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Smart Aquaponics Guide : Plant production

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Preamble:

This document was inspired by the aqu@teach textbook (Jungle et al. 2020) and includes parts of the aqu@teach textbook. This textbook is available at on http://doi.org/10.5281/zenodo.3948179 .

1 Introduction

The approach developed by Smart Aquaponics consists in predicting the organism (plant, fish and bacterial) development according to the environment experimented by the organisms. For all these organisms, the smart aquaponic model predicts the optimal development and the environmental factors can either speed up or slow down its development. The major environmental factors influencing the plant development are the temperature, light, water quality, humidity and $C0_2$ concentration. The plant physiology chapter explains the most important physiological processes influenced by environmental factors, make the link with the crop management and quantify the effect of these environmental factors on yields. The chapter climate management describes the different tools accessible to the grower to influence the environment with a greenhouse. The chapter plant nutrition describes the major elements of plant nutrition, make the link with crop management and quantify of these environmental factors on yields. The section hydroponics describes the tools accessible to the grower in order to implement hydroponics systems.

1.1 Plant physiology.

Plants are composed of three vegetative organs: (i) roots, which main function is to provide anchorage, water, and nutrients, and to store sugars and starch; (ii) stems, which provide support; and (iii) leaves, which produce organic substances via photosynthesis. The reproductive organs are the flowers and the fruits. Within the context of plant production, we generally distinguish different categories of vegetables. First, plants whose vegetative organs are consumed are the leafy greens (lettuce, chard, spinach, …) and aromatic plants (basil, mint, coriander, …). Secondly, the plants whose reproductive organs are consumed are fruit vegetable (tomato, eggplants or cucumbers).

Beside these categories, it is possible to distinguish the vegetables according to the duration of their development. Plant with a determinate growth stop growing when they reach a certain level of development. Most leafy vegetables and aromatics are generally harvested at that level of maturity. The arrest of development is often associated with the flowering. Moreover, after flowering, many leafy greens or aromatics are not adapted to market; the plant shape may change due to the apparition of flowering stems, the taste or texture may change, some organs become more bitter or woody. In fine, most determinate vegetable needs to be harvested when they are big enough, but before the flowering process start. Most fruit vegetables also have a determinate growth, but the plant continues growing after flowering. Plants with indeterminate growth never stop growing when they are in optimal condition. The development of these plants will slow down and possibly stop when the environmental conditions are less optimal (temperature, light intensity, disease, …). Within the same specie, some varieties can have a determinate growth and other varieties indeterminate growth. This is the case of tomatoes, whose most professional or hybrid varieties are indeterminate, but other varieties, most commonly used by gardeners are determinate and stop growing after reaching a certain level of development.

The speed of the vegetative development change during the plant life cycle. Indeed, after the germination, plants are growing very slowly and then gradually more rapidly. Then, the plant experiment a rapid vegetative growth phase. Then after the determinate plants slow down their vegetative development. In the case of indeterminate plant, the plant will continue producing fruits and vegetative organs and fruits as long as all environmental parameters remain optimal (figure 1).

Figure 1 : Graphical representation of the plant development in optimal condition for determinate plant (blue) and indeterminate plant (orange).

The flowering initiate the fruit production of the fruit vegetable and arrive after the plant has reached its commercial maturity development in the case of leafy greens and aromatics. The beginning of flowering can start when the plant achieved a certain level of development, which is the case of most fruit vegetables. Besides, the initiation of flowering may be associated with photoperiod (duration of the day), some plant species will flower faster when the duration of the day is longer, other when it is shorter. For example, beets, chard or carrots will flower more rapidly when days are longer. Other factors such as drought or temperature stress can trigger the flowering. Drought is generally not an issue in hydroponics, but heat shock may happen, and in the case of lettuce, this may trigger the flowering (bolting) and hastily stop its development.

1.2 Modeling

An abundance of plant growth models has been created. These range from simple empirical curves to very complex set of physiological equations. The Smart Aquaponics goal is to provide a greatly modular model able to anticipate the vegetative mass and the fruit mass of crop species commonly used in aquaponics. The selected sub-model for vegetative and fruit mass of determinate plant is a “simple” sigmoid curve. Sigmoid curve unable to model simulate the slow development at the beginning of the plant life, the rapid development phase and the decrease of the development when the determinate growth plant reaches its maturity. The mass of the vegetative organs and fruits are modeled independently according to the following sigmoid equation:

$$W = Wmax / (1 + e^{-K(t-t_0)})$$

where W represents the fresh mass at the time t after the germination. $Wmax$ is the final mass of the plant, K is the growth coefficient, $_0$ is a theoretical value calculated to obtain the size or the mass at age 0. Plants grow faster with a lower K. The time unit is not the linear time (minutes hour, days,…) but the degree-day units, a concept that will be explained in the paragraph 2.1.2. The fresh mass of the vegetative organs and fruit are modeled independently, therefore, fruit species have specific Wmax, K and t_0 for the vegetative organ and for the fruits. The Figure 2 presents the Wmax and K factor of the determined vegetable present in the Smart Aquaponics Model. These values are general value these species, it is important to notice that different cultivars of the same species may have different Wmax and K value.

	Vegetative organs			Fruit		
	Wmax (g)	K (/hrs]	t_0 (degC)	Wmax (g)	K (/hrs]	t_0 (degC)
Lettuce	845.99		791.45	0	0	0
basil	366	0.005	1100	0	0	0
mint	657.3	0.004	1580	0	0	0
coriander	30.05	0.0086	577.27	0	0	0
tomato	4500	0.0035	1600	5048	0.0037	3300
pepper	5452	0.0035	1890	1213	0.0034	1978
eggplant	2506	0.0102	659.88	2890	0.0093	906.41
cucumber	3383	0.01	515	8685	0.009	601

Figure 2 : Wmax, K, t_0 values used by the Smart Aquaponics model for plant and fruit weight.

The sigmoid model was adapted for indeterminate growth. With this adaptation, plant keeps on growing as long as the development conditions are favorable. The adaptation enable the plant to continue in definitively the rapid vegetative growth phase. Therefore, after the inflection point of the sigmoid growing curve, the rate of development remains constant. Tomato is the only plant with indeterminate growth and its growth rate after the inflection point is 3.94 g/dd and 4.67 g/dd for the vegetative organs and fruits respectively.

