	-38.8344
H20	Water	Triple point	273.16	0.01
Ga	Gallium	Melting point	302.9146	29.7646
In	Indium	Freezing point	429.7485	156.5985
Sn	Tin	Freezing point	505.078	231.928
Zn	Zinc	Freezing point	692.677	419.527
Al	Aluminium	Freezing point	933.473	660.323
Ag	Silver	Freezing point	1234.93	961.78
Au	Gold	Freezing point	1337.33	1064.18

Figure 12: ITS-90 fixed reference points for temperature measurement

These standards are those which are used by manufacturers or laboratories to have a good calibration of the apparatus dedicated to temperature measurement.

2.4.1.3 Classification of temperature measurement sensors

In accordance with the definition of sensor, a temperature sensor converts the received electrical outputs (in V or mV) into an equivalent value in temperature units (°C, °F or K) (Euramet, 2011).

Temperature measurement could be classified into 5 classes:

- Thermocouple: difference between hot and cold junctions give a small voltage and indicate a change in temperature
- Resistance thermometer (RTD): changes in temperature corresponds to change in the resistance R (U = R x I), with a linear correlation
- Thermistor: similar to RTD, but there is a nonlinear correlation between resistance and measured temperature (highly sensitive device)
- Semi-conductor sensors: high accuracy and high linearity over an operating range of about 55°C to 150°C

- Thermopile (Infrared) sensors, measuring the surface temperature from -70°C to about 1000°C depending on the manufacturers. They convert thermal energy sent from an object in a wavelength range of 0.7 to 20 micrometers into an electrical signal that converts the signal for display in units of temperature after compensating for any ambient temperature (Agarwal, 2017).

In aquaponics systems, the most adapted classes of temperature sensors are the 4 first classes which are also known as contact sensors. Thermopile infrared sensors are contactless sensors, and the nature of the surface and its environment could influence the measurement.

The following parts will focus on those 4 first classes of temperature sensors.

2.4.1.3.1 Thermocouple temperature sensors

The thermocouple is the simplest way and widely used tool for temperature measurement. A thermocouple contains two different metal wires joined together at one end corresponding to the "measurement junction" or "hot junction". At the other end, named "reference junction" or "cold junction", the two metal wires are not joined but connected to a conditioning circuitry usually made of copper (Figure 13). A voltmeter could be put on the system to measure the tension, or the voltage produced at the reference junction which depends on the temperatures. To get an absolute temperature measurement, the temperature at this reference junction has to be known.

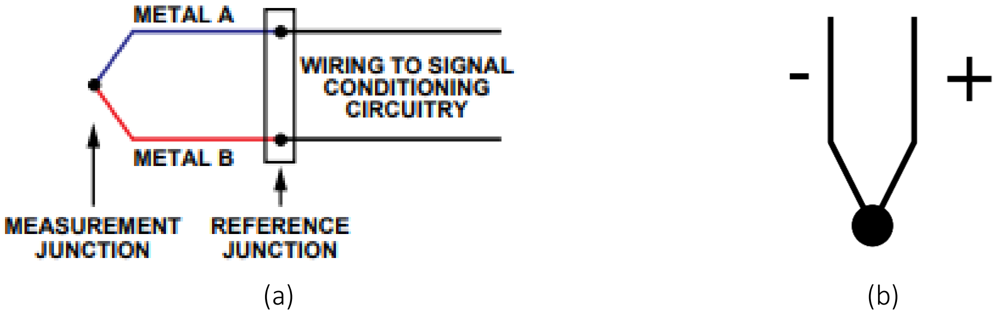


Figure 13: (a) working principle of a thermocouple (Duff and Towey, 2010) and (b) graphical representation symbol of a thermocouple in a circuit

Thermocouple temperature sensors are the most cost-effective industry-standard tool with acceptable accuracy, able to measure temperature as high as thousands of Celsius degrees. Most popular metal wires used for thermocouples are using Nickel-Chromium and Nickel-Alumel and such thermocouple is able to measure temperatures ranging between -200°C to +1250°C. Besides Type K, there are other types of thermocouples: type E, type J, type T, type R, type S and type B (table 4). The types J, K, T and E are known as "base metal" thermocouples as they are commonly used. The types R, S and B are known as "noble metal" thermocouples and they are used for high temperature measurements.

The voltage signal detected at each change of temperature of 1°C is indicated by the Seebeck coefficient (expressed in uV/°C). It shows very small voltage signal with a maximum of 61uV/°C for type E (Figure 14). As this signal is very small, knowing the reference temperature is very important to have a reliable measurement.

Type	Metal wires components	Seebeck coefficient (uV/°C)	Temperature range (°C)	Standard accuracy (°C)
K	Nickel-chromium and Nickel-alumel	41	-200 to 1250	+/- 2.2
J	Iron and Constantan	52	-210 to 760	+/- 2.2
T	Copper and Constantan	41	-270 to 370	+/- 1.0
E	Nickel-chromium and Constantan	61	-270 to 870	+/- 1.7
N	Nicrosil and Nisil	27	-270 to 392	+/- 2.2
S	Platinum Rhodium 10% and Platinum	6	-50 to 1480	+/- 1.5
R	Platinum Rhodium 13% and Platinum	9	-50 to 1480	+/- 1.5
B	Platinum Rhodium 30% and Platinum Rhodium 6%		0 to 1700	+/- 0.5

Figure 14: The different types of thermocouple and their characteristics

2.4.1.3.2 Resistance temperature detectors (RTD)

Resistance temperature detectors are usually made with metals which have positive temperature coefficient. It means that when temperature is raising, the resistance of these metals does the same. Compared to the thermocouple which used voltage change to measure the temperature, RTDs are using the resistance.

There are three different types of RTDs based on the materials used to build them: platinum RTD, nickel RTD and copper RTD (comparisons in Figure 15 and Figure 16).

Copper RTDs are the less expensive type and have the best temperature linearity between the three types. However, as copper is subject to oxidation at high temperatures, the measurement range is limited between -200°C to +260°C.

Nickel RTDs have a good resistance to corrosion and the cost is in the middle from copper to platinum types. But the nickel based RTDs age faster and could lose their precision at high temperature. However, nickel RTDs are able to measure temperature at range between -80°C and +260°C.

Platinum RTDs are the most used temperature measurement sensor for industrial use due to their excellent resistance to corrosion, their excellent long-term stability. Finally platinum RTDs are able to make temperature measurements between -200°C and 850°C.

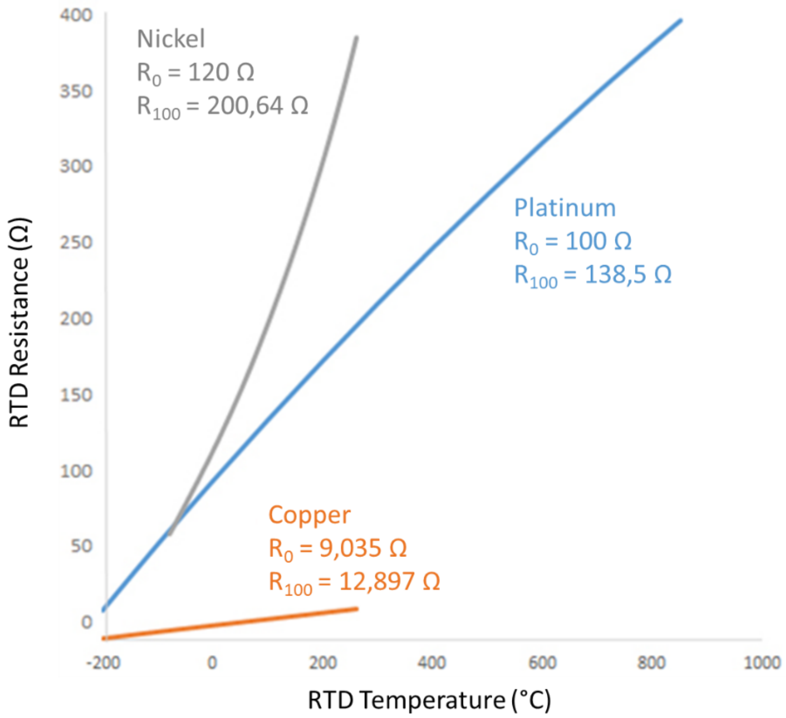


Figure 15: Sensitivity comparisons of the 3 different types of RTD temperature sensors (Nickel, Copper and Platinum) (adapted from PR electronics, ND)