The growth rate described by the sigmoid model is barely achieved in reality. Indeed, suboptimal environmental parameters may slow down, even stop the development. These environmental factors are the air temperature, water temperature, pH, light, humidity, pH, CO_2 and concentration of the following elements in the nutrient solution: oxygen, nitrogen, phosphorous, potassium, sodium. Smart aquaponics use a limiting function describing the limiting effect of an environmental factor. The development of the plant is affected by the limiting factor according to the following equation:

$$W=Wmax /(1+e-K(\mathrm{t}-\mathrm{t}_0))*\text{Limiting Factor}$$

where W represents the fresh mass at the time t after the germination. $Wmax$ is the final mass of the plant, K is the growth coefficient, $_0$ is a theoretical value calculated to obtain the size or the mass at age 0. The limiting factor is ranging from 0 to 1, 0 means that the plant is not growing and 1 that the plant development is optimal. This means that within the Smart Aquaponics model, limiting factors affect the final plant yields.

Most environmental factor parameters have an optimal range of value delimited by a maximal optimal value and a minimal optimal value. Within this range, the liming factor is equal to 1 within and plant are growing equally well. For example, for lettuce, the minimum optimal and maximum optimal water temperature are respectively 17C° and 26C°. Within the model, lettuce development will be the same if the root is immersed in water at 17C°, 21 C° or 26C°. The plant will stop growing if the environmental parameter is below a minimal value or above a maximal value. The Limiting factor is equal to 0 if the limiting factor is above the maximum value or below the minimum value. For example, for lettuce, the minimum and maximum water temperature are respectively 10 C° and 35 C°. Within the model, lettuce will not grow if the water temperature is 10 C° or 35 C°. When the parameter value is ranging between the minimal and minimal optimal or between the maximal optimal and maximal, the development will be slower than the optimal development (Figure 3). Within these ranges, the limiting factor will be defined according to the following equation:

If the value is ranging from Maximum Optimum Value to Maximum Value:

Limiting factor = Maximum Value - Value / Maximum Value – Maximum Optimum Value

If the value is ranging from Minimal Value to minimal optimal Value:

Limiting factor = Minimum Optimal Value - Value / Minimum Optimal Value – Minimum Value

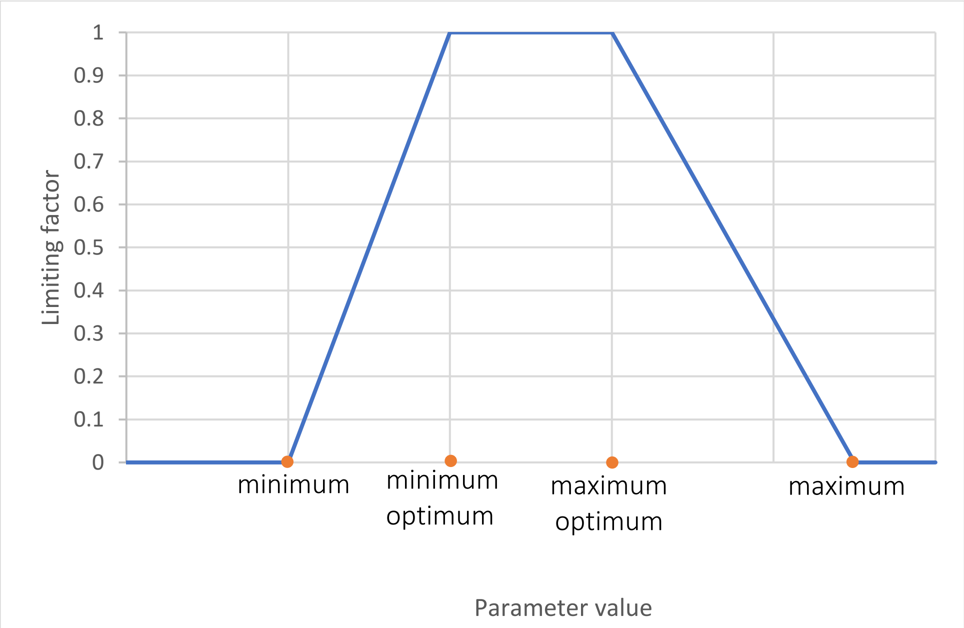

Figure 3 : Limiting factor value according to the parameter value.

Liebig law is that the most limiting factor is the one limiting the plant development. This principle is very important because it involves that improving the different element within a plant production is pointless if we do not improve the most limiting factor. For example, if the limiting factor experimented by the plant is 0,7 for the water temperature and 0,8 for the acidity, the plant will grow faster if we improve the water temperature, but won't grow faster if we improve the pH.

2 Physiology and growing requirement

2.1 Temperature

2.1.1 Physiology

Temperature is one of the major environmental factors influencing the plant development and this, during all its life cycle, from the initial stage of development to fruit maturation. The main effect of temperature is to influence the rapidity of the different physiological process, including organ development, maturation of fruit, organ generations. Indeed temperature directly influences the chemical and enzymatic reaction occurring in the plant. When temperature diverges from the optimal temperature range, this decreases the efficiency of most physiological process and decrease the rapidity of growth of the plant. In case of extreme temperature such as very low or high temperature, the temperature can damage plants. Indeed, very low or high temperatures may destroy some organs or be detrimental to various metabolic processes such as nutrient uptake, chlorophyll formation, or photosynthesis.

High temperatures can be detrimental to plant growth, especially if there is low light intensity. When the temperature is higher than the maximal optimal temperature, the only effect is the decrease of the rapidity of growth. Above the maximum temperature, the plant stop growing and can experiment some problems. High temperatures can cause problems such as thin, weak stems, reduced flower size, delayed flowering and/or poor pollination/fertilization and fruit set, and flower and bud/fruit abortion or bolting. For example, abortion of tomato flowers can reach up to 38 % when the tomato experiment a day and night temperature of 32 C° and 28 C° respectively. Concerning the bolting, lettuce can bolt when exposed at a temperature above 33 C°. In soil cultivation, the effect of high temperature is commonly associated with effect of drought. Hopefully, this is not the case in hydroponics and aquaponics.

The different plant species react differently to the cold temperature. Some of them, such as lettuce, cabbage, coriander, spinach are frost tolerant and can be kept outside during the winter. Many other species such as cucumbers, tomatoes, or eggplant are damaged when exposed to frost. These plants are generally planted outside after the last night's frost that occurs between late April and mid-may in Belgium and North of France. These plants are generally destroyed by the first autumnal frost occurring in October November. The symptoms are varying according to the intensity and the duration of the freezing temperature. A light exposure can result in small deterioration on some leaves resulting in gray spots on the leaves (see Figure 4). Larger exposure can result in the complete destruction of the leaf or plant. We can notice that the non-damaged part of the plant can recover. Some plant such as basil can be damaged when exposed to cold but non-freezing temperatures.

Figure 4 : Zucchini leave damaged by night frost (-1C°)

A specific point of hydroponic and event more in aquaponic is the water temperature. Indeed, in soil cultivation, the temperature of the root is generally very stable and the grower has no influence on the soil temperature. In hydroponics systems, the temperature of the nutrient solution can easily change. For example, the nutrient solution in NFT or raft system can warm up and influence the development of the plant. This is taken into account in the smart aquaponics model. Plant appreciates a water temperature within a certain range of value.

2.1.2 Modeling

Each plant species and variety is growing within a specific range of air temperature. The lowest limit is generally named base temperature. The plant does not grow below this **base temperature**. For example, the lettuce will start growing when the temperature rise above 3,5 °C and the tomato above 8 C°. When the temperature is between the base temperature and the **maximal optimal temperature**, the development of the plant is proportional to the temperature. The Smart Aquaponics Model is using a realistic simplification stating that the development rate is directly proportional to the temperature.

The plant development is proportional to the difference between the temperature and the base temperature: $GR = f\ (T° - T_{base})$

For example, the lettuce will achieve the same development within 3 days at 7 C° or 1 days at 14 C°. The tomato would grow the same in 4 day days at 12 C° as one day at 24 C°.

When the temperature rises above the maximal optimal temperature, the development rate of the plant decreases. The plant development completely stops when the temperature rises above the maximum air temperature. For example, a lettuce grow equally well when exposed to 18C° and 28 C°.

The main consequence of this decrease in development rate increase is that each degree above the Maximal temperature result in a diminution of development. Therefore, the producer will try to keep the plant environment below the maximum temperature.

In the previous section, we have seen that plant experimenting different temperatures have a different development. For exempt, after 30 days, a lettuce grown at 10 C° will be much smaller than a lettuce grown 30 days at 23C°. Therefore, the time measured in days or hours is not a good reference to quantify the "age" of a plant. The most common measurement of time for plant is the growing degree day system. This system aims to quantify the time by taking into account both the time and the temperature.

Growing degrees (GD) is defined as the amount of temperature degrees above the base temperature.

GD = T(t)-Tbase

Where T(t) is the average temperature measured at the day t and TBase is the base temperature. For example, for the lettuce, one day at 4,5 C° result in 1 GDs = 4,5 C° - 3,5 C°, and one day at 18 C° result in 14,5 C°.

The Growing degree days (GDD) are accumulated by adding each day's GDs contribution of a period.

GDD = (T(t1)- Tbase) + (T(t2)- Tbase) +(T(t3)- Tbase) +…

For example, if the lettuce experiment one day at 16 C° and two days at 18, the GDD will be (16-3,5)+(18-3,5)+(18-3,5) = 41,5C°/Day

Since the temperature is changing during the day and across long periods, the GDD are integrating daily temperature changes across time.

$$\mathrm{GDD} = \int \mathrm{T_t} - \mathrm{T_{base}}$$

The GDD is the time unit used for t_0 in the equation $W = Wmax$ /($1+e-K$(t-t_0))*Limiting Factor such as described in the proposed in the paragraph 1.2

In the previous section, we have seen that the plant development is hampered by the most limiting factor. The temperature can be a limiting factor when the temperature rise above the Maximal Optimal Temperature. The base, maximum optimum and maximum temperature used by Smart Aquaponics Model for different plants are presented in Figure 5.

	base temperature (C°)	maximum optimal temperature (C°)	maximum temperature (C°)
Lettuce	3.5	26	41
basil	8	26	31
mint	6	23	28
coriander	0	24	28
tomato	8	28	40
pepper	10	25	31
eggplant	15.5	33	40
cucumber	11	26	31

Figure 5 : Base temperature, maximal optimal temperature and maximum temperature used by the Smart Aquaponics Model.

2.2 Photosynthesis

2.2.1 Physiology

All green plants generate their own food using photosynthesis. Photosynthesis is the process by which plants are able to use light to produce energy and carbohydrates through the fixation of CO_2.

$$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$$

Although photosynthesis occurs in all green parts of a plant, the main site for this process is the leaf. Small organelles called chloroplasts contain chlorophyll, a pigment that uses energy from sunlight to create high-energy sugar molecules such as glucose. Once created, the sugar molecules are transported throughout the plant where they are used for all the physiological processes such as grow.

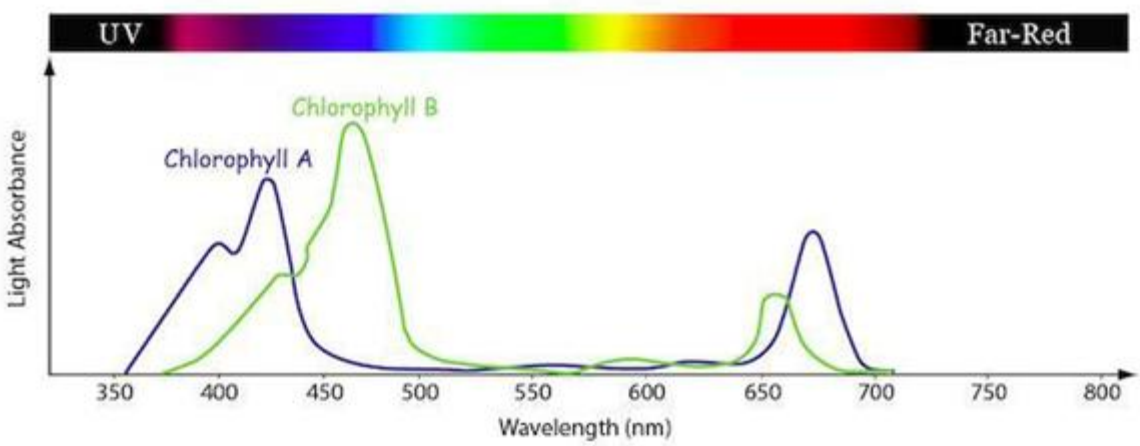

Figure 6 : Chlorophyll absorption spectrum (source: https://www.flickr.com/photos/145301455@N07/29979758460).

There are two different types of chlorophyll – chlorophyll a and chlorophyll b. Chlorophyll a is the most common photosynthetic pigment and absorbs blue, red and violet wavelengths in the visible spectrum. Chlorophyll b primarily absorbs blue light and is used to complement the absorption spectrum of chlorophyll a by extending the range of light wavelengths a photosynthetic organism is able to absorb. Both of these types of chlorophyll work in concert to allow maximum absorption of light in the blue to red spectrum. It worth notice that beside the role of light.