RTD Type	Measurement range (°C)	Long-term stability	Corrosion resistance	Temperature linearity compared to resistance	Resistance at 0°C (R_0 in Ω)	Resistance at 100°C (R_{100} in Ω)
Platinum	-200 to 850	Excellent	Excellent	Good	100	138,5
Nickel	-80 to 260	Rather good	Good	Rather good	120	200,64
Copper	-200 to 260	Good	Rather good	Excellent	9,035	12,897

Figure 16: Comparisons of the 3 different types of RTD in terms of measurement range, stability, corrosion resistance and temperature linearity (adapted from PR electronics, ND)

In terms of conception, RTDs could be with coiled wire, with spiral element or with thin layer (Figure 17).

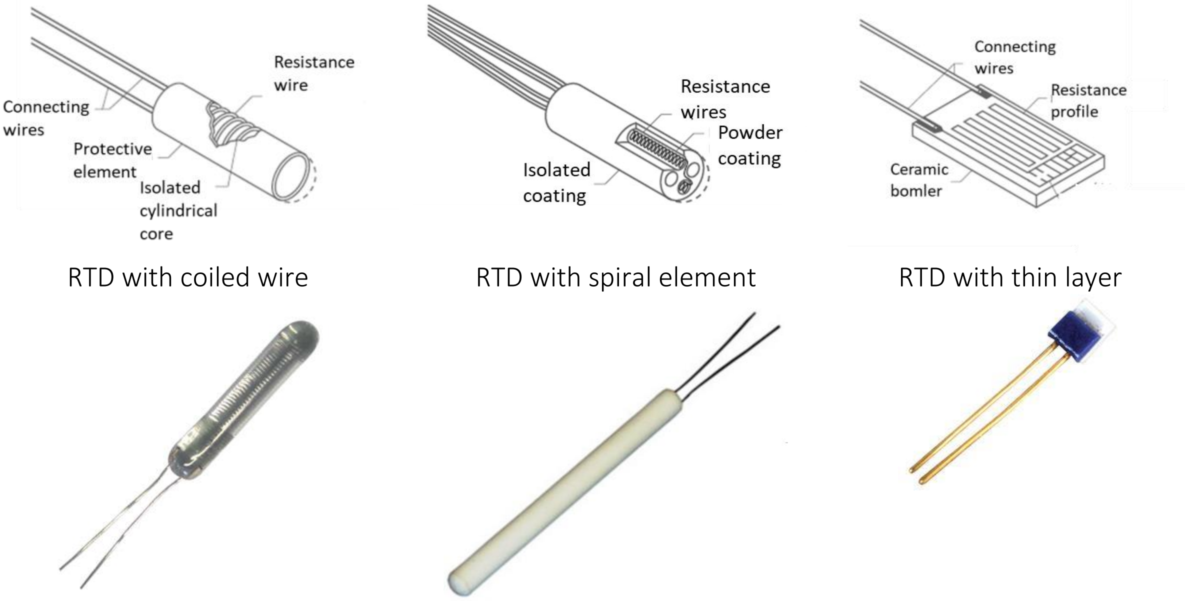


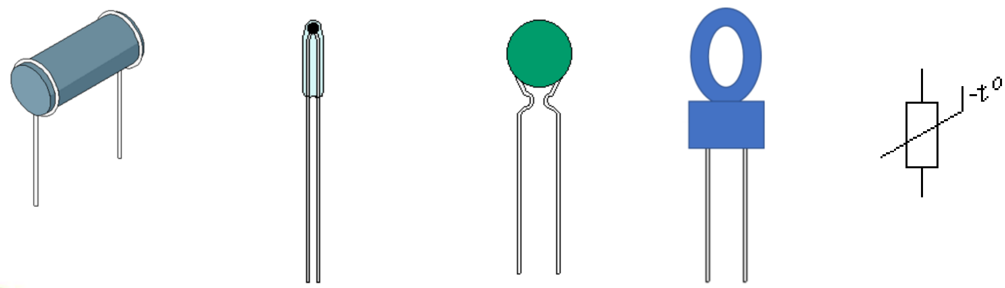
Figure 17: Description of the 3 types of RTD conception (images taken from PR electronics, ND)

In a RTD with spiral element, resistance wire is wound in small coils within a ceramic material. This ceramic is afterwards fulfilled with non-conductive powder. This powder is essential to increase the heat transfer within the coils, increasing also the response time.

In a RTD with thin layer, a thin layer of metal is deposited on a ceramic basis. This concept of RTD is the least expensive model, but also the smallest and the one giving the best response time.

2.4.1.4 Thermistor

A thermistor is also a temperature sensor which bases its measurement with resistance values. The difference with RTD is their conception based on the use of semi-conductor (ceramic or polymers) and not on the use of metals. Thermistors could be found in different formats (Figure 18).



(a) (b) (c) (d) (e)

Figure 18: the different formats of thermistors: (a) rod, (b) bead, (c) disc, (d) washer and (e) graphical representation of a thermistor in a circuit (adapted from Instrumentation tools, 2019)

The advantages of using a thermistor are their size, their accurate value and their cheapness compared to the RTD. The main disadvantage is that it does not fit with extreme cold or extreme hot conditions. In extreme conditions, RTDs are better.

For thermistor, the correlation between the temperature and the resistance variations is linear but could be positive or negative. The positive correlation means that when the temperature is increasing, the resistance is also increasing while the negative correlation means that when the temperature is increasing, the resistance is decreasing. These characteristics led us to respectively the two types of thermistors which are: negative temperature coefficient or NTC (negative correlation between temperature and resistance) and positive temperature coefficient or PTC (positive correlation between temperature and resistance).

2.4.1.5 Calibration of temperature sensors

Concretely, the calibration of the tools realizing temperature measurement has to be done by accredited laboratories. List of accredited laboratories could be obtained directly from the website of the accreditation structure. In France, such list is available through COFRAC and in Belgium through BELMET.

Based on the definition of temperature sensors (reliability of the electrical stimuli output with the temperature value), this calibration step is very important as each sensor has its specific range of measurement and accuracy. Before choosing and investing for a sensor, it is important that the users refer to the documented measurement methods, range, accuracy, and maintenance of the chosen sensor. The change of the accuracy of the sensor could occur along time and is called a drift. This drift is normal and, on average, it occurs each year but this drift time is also documented by the sensors' providers.

The calibration of sensors in general could be done using two methods:

- Laboratory calibration, with an accredited laboratory (see previous section)
- Self-calibration, based on the comparison of the sensor measurement and a reference

This section is dedicated to the self-calibration methods for temperature sensors.

For temperature measurement, its calibration aims at providing a reliable, reproducible and documented comparison of one piece of equipment under test (data logger, sensor, thermometer) with another piece of equipment that has been temperature calibrated and referenced to a known set of parameters (example: the ITS-90 reference). The referenced equipment is a high-precision instrument which is checked regularly by an accredited laboratory (France: COFRAC, Belgium: BELMET, Switzerland: SAS/SCS, USA: NIST, Germany: DaaKs, UK: UKAS) (Elpro, 2020).