All plants respond differently to high and low light conditions, but some species are adapted to perform optimally under full sun, while others prefer more shade. In darkness, plants respire and produce CO_2. As the light intensity increases, the photosynthetic rate also increases, and at a certain light intensity (the light compensation point), the rate of respiration is equal to the rate of photosynthesis (no net uptake or loss of CO_2). In addition to light intensity, the day length and the spectral composition, (including the PAR and other wavelengths) also influences other development process such as flowering initiation, elongation of plants, shape of the plant.

The sun produces photons with a wide range of wavelengths: UVC 100-280 nanometres (nm), UVB 280-315 nm, UVA 315-400 nm, far-red 700-800 nm, and infrared 800-4000 nm. Photosynthetically active radiation (PAR) represent the wavelength used by chlorophyll to achieve the photosynthesis, and is ranging from 400 to 700 nm. Within the PAR, the Wavelength ranging from 500 to 650 are not involved in the photosynthesis. In the context of pant production, the objective is to identify the quantity of light accumulated by the plant during the day, independently of the daylenthgh. Therefore the most suitable light measurement for use with plants is PAR photon irradiance also called photosynthetic photon flux density, PPFD). PPFD photo irradiance indicates the number of photons that are incident on a surface measured in micromoles per meter squared per second ($\mu mol\ m^{-2}\ s^{-1}$) or in moles per meter squared per day ($mol\ m^{-2}\ d^{-1}$). Because photosynthesis is measured in similar units ($\mu mol\ [CO_2]\ m^{-2}\ s^{-1}$), use of PAR photon irradiance allows direct comparisons between the amount of light and the amount of photosynthesis to be made. Plant start growing when the PPFD is above 1,2 $mol\ m^{-2}\ d^{-1}$, but start growing without limitation when the PPFD is about 10 $mol\ m^{-2}\ d^{-1}$ for the leafy greens and above 22 $mol\ m^{-2}\ d^{-1}$ for the fruit vegetables.

During photosynthesis, plants use CO2 to make food, and release oxygen as a result. Increased concentrations of CO2 increase photosynthesis, spurring plant growth. Fresh air contains CO2 at about 0.037%, but in a tightly enclosed greenhouse or grow room, ambient CO2 can get used up quickly. For example, in a plastic greenhouse, CO2 levels can be reduced to less than 0.02 % just 1-2 hours after sunrise. At levels below 0.02%, plant growth will be greatly limited, and at levels below 0.01%, plants will stop growing altogether. By increasing CO2 levels to 0.075-0.15%, growers can expect a 30-50% increase in yields over ambient CO2 levels, and time to fruit set and flowering can be reduced by 7-10 days. However, excessive levels of CO2 enrichment can have adverse effects. Levels above 0.15% are considered wasteful, while levels above 0.5% are harmful. Excessive levels will cause the stomata on plant leaves to close, temporarily stopping photosynthesis, and since plants are no longer able to transpire water vapor adequately when the stomata are closed, leaves can become scorched.

2.2.2 Modeling of light

Light Intensity and daylight are both used as limiting factor within the Smart Aquaponics Model (Figure 7).

	PPFD (mol m^{-2} d^{-1})		light duration (h)			
	Minimum	Minimum Optimum	Minimum	Minimum Optimum	maximum Optimum	maximum
lettuce	1,296	9,72	7	17	19	24
basil	1,296	22	7	16	19	24
mint	1,152	8,64	6	15	18	24
coriander	1,296	22	7	17	19	24
tomato	1,296	22	7	17	19	24
pepper	1,152	8,64	6	14	18	24
eggplant	1,296	22	7	17	19	24
cucumber	1,296	22	7	17	19	24

Figure 7 : Minimum, PPFD, minimum optimum PPFD ;minimum light duration, minimum optimum light duration, maximum optimum light duration, maximum light duration used by the Smart Aquaponics Model.

2.3 Respiration and Oxygen

2.3.1 Physiology

The process of respiration in plants involves using the sugars produced during photosynthesis plus oxygen to produce energy for plant growth. While photosynthesis takes place in the leaves and stems only, respiration occurs in all parts of the plant. Plants obtain oxygen from the air through the stomata and roots, and respiration takes place in the mitochondria of the cell in the presence of oxygen. Plant respiration occurs 24 hours per day, but night respiration is more evident since the photosynthesis process ceases. During the night, it is very important that the temperature is cooler than during the day because this reduces the rate of respiration, and thus allows plants to accumulate glucose and synthesize other substances from it that are needed for the growth of the plant. High night temperatures cause high respiration rates, which could result in flower damage and poor plant growth.

The oxygen access is generally not limited to the aerial part of the plant. Nevertheless, for the roots access to oxygen can be limited in waterlogged areas and in hydroponics. Under limiting oxygen access to the roots, the plant performance decrease and the roots are more prone to the apparition of disease. Extreme oxygen limitation ca lead to the death of the roots. The different species experiment different sensitivities to oxygen need for the roots system. Lettuces and basil are generally less sensitive to oxygen depletion than fruit plants. The optimal oxygen concentration are about 7 mg/l for lettuce and basil and about 9mg/l for fruit plants such as tomato, eggplant or pepper. Lettuce will stop growing when O_2

concentration drop below respectively up to 3 or 5 mg/L (Figure 8) whereas most other species will stop growing below 5mg/.

Figure 8 : lettuce growing in a nutrient solution with respectively, from left to right less than 1 mg/l of O_2, less than 3 mg/l of O_2 and 7 mg/l of O_2 (Picture credit: Mohyuddin Mirza).

The temperature influences the oxygen solubility. The maximum solubility is about 10 mg/l at 15 C° and 8mg/l at 26 C° (Figure 9). Therefore, the access to oxygen can be more difficult in high temperature.

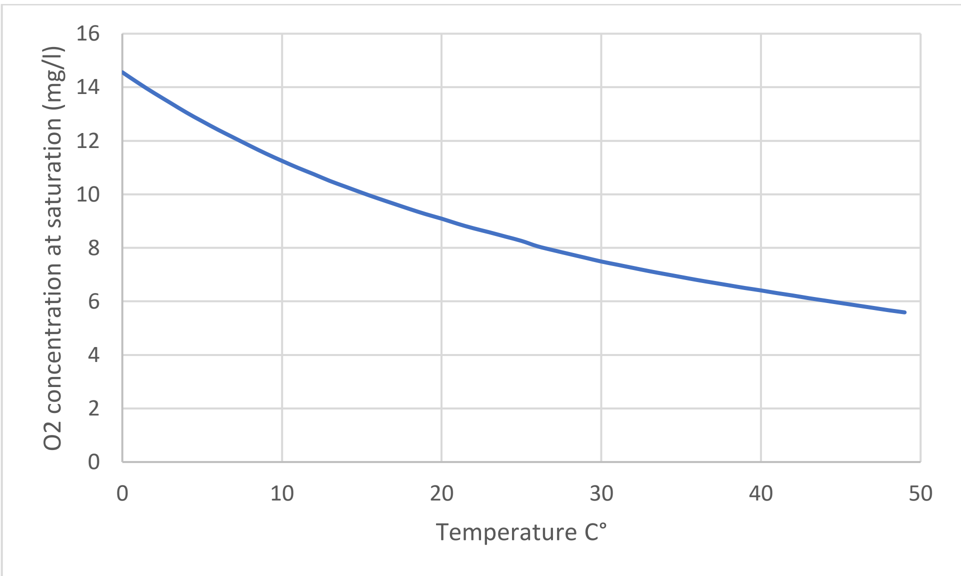

Figure 9 : Maximum O_2 concentration in water according to the temperature.

2.3.2 Modeling

The Smart Aquaponics Model uses oxygen concentration in the nutritive as a limiting factor (Figure 10).

	02 (mg/l)	
	Minimum	Minimum Optimum
lettuce	3	7
basil	5	7
mint	7	9
coriander	7	9
tomato	7	9
pepper	7	9
eggplant	7	9
cucumber	7	9

Figure 10 : Minimum and Minimum optimum 0_2 concentration in the nutritive solution used by the Smart Aquaponics Model.

2.4 Transpiration

2.4.1 Physiology

Transpiration is the loss of water from a plant in the form of water vapor. This water is replaced by additional absorption of water through the roots, leading to a continuous column of water inside the plant. The process of transpiration provides the plant with evaporative cooling, nutrients, carbon dioxide entry, and water. When a plant is transpiring, its stomata are open, allowing gas exchange between the atmosphere and the leaf. Open stomata allow water vapor to leave the leaf but also allow carbon dioxide (CO2), which is needed for photosynthesis, to enter. The main parameters influencing the transpiration are the temperature, the relative humidity (RH), the vapor deficit pressure (VPD) and the light intensity.

As air temperature increases, the water-holding capacity of that air increases sharply. Warmer air will therefore increase the driving force for transpiration, while cooler air decreases it. Relative humidity (RH, expressed in %) is the amount of water vapor present in air expressed as a percentage of the amount needed for saturation at the same temperature. Lower RH means that the air can accept more water vapor and therefore will increase the driving force for transpiration. Temperature and RH alone does not have a direct correlation with the transpiration, so that they aren't the best indicator of transpiration. The VPD, expressed in kPa, the vapor deficit pressure, is directly correlated to the transpiration and is dependent on the temperature and RH. VPD is the difference between saturation pressure and the actual vapor pressure and can be computed with the following equation:

$$VPD=exp(6.41+0.0727T-3\ 10\text{-}4T^2+1.18\ 10\text{-}6T^3-3.86\ 10\text{-}9T^4)\ *(1-RH/100).$$

The light intensity or solar radiation also influence the transpiration by providing energy that fosters evaporation. It is worth noticing that the effect of light and VPD on transpiration are independent.

In hydroponics greenhouses, the production of tomatoes and lettuce consumes respectively about $1m^3/m^2$ and $0.6\ m^3/m^2$ respectively. It should also be noted that water consumption varies throughout the year. Indeed, in the case of the tomato, there is no water consumption during the period of sanitary vacuum, which generally extends from December to January. July and August are the hottest and most water-intensive months, with a monthly water consumption of $0.2m^3/m^2$ in July and August. In Belgium, the annual rainfall varies from 0.7 to 1.4 m^3 per m^2. Therefore, with good water storage facilities, it may be possible to water a hydroponic or hydroponic farm base on rainwater only.

Relative humidity directly influences the water relations of a plant, and indirectly affects leaf growth, photosynthesis, and the occurrence of diseases. Under high RH the transpiration rate is reduced, turgor pressure is high, and plant cells grow. When RH is low, transpiration increases, causing water deficits in the plant, which may result in plant wilt. The water deficits cause partial or full closure of the stomata, thereby blocking the entry of carbon dioxide and inhibiting photosynthesis. The incidence of insect pests and diseases is high under high humidity conditions, and high RH favors easy germination of fungal spores on plant leaves.

The optimal RH of most species is generally ranging from 50% to 90 % and is lower for some species such as tomatoes (40-65 %). The optimal VPD is ranging from 0.3 to 1 kPa. Dry environment (RH lower than the optimal range) induce the stomata closure, a decrease or arrest of plant development and in fine, lower yield. Extended dry periods can result in the dry out of some plant organs. High RH barely affect plant development and yield. Nevertheless, it is important to avoid high humidity since it can result in harmful effect such as the apparition of diseases and reduce the quality of fruit production.

2.4.2 Modeling

Plant transpiration has no influence on yield within the Smart Aquaponics model. Nevertheless, Plant transpiration is an important parameter of the Smart Aquaponics model, since it defines the quantity of water that is removed from the nutrient solution and transferred in the air surrounding the plant. This total water consumption has to be taken into account as it can lead to significant water exchanges for the aquaponic system as a whole. Within the Smart Aquaponics Model the transpiration of a plant is linearly linked to the incoming solar radiation and the vapor pressure deficit, such as defined in the following equation:

$$T = A \cdot (1 - e^{-K \cdot LA}) \cdot G + B \cdot LA \cdot VPD$$

where T is the individual current plant transpiration (ml/hrs), LA is the total leaf area of the concerned plant (m^2), K (m^{-2}), A ($ml \cdot m^2/J$) G is the measured solar radiation, VPD is the calculated air vapor pressure deficit (kPa) and B ($ml/(hrs \cdot m^2 \cdot kPa)$) are the new equation parameters.

Relative humidity is a limiting factor for plant growth within the Smart Aquaponics Model (Figure 11). Interestingly, the maximum RH value is above 100%, this mean that plants are still growing when the air is saturated (RH=100).

	RH (%)			
	Minimum	Minimum Optimum	Maximum optimum	Maximum
lettuce	20	50	90	150
basil	20	60	90	150
mint	20	60	90	150
coriander	20	30	70	150
tomato	10	40	65	120
pepper	10	40	65	120
eggplant	20	60	90	150
cucumber	20	60	90	150

Figure 11 : Minimum, Minimum optimum, Maximum optimum, Maximum RH (%) used by the Smart Aquaponics Model.