2.4.1.6 How to choose the sensors?

	Thermocouple	RTD	Thermistor
Temperature range	-270 to 2300°C	-250 to 900°C	-100 to 500°C
Accuracy	±0.5°C	±0.01°C	±1°C
Excitation	None required	Current source	Voltage source
Typical size	Bead diameter of about 5 x wire diameter	About 0.65 x 0.65 cm	About 0.25 x 0.25 cm
Price	Moderate	From 25€ to 1000€	Low to moderate

Figure 19: Comparison of the 3 major types of temperature sensors in terms of advantages and disadvantages (Adapted from Baker, 2005)

According to the table 6, the least expensive type of sensors are thermocouple and thermistor. However in terms of accuracy, the RTD type of sensors are the most interesting, followed by thermocouple and thermistor. Based on those two kinds of sensors, considering that the financial aspect may be the key factor for taking decision, the thermocouple and thermistor are the most popular as trade-offs between price, accuracy and installation mode.

2.4.1.7 Inventory of temperature sensors used in agriculture

Agriexpo[1] inventoried, in June 2022, 57 temperature sensors belonging to 31 companies. It includes air, water but also seeds and soil temperature measurements.

For air temperature measurement, the SmartAquaponics project is using Campbell Scientific CS215 temperature and humidity sensor (Figure 20)

[1] Agriexpo is a free website making inventory of tools, including sensors, used in agriculture. For temperature measurements: https://www.agriexpo.online/fr/fabricant-agricole/capteur-temperature-349.html (June 2022)

(a) CS215 sensor (b) SHT7x sensor

Figure 20: Air temperature and humidity sensors used in SmartAquaponics project (Images are taken from Campbell Scientific and Sensirion websites)

The CS215 sensor (figure 14a) is using a specific type of temperature sensor named Sensirion SHT75 (figure 14b). It is based on silicon bandgap type of temperature detector commonly employed in electronic devices. The cost is quite high (between 200€ to 300€ per sensor) but it has a good accuracy and could operate at extreme environmental conditions. The main characteristics of this sensor are:

- it is operating between -40°C to +70°C,
- it has a diameter of 1.2 cm at sensor tip and 1.8cm at cable end
- it weights 150g with 3m of cable

2.4.2 Humidity sensors

2.4.2.1 Terminology

At this beginning, some important terminology has to be used to understand this section dedicated to sensors used for humidity measurement.

- Moisture: water content of a material/substance
- Humidity (H): the amount of water present in the surrounding air (soil)
- Absolute humidity (AH): ratio of mass of the water vapor to the volume of the air (AH = m/V). It changes with temperature and pressure
- Relative humidity (RH): ratio of the actual water vapor pressure present in the air at a temperature to the maximum water vapor pressure present in the air at the same temperature. Useful in weather forecasts (probability of precipitation, dew, fog)
- Dew point temperature: temperature at with the water vapor content is saturated in the air (RH = 100%)

2.4.2.2 Classification of humidity sensors

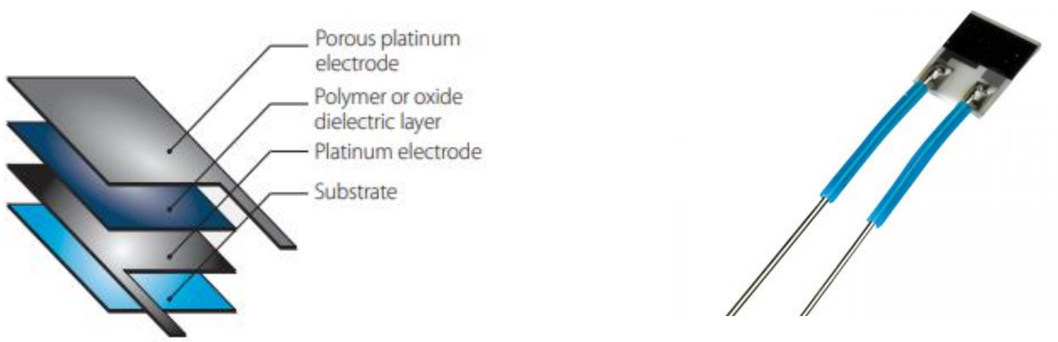
Then, humidity sensors could be classified in 4 according to their working principles (Korotcenkov, 2019):

- electrochemical or electrical sensors, measuring humidity through changes in voltage, capacitance, or conductivity;
- mass-sensitive sensors, measuring humidity through changes in weight;
- optical sensors, measuring humidity through changes in light intensity, color or emission spectra;
- thermometric sensors, measuring humidity through changes of temperature induced by a specific chemical reaction.

However, there are 2 major types of sensors commercialized and used in practical for relative humidity measurements:

- capacitive sensors: it measures relative humidity by placing a thin strip of metal oxide between 2 electrodes (Figure 21). The metal oxide's electrical capacity changes with the atmosphere's relative humidity (Gupta, 2020). RH is expressed in percentage (%) and ranges from 0% to 100%.
- resistive sensors (or electrical conductivity sensors): it measures the water content of an element, expressed in percentage. The measurements are done through ions in salts to determine the electrical impedance of atoms. Changes in humidity induce changes in the resistance of the electrodes. The relationship between resistance and humidity is inverse exponential.

For absolute humidity measurement, thermal conductivity sensors could be used. They are based on the use of 2 thermistors. One thermistor is hermetically sealed in a chamber filled with dry Nitrogen while the other is exposed to an open environment through small venting holes. When the circuit is powered on, the resistance of the 2 thermistors are calculated and the difference between those 2 values is directly proportional to AH (Figure 22) (Gupta, 2020).



(a) (b)

Figure 21: (a) simplified structure of a capacitive sensor (image provided by Andivi, ND) and (b) example of relative humidity capacitive sensor (model KFS140-D by bb-sensors)

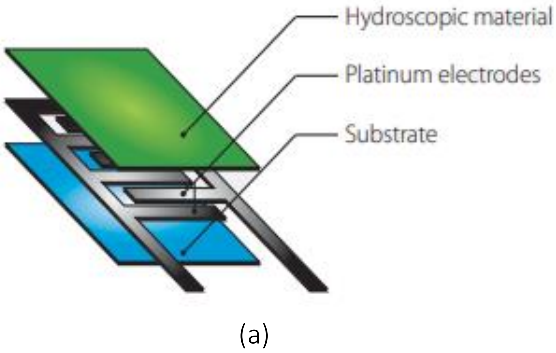


Figure 22: (a) simplified structure of a resistive sensor (image provided by Andivi, ND) and (b) example of relative humidity resistive sensor (model SHS-A4L by bb-sensors)

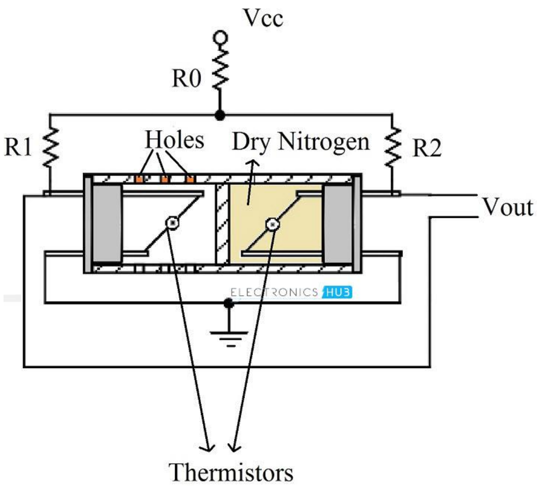


Figure 23: structure of a thermal conductivity sensor (image provided by Electornics hub)

The Figure 24 summarizes the main types of humidity measurements tools that are available (Institute of measurement and control, 1996).