3 Climate management

Temperature is the main factor influencing the plant development, indeed, below the maximal optimal temperature, each supplementary degree has the capacity to speed up the plant development, nevertheless, each degree above this maximal optimal temperature drastically decrease the development of the plant. Humidity, light and $C0_2$ have also have an important influence on plant development. Greenhouses are excellent tools to help the grower to improve these parameters. This section proposes a description of the different type of elements enabling to control the climate, this includes greenhouse and the different elements of the greenhouse.

3.1 External climate

The climate is generally defined by the geographic location. The Figure 12 present the monthly value of most environmental parameters in Uccle, Belgium. The Smart Aquaponic Application has the possibility to place your aquaponic system at different locations and select either (i) a standard climate which is the average climate of the last 10 years or (ii) to select the climatic data of a specific year.

	Jan	Feb	March	Apr	May	June	Jully	Aug	Sept	Oct	Nov	Dec
Temperature (°C)	3.5	3.9	6.4	9.9	13.5	16.6	18.5	18	15.3	11.8	7.4	4.3
Minimal temperature (°C)	1.2	1	2.6	5.2	9	11.9	14.2	13.9	11.6	8.8	5	2.1
Maximal temperature (°C)	5.9	6.9	10.4	14.4	17.7	20.8	22.5	22.1	19.2	15.1	9.9	6.5
Precipitation (mm)	69	63	60	54	67	72	76	78	58	61	70	79
Humidity (%)	85	81	77	71	72	71	71	73	76	80	86	86
Day of rain (d)	9	9	9	9	9	9	10	9	8	9	9	10
Daily sunshine duration (h)	3.1	3.9	5.5	7.8	8.7	9.1	9.5	8.7	6.9	5.1	3.5	3
PPFD (mol $d^{-1}m^{-2}$)	4.9	14.8	17	29.6	42.7	38.5	46.5	34.4	26.4	17	7.9	4.8

Figure 12 : Monthly average value for temperature, minimal day temperature, maximal temperature, precipitation, humidity, sunshine duration, PPFD in Uccle, Belgium, used by the Smart Aquaponics Model.

3.2 Greenhouse

A wide range of greenhouses is available on the market. The different type of greenhouses presents a large range of price and technical characteristics. For example, the price of a simple tunnel greenhouse can be less than 25 €/m² when a double glass rooftop greenhouse can rise up to 3000 €/m². In the latest case, the price of the greenhouse can be one of the major investments in the aquaponic farm. Therefore, the type of greenhouse needs to be selected according to the level of technology and the business model of the project. An efficient high-tech greenhouse will be interesting in the case high land price and high-tech production system, whereas in case of cheap low-tech system, the aquaponic farmer will tend to a very cheap greenhouse.

The Smart Aquaponics model enable the user to test different types of greenhouse, in terms of shape, size, covering material and heat management. Therefore the user can test the influence of the greenhouse type and management on the yield and energy consumption. Besides, the price of a greenhouse depends on so many parameters (design, location, suppliers) that the best strategy to evaluate the price of a greenhouse is to design the project with one or several greenhouse builders.

The first section of this chapter will describe the main technical characteristics of a greenhouse; the second section will present the different type of greenhouse existing on the market.

3.3 Technical characteristics of the greenhouse covering

The greenhouse is a system that maintains an equilibrium between losing heat and taking the heat provided by the sunlight. The major heat loss are due to (i) the heat transmission of the covering material, and (ii) the air exchanges due both to the ventilation system and greenhouse leaks. The main technical characteristic of a greenhouse is the insulation capacity, ventilation system, leaks, ratio between volume and surface and the light transmittance and orientation of the greenhouse.

Insulation is the ability of the greenhouse material to limit the heat exchange between the two faces of the material. In the particular case of the greenhouse in Belgium and in the north of France, it is the capacity of the greenhouse to keep the heat inside. In the particular case of a building, such as the building hosting a RAS, it is both (i) the capacity to keep the heat outside the building and the freshness inside and (ii) the capacity to keep the heat inside the building.

The most common measurement of the insulation capacity is the thermal transmittance, also referred as the U value. Thermal transmittance takes into account heat loss due to conduction, convection and radiation. This unit measures the energy passing through a material. The unit of measurement is W/m^2K, therefore it quantity of energy (Watt) that pass through one square meter (m^2) when the two sides of the material are exposed to a difference of one kelvin degree (K). A material with a better insulation property will have a lower U value.

When evaluating the insulation properties of a greenhouse, we can either use (i) the U value of the covering material (Ug), which is the U value of the plastic, glass or polycarbonate only, either (ii) the global U value of the greenhouse (Uw), that integrate the insulation capacities of the covering material, and frames. The Uw is generally a bit higher than the Ug because the frame generally has a lower insulation capacity. The notation of the Ug and Uw are not standard. Therefore, when talking with a greenhouse supplier or looking to the technical characteristic of a greenhouse, it is important to check if we are talking about the thermal transmittance of the covering material Ug or of the greenhouse Uw.

The heat loss of a greenhouse is directly proportional to the Uw value and the area of the covering material. The inertia of the greenhouse will be higher when the volume is larger. Therefore the greenhouse will be more efficient if it has a huge volume compared to the area of covering material. This explains the importance of the greenhouse shape and the fact that large greenhouses are more efficient than smaller greenhouse. Moreover, large volume ease the ventilation process in summer.

The opening of the greenhouse another important parameter affecting the climate of the greenhouse. It represents the area of the greenhouse surface that is not closed. This includes (i) the small leak of the greenhouse and (ii) the ventilation, window and door when the greenhouse is open.

The light transmittance is the second most important characteristic of the material. First because the light will provide energy to heat the greenhouse. Secondly, because the amount of light arriving within the greenhouse will directly influence the plant growth. The light transmission is measured in the percentage of light passing through a material. We can distinguish the light transmittance of the solar spectrum, the light transition within the photosynthetic active radiation (PAR) and in the UV spectrum. The light transition within the solar spectrum and PAR are generally very close, nevertheless, the UV transition is very variable. When it is not specified, the light transmittance generally refers to the solar spectrum transmittance.

As for the thermal transmittance, it is important to make the distinction between the properties of the material and of the greenhouse. The light transmittance of the covering material generally range from 70% to 95 %. Nevertheless, the frame of the glass and the greenhouse structure generally range from 5 to 15 % of the greenhouse surface.

The table presents the Ug and light transmittance properties of different covering materials proposed by different suppliers. This table presents a very small subset of the product existing on the market. We can see that for one each material, such as glass or polycarbonate, there is a wide range of commercial products with different technical properties. For example, Ug of the different polycarbonate range from 2,5 W/m²K to 3,8 W/m²K. The general observation is that on average, glass has better properties than polycarbonate, and polycarbonate as better properties than ETFE and plastic. Unfortunately, the price of the material can be very different too.

	Ug (W/m²K)	Light transmitance (%)
Plastic for tunel	6,5	90
ETFE single layer	6,4	95
ETFE double layer	3	87
ETFE triple Layer	2	82
Polycarbonate A	3,83	0,89
Polycarbonate B	3	0,91
Polycarbonate C	2,5	0,91
Glas 16mm 4/8/4	3,1	0,81
Glas 16mm 4/6/3.3.1	2,4	0,78
Glas 26mm 4/16/3.3.1	1,4	0,78

Figure 13 : Ug and light transmittance of different covering materials proposed by different suppliers. In order to avoid conflicts of interest, the products have been anonymized.

The insulation, light transmittance and opening of a greenhouse are the main parameters affecting the climate within the greenhouse. Different devices can change this characteristic of the greenhouse. The most obvious are the window and ventilation system of the greenhouse, but others such as energy screen can affect both the Light transmittance and insulation capacity of a greenhouse. These elements will be discussed in the different following sections.

Other parameters influence the properties of the greenhouse such as orientation of the greenhouse, presence of shading elements (three, building), … Nevertheless, they will not be discussed in this document.

3.4 Tunnel greenhouse

The tunnel greenhouse is the simplest and cheapest professional greenhouse type. It consists of a metallic frame with a semicircular shape covered by a plastic sheet. Professional greenhouses are generally 6 m to 8 m wide, 3 to 5 m high and can be very long (up to 100 m). The price of such greenhouse is very low, the simplest form of such professional greenhouse is about 25€ /m². The life span of the plastic film is ranging from 5 to 10 years. The metallic structure can be used for more than 20 years.

The insulation capacity of the plastic sheet is very low, the U value is ranging from 6 to 8 W/m²K and the light transitivity is ranging from 80% to 90 % according to the material. Moreover, such greenhouse has many leaks that contribute to heat loss. The leaks are located at the border of the doors, borders of the front end of the greenhouse and at the connection between the plastic sheet and soil (Figure 14). For example, for a 100 m2 tunnel greenhouse, we have between 0,5 and 0,7 m2 of leaks. In most tunnel greenhouse, ventilation is obtained by manually opening the door, or manually opening the lateral side of the greenhouse (Figure 14). Most of the tunnel greenhouse doesn't have more equipment. Nevertheless, it is possible to install automatic opening of the greenhouse or install manual shadow screen.

Due to its low insulation capacity, the nocturnal temperature within such greenhouse is very similar to external temperature during the night. Without aquaponic system in the greenhouse, It can barely protect from the last spring or first autumnal frost (-1C°). Nevertheless, such greenhouse has the ability to increase the diurnal temperature. In fine such greenhouse is used to extend the growing season compared to outdoor. In the north west Europe area, such greenhouse is used to grow tomatoes from may to October and leafy greens or root vegetables from October to may.

Figure 14 : Top left : tunel greenhouse on the rooftop of pakt (Antwerpen). Top Right: detail of the leeks on the front end of a tunnel greenhouse. Bottom left: tunnel greenhouse with lateral opening. Bottom Right, tunnel greenhouse of Cycle Farm (Brussels).

Gardeners can easily find smaller reliable tunnel greenhouses on the market with similar structure, characteristics and price per square meter. Nevertheless gardeners can also find very low cost (less than 10 €/m²) tunnel greenhouse. The plastic film of such greenhouse generally have a short lifespan (2 years).

3.5 Multitunnel greenhouse

The next level of professional greenhouse is the multitunnel, also referred as poly tunnel and sometime multichapel greenhouses. They generally consist into a metallic structure covered by a material, such as plastic film, ETFE, and sometime polycarbonate. This section focuses on the chapel and multi chapel greenhouse covered by plastic which are generally polyurethane, PVC or ETFE.

Plastic multichapel greenhouse may look like multiple tunnel greenhouses put side by side (Figure 15). Alike the tunnel greenhouse, they consist in a metallic structure and are isolated with a plastic film. They have vertical sidewalls and a semicircular or triangular roof section. They are generally higher than the tunnel greenhouse, the lowest part of the roof is between 2 and 3 m high and the highest part of the 2 m higher than the lowest part of the roof. Compared to tunnel greenhouse, this shape result in a higher ration Volume/covering material and is better for the greenhouse inertia.

Figure 15 : Left : Multitunnel with automatic opening of the vent at L'Écho-Village (Santes, Fr). Right: Simple multitunel at La Ferme des 3 Moutons (Braives, Be).

Alike tunnel greenhouse, these greenhouse are generally covered with plastic film with low insulation properties (6 to 8 W/m²K) and the cheapest version are also subject to important leaks. Nevertheless, high quality greenhouse can have less leaks. These greenhouses are generally equipped with a ventilation system that consist in the opening of one part of the roof on all the length of the greenhouse. The location of these vents is more efficient than the lateral vent of the tunnel greenhouse. These greenhouses can also be equipped with shadow screens and all this equipment can be managed by an automation system. Due to the low insulation of the plastic film, tunnel greenhouse and multichapel plastic greenhouse are generally not equipped with heating system.

In fine, these greenhouses have a better heat management during the summer and a slightly better inertia than tunnel greenhouse. Similar greenhouses can be covered by other materials such as a double layer of plastic film or semi-rigid panel made out of polycarbonate. These materials have a better insulation properties but with higher insulation properties. Compared to simple layer, double layer plastic film has a lower light transitivity.

3.6 Chapel greenhouse

The chapel and multi chapel greenhouse covered with rigid material such as glass and polycarbonate are also named venlo greenhouse. These greenhouses are generally made out of a solid structure that supports the frame, covering material and the equipment presents in the greenhouse. Such greenhouse can cost between 200 €/m² to 2000€/m² according to the covering material and the level of equipment. This reveals the high diversity of greenhouse types and equipment available in venlo greenhouses.

Compared to plastic films, most rigid covering material such as polycarbonate, single layer glass and double layer glass provide a better insulation. The U value of the covering material is ranging from 1 W/m²K for the best double glass available on the market to 4 W/m²K for the cheapest polycarbonate materials. The light transmission of these materials is generally ranging from 70% to 90%. An important point is that, compared to plastic greenhouses, such greenhouse has fewer leaks. In the Smart Aquaponics Model, we consider that such greenhouse has no significant leaks.