Sensor type	Absolute or Relative humidity	Typical range of measurements	Displayed units	Sampling configuration	Uncertainty in use
Mechanical	RH	20% to 80%	% RH	Whole immersion	± 5 to 15%
Psychrometer	RH	5% to 100%	% RH	Whole immersion or sample gas flow	± 2 to 5 %
Resistive	RH	5% to 99%	%RH	Probe or whole immersion	± 2 to 3%
Capacitive	RH	0% to 100%	%RH	Probe or whole immersion	± 2 to 3%
Impedance dew-point	AH	Dew points of -85°C to +60°C	Dew point, vapour pressure	Probe	± 2 to 5°C
Condensation (optical)	AH	Dew points below -85°C to + 100°C	Dew point	Sample gas flow or probe	±0.2 to 1°C
Lithium chloride	AH	Dew points of -45°C to +60°C	Dew point	Probe	±2 to 4°C
Spectroscopic	AH	Extremely wide range	Ppm	Gas sample	± 3 to 10% of reading
Colour change	RH	20% to 80%	%RH	Paper test card	10-20% RH

Figure 24: The main types of humidity measurements tools (Institute of measurement and control, 1996).

2.4.2.3 Sensors used in agriculture for humidity measurement

Agriexpo[2] online inventoried 69 products in 2022, belonging to 32 suppliers. Only 3 of them are used for air relative humidity measurements, while the others are dedicated to grains or soil humidity measurements. Those 3 tools are all capacitive sensors. Direct Industry listed 126 products from 61 suppliers, in 2021, for the tools measuring relative humidity but all the tools are not necessarily adapted for agricultural use.

In SmartAquaponics project, users have chosen to use the Campbell Scientific CS215 sensor for air humidity measurements. This sensor is able to measure relative humidity for 0% to 100% (between -20°C to 60°C) with a precision of 2% between 0% to 90% of RH at 25°C and 4% elsewhere.

The Figure 25 could be used as a guide to choose the adapted type of sensor, as it highlights their advantages and weaknesses. It shows the performances of sensors using electrical impedance, including capacitive and resistive sensors, as they are easy-to-use and provide continuous data for a permanent monitoring of the environment in terms of humidity.

[2] Agriexpo is a free website making inventory of tools, including sensors, used in agriculture. For humidity sensors: https://www.agriexpo.online/fr/fabricant-agricole/capteur-humidite-330.html (June 2022)

Sensor type	Advantages	Weaknesses
Mechanical	- no need of battery nor electricity power - cheap - easy to understand charts	- slow response to change in humidity - highly disturbed by vibration or transportation
Psychrometer	- simple, cheap, reliable and robust - stable and measures wide range of humidity - high tolerance of temperature and condensation	- large air sample is required - needs of some skills to use and to maintain the tool - sometimes calculation from temperature readings is needed - contamination possible with airborne particles - measurement may be difficult below 10°C
Electrical impedance	- easy to use - presence of memory to store results - adaptors are available for wide use - capacitive sensors tolerate condensation	- calibration shifts at high temperature (above 40°C) - can be damaged by aggressive chemicals
Condensation (optical)	- used as reference standards - precise measurement - long-term performance - wide range of measurement	- expensive - skills are required to operate - contamination can caused incorrect readings - measurement below 0°C has to be interpreted carefully
Lithium chloride	- cheap	- cannot operate below 10% of RH - does not tolerate condensation - slow response - affected by contamination from hygroscopic materials or solvents - skills required for maintenance
Spectroscopic	- suitable for measurement with any gas, even corrosive or reactive - can be used to measure concentrations - operate at high temperatures - non-contact measurement - fast response and high sensitivity	- expensive - sophisticated technology - difficult to calibrate
Colour range	- cheap and simple - no need of power or battery - can be observed remotely (depending on its location)	- only give an estimation of humidity (not precise) - difficult to calibrate

Figure 25: Advantages and weaknesses of the main types of humidity sensors (Institute of measurement and control, 1996)

2.4.2.4 Calibration of humidity sensors

As for temperature sensors, the best way to calibrate humidity sensors is to be in contact with an accredited laboratory (accreditation from COFRAC in France or from BELMET in Belgium). Those laboratories are following ISO/IEC 17025:2017 standard guiding general requirements for the competence of testing and calibration.

The ISO 8756:1994 is the reference describing "procedures for adjusting air quality measurements for changes in temperature, pressure and humidity during the sampling period".

There are several types of calibration methods for hygrometry:

- dew-point generator
- two-temperature generator
- two-pressure generator
- humidity chambers
- mixed-flow generator
- salts
- bottled gas

The four first methods mentioned on this list are the most used for laboratory calibration. The following section is described by the British Institute of measurement and control (1996).

All calibrations could be done within humidity chambers as in this method, the temperature and the humidity could be controlled accurately and could be varied using steam or spray injection or one of the methods described below.

For dew-point generator method, the goal is to have a gas with the closest dew point from temperature of saturator. For that, the gas is humidified by bubbling through water or ice at a given temperature. For two-temperature generator method, the goal is to obtain values of relative humidity or dew point by varying one or two gas temperatures: the gas is firstly humidified at a first given temperature giving its own dew point or vapor pressure, then this same gas is given to a second chamber at a higher temperature in order to check the variation of the previous dew point.

For two-pressure generator method, the goal is to obtain values of relative humidity or dew point by varying pressures (or temperatures or both): the gas is firstly humidified at an elevated pressure and is secondly expanded at a lower pressure. The variation of pressure has to be done under the same temperature. The pressure of the water vapor falls with the pressure and if the initial humidity is known, the humidity after expansion could be determined.

2.4.3 Light measurement sensors

2.4.3.1 A small history

Our eye is the organ which captures light emission allowing us to see and to analyse our direct environment by giving this raw information to our brain. From childhood, human eyes are trained to recognize different things such as letters, then words allowing us to read books, or to recognize colours, then object format allowing us to define objects or other traits to recognize plants, animals, and other people. Without light source, it is not possible for our eyes to make such appreciation.

The light itself was a subject of discussion and research, since couple of centuries, on the basis of the fact that human appreciation cannot be objective and depends on the current environment. So, to try to have an objective measurement of the light intensity, it was necessary to imagine and to build different tools. Johnston (2001) published a complete and interesting book dedicated to the history of light and colour measurements. The first assumption he made about such history is the scarcity of depictions of the tools. In this document, the first attention given to the light measurement dated on the 18th century with the construction of an apparatus, by R P François-Marie, which scale light intensity by passing light through cascaded pieces of glass to estimate its progression arithmetically. After this trial, Christian Huyghens used a long tube with a hole at the top to compare the light of the sun with the light of Sirius. Other 18th names that tried to build tool for light measurement are:

- Pierre Bouguer in 1729 who set up a device named “lucimètre” having two tubes directed at two light sources and converging at a paper screen viewed by the eye. The goal of this device was to understand how light brightness varies with distance from a light source
- Benjamin Thompson or Count Rumford built a “visual photometer” for measuring light intensity when different sources of light (candles, lamps and oil burners) pass through glass or reflected by mirrors

From those practical uses, in the mid-19th century, light measurement apparatuses were used more by astronomers then by the gas lighting industry and finally by the electric light industry to highlight their higher performance. It was also the period of the birth of different theories about light such as Bouguer, Lambert and Beer statement telling that “the logarithm of the quantity of light received is inversely proportional to the thickness (‘Bouguer’s law’) and to chemical concentration (‘Beer’s law’) of an absorbing material, and the quantity of light to the cosine of the angle of incidence on the illuminated surface (‘Lambert’s law’)”.

The beginning of 20th century was the rise of the organizations and institutions, such as national laboratories, dedicated to light measurement. From those organizations, three topics raised concerning light measurement:

- photometry for the measurement of visible light
- radiometry for the measurement light invisible radiations
- colorimetry for the measurement of colors

Then the visual observations, using human eyes, were progressively replaced by the use of physical means with the rise of mechanized and automated light measurement tools. The use of photoelectric techniques gave a great impulse to the domain and interests more and more users, including militaries.

In plant sciences, the studies to understand how plants are growing started a bit earlier than the studies about light. In the 17th century, Jan Baptist van Helmont ran experiments with willow trees: he rejected the old theory telling that plants are growing and taking their biomass only from soil and concluded that they are growing through water, without, at this time, any notion of gas exchanges (Shipunov, 2020). Then in the late 18th, Joseph Priestley put candle and mouse separately within hermetically sealed jars, then put candle and mouse together with a sprig of mint in similar hermetic jars. He concluded that mouse and candle had the same behavior by consuming the air inside the jars (mouse was dead and candle was extinguished), but when combined with the mint sprig, the air is revived. From those two conclusions, no relationship was yet established between the light, the biomass and "revived air" productions from plants. In late 18th, Jan Ingenhousz confirmed the conclusion of Joseph Priestley but added three other facts: the air is only revived during the day time, only plants green parts are inducing those revived air, while the other plants parts are consuming that air (but this consumption is neglectable compared to the revived air production). This revived air has been studied later on by Antoine Lavoisier who gave to it the name of oxygen. One century after Ingenhousz experiment, Thomas Engelmann studied the effect of different lights on the production of oxygen and concluded that this production is higher under blue and red parts of the light spectrum. It was a huge discovery showing the role of chlorophyll, the green pigment of plants, in such process including light.

Jan Ingenhousz is known as the discoverer of "photosynthesis", although this word has been used and defined much later by Charles Barnes in the end of 19th century (Gest, 2002). Photosynthesis could be defined as the process in which "a plant uses carbon dioxide from the air, water from the ground, and the energy from the light of the sun to produce its own food and oxygen", according to Cambridge dictionary (consulted on 2022). So, light is very important for green plants, in order to perform photosynthesis as an autotroph organism and to generate elementary product for human which is the main objective of agriculture domain.

2.4.3.2 The photosynthetically active radiation (PAR) and its measurement

The visible light is the part of the electromagnetic spectrum that the human eye can view. It ranges from 380 nm to 700 nm (Figure 26). The photosynthetic activity depends on specific light wavelengths and occurs only between certain part of light spectrum. McCree's experiments (McCree 1972; McCree, 1973) defined that the photosynthetically active radiation ranges between 400 nm to 700 nm. Outside this region, the photosynthesis activity is very limited. Light in the red region (i.e. 600 to 700nm) induces the highest assimilation of CO2 per mole of photons (named "quantum yield" of CO2) (Liu and Van Iersel, 2021). This notion of "quantum yield" is often used to present efficiency of photosynthesis (Mötus et al., 2011).

In plant science, and in agriculture, PAR measurement aims at quantifying radiation that drive photosynthesis, that furtherly lead to the production. Its intensity is well predicted by the number of absorbed photons than by the radiant energy received be the plant leaf (Mötus et al., 2011). To quantify PAR included particle flux, the photosynthetic photon flux density (PPFD) is used and is expressed in micromoles of photons per square meter per second (µmol.m^{-2}.s^{-1}). However it could be also quantified using irradiance or PAR irradiance, expressed in Watts per square meter (W.m^{-2}).

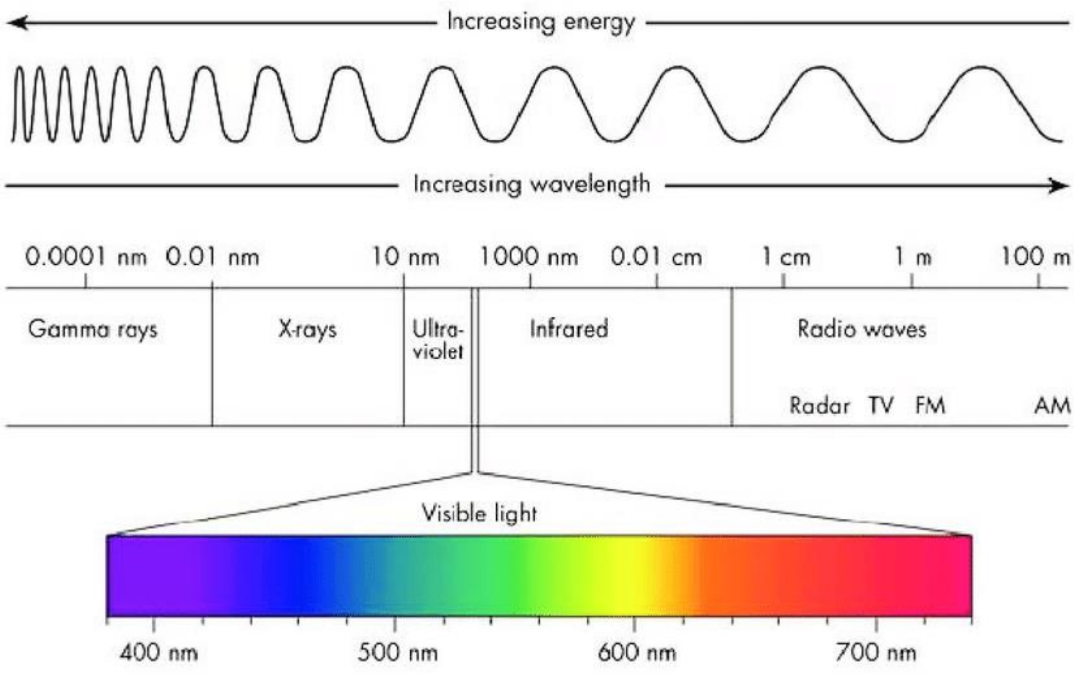


Figure 26: Diagram of the light spectrum, highlighting the visible light wavelengths (Secades et al., 2014)

2.4.3.3 Sensors to quantify photosynthetically active radiation (PAR)

For PAR measurement, sensors transforming radiation to voltage could be used. Mötus et al. (2011) classified those sensors in two:

- PAR quantum sensor measuring the PPFD (giving data in µmol.m^{-2}.s^{-1})
- PAR energy sensor measuring the irradiance (giving data in W.m^{-2})

PAR quantum sensors are the most used tools. They are made with photodiodes (photovoltaic sensors) based on the photoelectric effect. Those sensors are very sensitive and respond to PPFD changes instantaneously.

Within SmartAquaponics project, users are using SKP215 PAR quantum sensors (Campbell Scientific) (Figure 27). The output is given in Volt, with a ratio of 1mV per 100 µmol.m^{-2}.s^{-1} and with an accuracy of ± 5%.

Figure 27: SKP215 PAR quantum sensor (Campbell Scientific)

2.4.3.4 Calibration of PAR sensors

In practical, users may be tempted to compare values given by two PAR sensors, to verify if the data given by the sensors are relevant or not. A direct comparison is difficult and conditioned by similar condition of measurement and knowledge about the sensitivity functions used by the two sensors (Möttus et al., 2013). It means that to calibrate a PAR sensor, it is highly recommended to do so in a controlled experimental environment where all light parameters are known, within accredited laboratory, for example, and using standard lamps.

2.4.4 Oxygen sensors

2.4.4.1 Definition

Oxygen is essential for living organisms in the air or in the water, although it is the third most abundant element after Hydrogen and Helium (Dole, 1965). For fish culture, part of aquaponics system, dissolved oxygen (DO) concentration is one of the most important water quality parameter (Hargreaves and Tucker, 2002). There are two sources of water oxygen (Mantexgroup, 2021):

- from the atmosphere: the atmospheric oxygen (from wind on the water surface, streams, waterfalls or water flows) is dissolved into water's surface;
- from algae and other underwater grasses that create oxygen through photosynthesis.

Apart from fish, oxygen is also important for some microorganisms, such as aerobic bacteria, to transform and reduce useless nutrients present in the water.

The units for the measurement of dissolved oxygen could be parts per million (ppm) or milligrams per liter ($mg.l^{-1}$), where 1 ppm is approximately equal to 1 $mg.l^{-1}$. The Figure 28 is showing the effect of different levels of DO on fish environment. Fishes, for example, cannot survive with dissolved oxygen less than 5 ppm or 5 $mg.l^{-1}$ (Bozorg-Haddad et al., 2021).

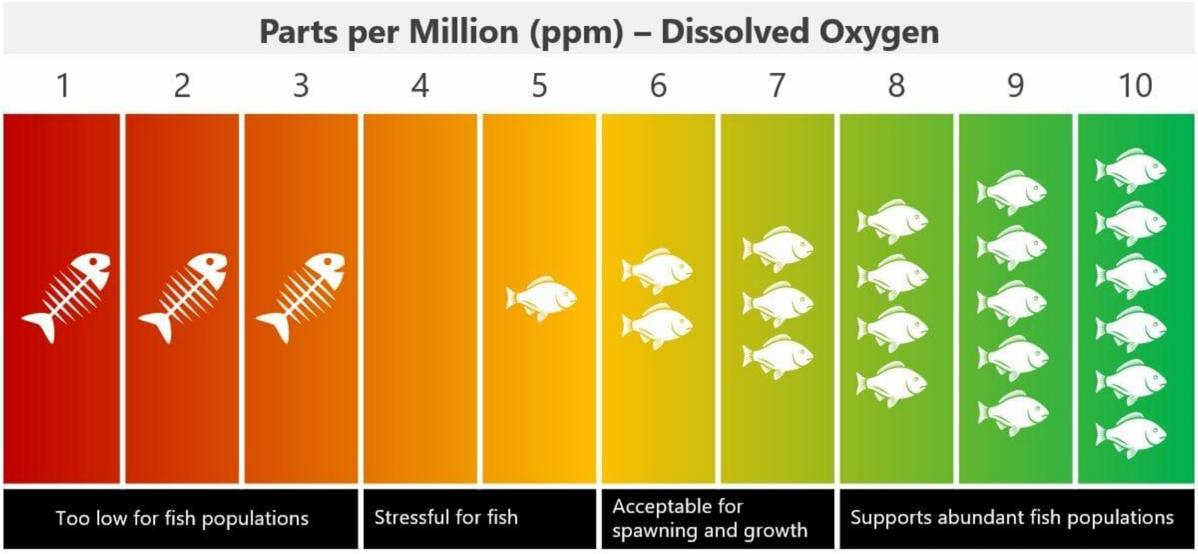


Figure 28: Effects of different levels of dissolved oxygen (DO) on fish life (Mantexgroup, 2021).

To measure DO parameter, different sensors may be used but the working principle is almost the same: an electrical signal is produced proportionally with the oxygen concentration. This signal is amplified and then displayed by the oxygen meter (Hargreaves and Tucker, 2002). The DO sensors often operate with electrochemical cells having positive and negative electrodes connected by a saturated electrolyte solution named “salt bridge”. The oxygen passes through a membrane during which a chemical reaction is occurring to reduce it. This reaction could generate some electrical impulse which is proportional to the DO concentration (Hargreaves and Tucker, 2002).

2.4.4.2 Classification

Hargreaves and Tucker (2002) classified the DO sensors in three:

- Polarographic sensors, also known as Clark sensors, which use of gold or platinum as cathode and silver as anode
- Galvanic sensors which use silver or platinum as cathode and lead iron or zinc as anode. One of the advantage of the galvanic sensors is their faster response times compared to the polarographic sensors, although they are more expensive
- Fiber optic oxygen sensors which use optical fiber with a sensor tip containing thin layer of oxygen-sensitive fluorescent dye dissolved in a pure silicon. This type of sensor is very sensitive even at low DO concentrations, although ambient light could create some issue. That is why some sensors are covered by a silicon coat, reducing the response time, but necessary to avoid the effect of ambient light.

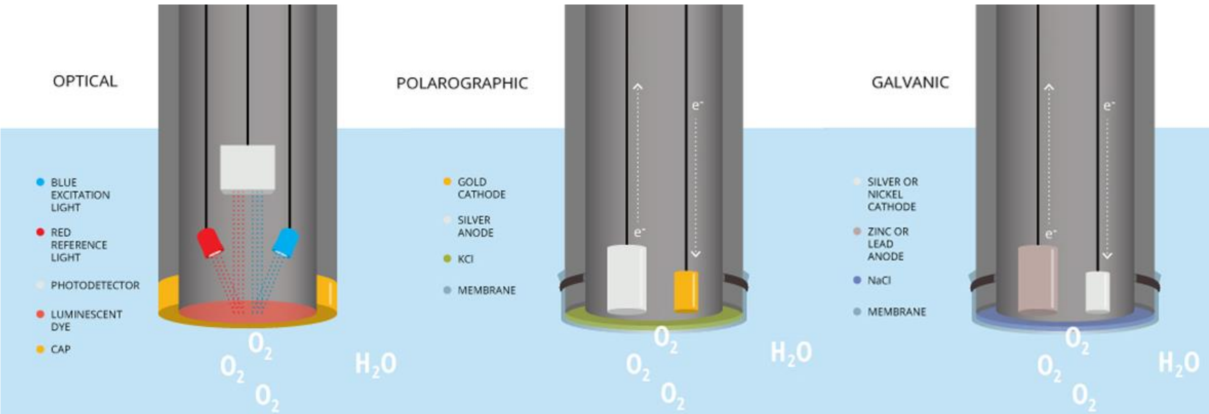


Figure 29: the 3 types of DO sensors (images provided by NexSens Technology Inc, 2019)

2.4.4.3 Inventory

Agriexpo[3] website inventoried 11 products sold by 6 companies for DO measurement.

SmartAquaponics project is using Oxyguard D0243C model for oxygen saturation and temperature measurements (Figure 30). It is DO sensor made of membrane covered by galvanic cell generating an electrical signal proportional to the oxygen pressure it sensors (Oxyguard, 2020).

Figure 30: Oxyguard D0243C dissolved oxygen sensor

The main specifications of this sensor are (Oxyguard, 2020):

- dimensions: diameter=58mm, length = 59mm
- standard cable length: 7m
- weight: 0.5kg with the standard cable

[3] Agriexpo is a free website making inventory of tools, including sensors, used in agriculture. For DO measurements: https://www.agriexpo.online/fr/tab/oxygene-dissous.html?suggest=32416846757467697265532b6950355833567a304565305743443275525073716d7073696b4b4b347444453d (June 2022)

- operating conditions: 0°C to 40 °C and submersible at maximum 50m
- response time: 90% of end value within 1 minute

7.1.1.1.1. Calibration

As for the other studied sensors, DO sensors are not measuring directly the oxygen concentration in water. In order to calibrate such oxygen meters, it is necessary to verify the electrical outputs given within environment under known DO concentration, such as in an air saturated with water vapor, i.e. with 100% of humidity. This method is corresponding to the ISO 5814 standard. The detailed process for making such calibration is given by Hargreaves and Tucker (2002), and could be done in practical.

Calibration may be needed in some specific situation: for a new installation, when the sensor's membrane needs to be replaced, after a maintenance or when unexpected values are given by the sensor.

2.4.5 pH sensors

2.4.5.1 A small history

In 1904, Hans Wilhelm Carl Friedenthal (1870 – 1942) established the first acidity scale by examining the color change of 14 solutions of known hydrogen concentration. The color change is proportional to the variation of hydrogen ion concentration. Afterwards, the first notation of pH, or "power of Hydrogen" ("pondus Hydrogenii" in Danish), was introduced by Søren Peder Lauritz Sørensen (1868-1939) in 1909 in order to measure the hydrogen ion concentration in aqueous solution (Spitzer and Pratt, 2011).

2.4.5.2 Measurements references

pH is a measurement of how acidic or how basic a substance is, including water. pH values range from 0 to 14: the substance is acid when the pH value is below 7 and tend to 0, while it is basic when the pH value is greater than 7 and tend to 14. A pH value equal to 7 means that the substance is neutral. The pH values have been determined for different substances, to have an idea of their acidity or basicity (Figure 31).

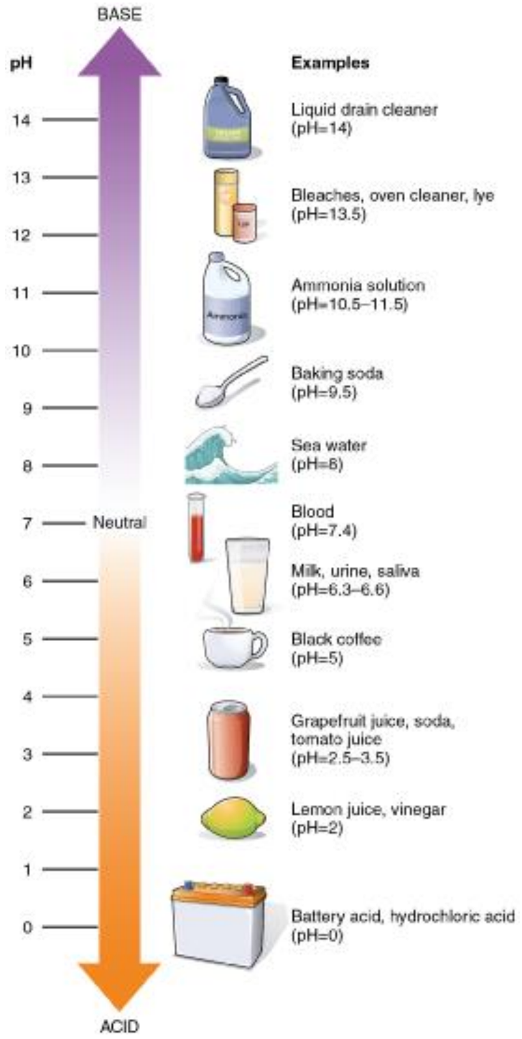


Figure 31: Example of pH scale illustrated by the pH values of various substances (USGS, 2019)

For water dedicated to fisheries, the ideal pH values have to range between 7 and 8.5 (Figure 32). This value could vary even along the day, so a nice attention should be given to this value to avoid serious problems.

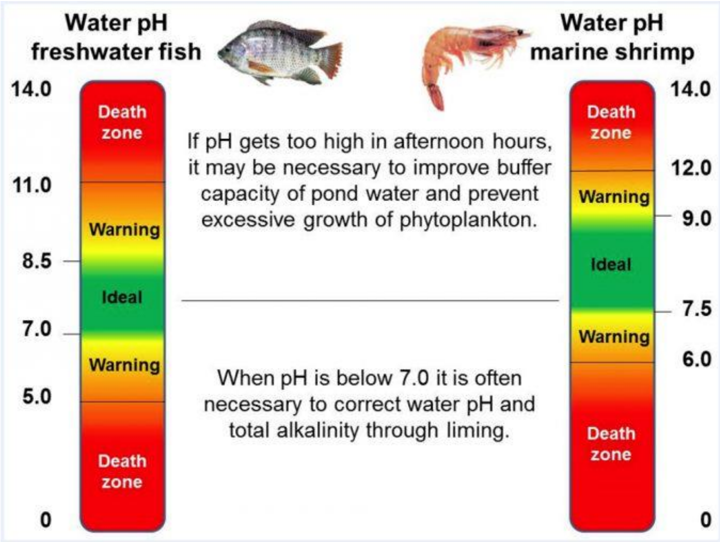


Figure 32: Indicative pH values for fish water monitoring (Kubitza, 2017)

2.4.5.3 Classification

To measure pH values, three major methods are highlighted by Baucke (2002) and Spitzer and Pratt (2011):

- primary pH standards as absolute measurement of pH: using the Harned cell, measuring the potential difference of an electrochemical cell without liquid junction, involving a selected buffer solution, a platinum hydrogen gas electrode and a silver/silver chloride reference electrode (Pt|H2|buffer, Cl-|AgCl|Ag) (Figure 33). This primary method uses reference buffer having pH variating from 3 to 10. However it is a very sophisticated method and time-consuming, not adapted for routine measurements.

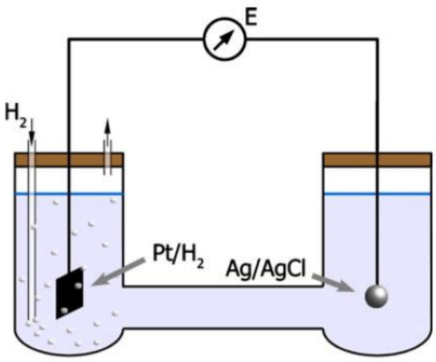


Figure 33: Primary pH measurement using Harned cell

- secondary pH standards for the determination of pH: using the Baucke cell, in which the difference from the previous method concerns the electrodes. Here, there are two identical electrodes made of platinum hydrogen (Pt|H2), and two quasi-identical buffers with known pH values (Figure 34). The first buffer (S1) is the same as for the primary measurement (using a

Harned cell) while the second buffer (S2) is a certified reference material buffer for which pH is to be assigned.

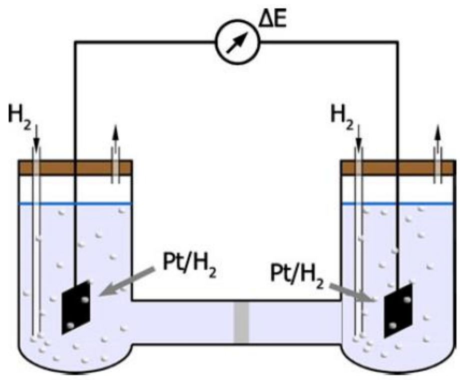


Figure 34: Secondary pH measurement using Baucke cell

- pH measurement using glass electrode for routine measurement: it contains a glass electrode and a reference electrode with a liquid junction or diaphragm. The glass electrode is surrounded by the reference electrolyte (Figure 35). This type of pH electrode is nowadays the most-used in practical.

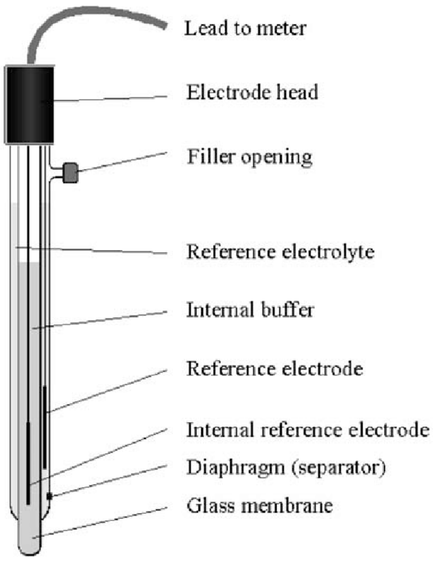


Figure 35: pH electrode schematic construction (Naumann et al., 2002)

2.4.5.4 Inventory

Agriexpo[4] inventoried 44 products from 14 companies to measure pH. For SmartAquaponics project, pH of water is measured using the pH sensor of IKS Aquastar (IKS, Germany) (Figure 36). It is a combined

[4] Agriexpo is a free website making inventory of tools, including sensors, used in agriculture. For pH measurement: https://www.agriexpo.online/fr/fabricant-agricole/ph-metre-360.html

glass electrode that is connected to the IKS aquastar board table in which pH values are displayed. Alarms could be configured and activated if the given pH values are outside the normal range for fish.

Figure 36: pH electrode of IKS Aquastar

2.4.5.5 Calibration

As all the other sensors, pH electrodes could be calibrated by accredited laboratories following international standards for sensors calibration.

What is interesting for pH sensors is that it is easy to verify if the values given by the sensors are correct or not. For IKS Aquastar pH electrode, the sensor is delivered with 3 buffer solutions with known pH: one acid solution (pH = 4), one neutral solution (pH = 7) and one basic solution (pH = 12.45). As pH is sensitive to the temperature, before any pH measurement it is necessary to verify the temperature of the solution. This rule is also working when calibrating the sensors: before measuring the pH of the buffer solutions, the temperature of the buffer solutions needs to be verified (by putting the buffer solutions bottles in the same measured water for example). Once the temperature is verified, the pH electrode could be put within one buffer solution, by starting with the acid solution, and the given value could be directly verified on the IKS board. Between two measurements, it is necessary to clean the pH electrode using distilled water. The pH electrode is working correctly if the values of the 3 buffer solutions are corresponding to the given pH at 4, 7 and 12.75.

2.4.6 Water electroconductivity sensors

2.4.6.1 Definition

Electrical conductivity (EC) is the measurement of ionic constituents of a solution, including waer, showing its ability to pass an electric current. This capacity for passing electric current depends on different factors such as temperature and ions characteristics in the water (concentration, mobility, valence) (Hach, 2015). As example, pure water has a very low conductivity while aqueous solution with concentrated chemicals has a high conductivity. The EC measurement is important for water quality monitoring, to know how much dissolved substances (chemicals, minerals, ions) are present.

2.4.6.2 EC measurements

The simplest illustration of EC measurement is the use of two electrodes, charged negatively and positively, immersed in a solution and measuring the resulting voltage (U) of an applied alternating electrical current (I) (Hach, 2015, based on ISO 7888:1985 standards). When applying the electrical current, the solution becomes an electrical conductor while the cations go to the negative electrode and the anions go to the positive electrode (Figure 37).

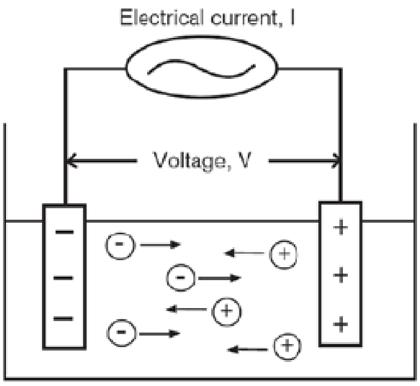


Figure 37: illustration of electrical conductivity of a solution, using two electrodes and applying an electrical current (I) to measure the voltage (U).

Using the Ohm's law, the resistance R of the solution could be calculated (R = U/I), then the conductance G which is the inverse of the resistance (G = 1/R). From this conductance calculation, it is necessary to include the dimensions of the device, named cell constant (K). K is the ration of the distance between the electrodes (d) and the area of the electrode (a) (K = d/a). Finally, to convert the conductance into conductivity measurement (noted Kappa or κ), the following relation is used:

$$\kappa = G \times K$$

where the conductance G is measured in Siemens (S) or microSiemens (µS) and the cell constant K is measured in per meter (m^{-1}) or per centimetre (cm^{-1}).

The reference for EC measurement at 25°C is the ultrapure water. It is important to notice that EC is strongly influenced by changes in temperature, about 2% per °C. That is why it is necessary to use this temperature coefficient as an automatic temperature compensation for EC measurement (Thirstrup and Deleebeeck, 2021).

2.4.6.3 Sensors classification

Thirstrup and Deleebeeck (2021) made an excellent review of EC measurement sensors. The Figure 40 summarizes the classification of EC sensors based on their configuration, the use of 2 or 4 electrodes, and the conductivity ranges of interest:

- for very low conductivity range (κ lower than 0.1 $mS.m^{-1}$), using coaxial cylindrical electrode (Figure 38);
- for low to high conductivity ranges (κ between 0.1 $mS.m^{-1}$ and 10 $S.m^{-1}$), using plane-parallel electrodes combined with AC power (Figure 39);
- for very high conductivity range (κ greater than 10 $S.m^{-1}$), using 4-electrode combined with DC power.

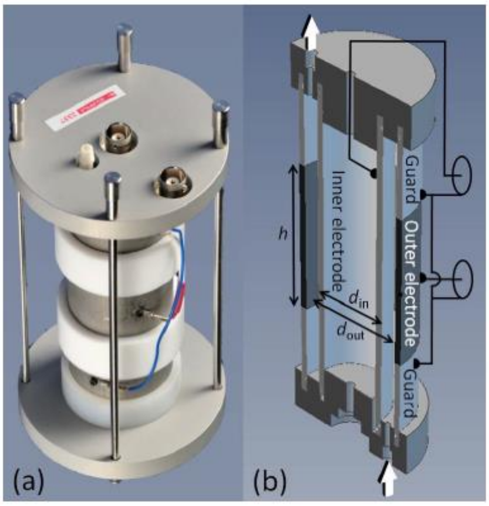


Figure 38: Schematic representation of a coaxial cylindrical EC cell with (a) optical micrograph and (b) drawing (Thirstrup and Deleebeeck, 2021)

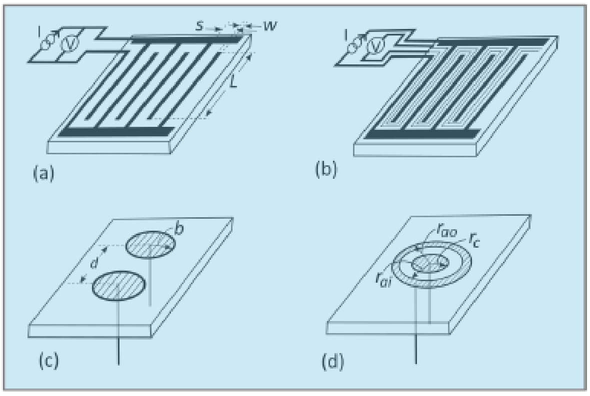


Figure 39: Schematic representation of a plane-parallel EC sensor with (a) 2-electrodes, (b) 4-electrodes, (c) pair of disk electrodes and (d) pair of annular electrodes (Thirstrup and Deleebeeck, 2021)

Sensor configuration	Number of electrodes	Typical measurement scheme (AC/DC and time/frequency domains)	Accuracy	Conductivity range	Examples of application
Plane parallel electrodes, center piece	2	AC (frequency)	High	Low to high	Metrology, calibration, dielectric spectroscopy
Plane parallel electrodes, center piece	4	DC	High	High	Metrology, calibration

Coaxial cylindrical electrode	2	AC (both frequency and time domains)	High	Low to medium	Metrology, industrial process monitoring
Van Der Pauw	4	AC (frequency)	High	Medium to High	Environmental
Planar electrodes	2 or 4	AC (both frequency and time domains)	Low	Low to high	Health care
Non-contact capacitively coupled	2	AC (frequency)	Low	Medium to high	Electrophoresis
Non-contact inductively coupled	4	AC (both frequency and time domains)	Low	High	Salinity, industrial process

Figure 40: Summary of sensors used for electrical conductivity (EC) measurements (Thirstrup and Deleebeeck, 2021).

2.4.6.4 Inventory of electrical conductivity sensors

Agriexpo[5] inventoried, in June 2022, 24 EC sensors belonging to 8 companies. It includes water, milk and soil measurements.

Within SmartAquaponics project, the IKS Aquastar conductivity electrode is the sensor used for EC measurement (Figure 41). This sensor has 4 electrodes and could measure EC from 10µS to 1mS or from 1mS to 100mS. The sensor could be automatically calibrated and provide automatic temperature compensation.

Figure 41: IKS aquastar EC module (Image taken from reef aquarium store)

[5] Agriexpo is a free website making inventory of tools, including sensors, used in agriculture. For electrical conductivity measurement: https://www.agriexpo.online/fr/fabricant-agricole/analyseur-conductivite-electrique-4627.html (June 2022)

7.1.1.1.2. Calibration

For EC measurements, sensors are often delivered with solutions of known EC values. For IKS EC sensors including an electrode for example, they are delivered with 2 solutions of 1mS and 50 mS. The calibration process is similar to pH sensors calibration (see section 7.2.4.5.4), with a high consideration of temperature variation as conductivity is very sensitive to temperature changes.

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