The high volume/covering ratios and the insulation properties of such material provide some inertia to the greenhouse. This inertia enable to keep the temperature within the greenhouse significantly higher than outside of the greenhouse and thus, even with no heating system, such greenhouse can protect the plant from frost in the spring and autumn. Greenhouse with no heating system are generally called cold greenhouse.

In some case, it makes sense to complement this inertia with an heating system. According to the need of the production and the insulation of the covering material different strategies can be implemented. The first strategy is to provide heat in order to prevent temperature to drop below a certain threshold, the seconds to provide an environment with the optimal growing conditions. These strategies affect both the investments, running costs and yields. When the greenhouse is dedicated to leafy greens and aromatic, heating can be provided to protect from frost or maintain 10 to 20 C° during the cold period. In such case it is important to maintain a good balance between heat and light. Indeed, high temperature associated with low light intensity in winter may result in low quality vegetables. In the case of industrial tomato production, many aquaponist are using greenhouse to extend the natural growing season of tomatoes and provide heat only to prevent from frost. Nevertheless, in north-west Europe, most of the industrial production of tomatoes, pepper and eggplant are carried out in the industrial greenhouse where temperature is maintained between 26 and 28 C° for 10 months per year. Such greenhouse is generally covered by material with good insulation properties, equipped with the heating system and cooling system for the summer. In some case, these greenhouses are equipped with supplementary lightning.

It is important to design the greenhouse according to the production expected and to the business model. Indeed, a cold greenhouse will achieve lower yield than heated greenhouses but enable a wider range of production (leafy greens, aromatics all year long and fruit vegetables during the summer) but will result in much lower implementation costs. On the other end, a heated greenhouse dedicated to tomato production can produce tomatoes when the market price is higher (spring and autumn) but require much higher investment and higher maintenance costs due to heating. Beside the level of technology, the size of the greenhouse influences the economies of scale, and this both in terms of investment costs and management costs. The investment costs associated with a 500 m², 5,000 m² and 50,000 m² structure are not proportional and so that the investment cost per square meter is difficult to anticipate.

3.6.1 Heating system

There are two main types of heating system in professional greenhouse. Both systems are using hot water from a boiler to heat the greenhouse. The first system is heating convector, it consists of a metallic tube transferring the heat of hot water by convection. The second is the aerotherm and consists in a heat exchanger a fan (Figure 16).

Figure 16 : Left : Greenhouse with tube of heat convector located on the soil (1) above the soil (2)and close to the wall (3) at BIGH Farm (Brussels, Be). Right: Heat convector at Gembloux Agro Bio-Tech (Gembloux, Be).

The tube of the heat convector is generally placed either at the soil level, above the soil level or the wall of the greenhouse. When placed at the soil level, for example below the production system, heat convectors have the advantage (i) to provide the heat right at the plant location and (ii) an homogenous heat in the greenhouse. Indeed, when placed at the ground level, the hot hair will come up and create an air flow. When located at the soil level, the disadvantage is the difficulty to change the greenhouse organization, since the tubes prevent the installation of other production systems. Heat convectors are generally used in fruit vegetable culture, where the greenhouse is heated all year long.

The aerotherm system is an heating system using and heat source and an air blower in order to defuse the air into the room. The heat source is either an electric heater or hot water that transfer heat to air a heat exchanger system. Some aerotherms can also use cool water in order to cool down the greenhouse. The aerotherm are generally placed above the crops. Therefore it has the advantage to let all the ground space free. It is interesting when we are regularly changing the organization of the greenhouse. Another advantage is that compared to heat convector, aerotherm are cheaper. The disadvantage is their high consumption of electricity.

An heating system of 2 kW/m² is generally used to heat industrial tomato greenhouse made out of polycarbonate (U ~ 2,5 W/m²K). The power can drop to 0,6 kW/m² in the case of the double glass greenhouse ((U ~ 2,5 W/m²K).

The smart aquaponics model simulate heating system, all systems can be simulated using (i) the power of the system, (ii) the efficiency of energy transformation. Up to now, the Smart Aquaponics model consider that heating system consume electricity only, not gaz or fluel.

3.6.2 Ventilation

Greenhouse ventilation design is key to ensure optimal environmental environment for crops. It affects the average temperature, CO2 and humidity of the greenhouse but it also affects the air stratification within the greenhouse. The two types of greenhouse ventilation are natural and forced ventilation.

Natural ventilation consists of vents present on the roof of the greenhouse. Many greenhouse suppliers propose vents systems ranging from 15 to 50 % of their soil surface. Natural ventilation work on the principle of thermal buoyancy, by allowing denser, cold air to lift warmer air up and out of the greenhouse. The efficiency of natural ventilation depends on wind speed and the inside to outside air temperature. It worth noticing that Insect screens significantly reduce the air flow of the vent. The use of anti-aphid screen in vent openings caused a 33% reduction in greenhouse ventilation rate.

Ventilation can be drastically improved with the use of active ventilation that forces air to go in or out of the greenhouse. This may be useful in hot area or when more accurate greenhouse climate is needed.

The smart aquaponics model compute both the natural and forced ventilation of the greenhouse. The ventilation modeling is based on the leak and vent area, external wind speed, external climate, internal climate of the greenhouse and the airflow of the fan. Smart Aquaponics model does not model aspects such as condensation and air stratification.

3.6.3 Thermal screen

Thermal screen consists in semitransparent sheets placed inside the greenhouse, just behind the covering material. They may have two functions, either to keep the heat inside the greenhouse, either to reflect solar radiation out of the greenhouse. Most thermal screens achieve the two functions. When used as energy saving screen, air blocked between the covering material and the screen can increase the insulation of the greenhouse. Such a system is generally used during the cool night of winter. When used as a shadow screen, they reflect the solar radiation and decrease the heating of the greenhouse by the sunlight. The different model of thermal screen generally have a light transmittance ranging from 50 to 70 %, so that they generally decrease the light intake by 50 to 30%. Thermal screens are generally activated when the temperature and possibly when light intensity are above or below a certain threshold. When there are not activated, they are either folded or rolled so that they let all the light to enter in the greenhouse.

Figure 17 : Left: Thermal screen at Gembloux Agro Bio-Tech (Gembloux, Be). Right: rolled thermal screen at Gembloux Agro Bio-Tech (Gembloux, Be).

When thermal screen are not available, it is possible to use lime to white wash the greenhouse. The whitewashing of the greenhouse decrease the light intake by 60 to 90. Therefore, the whitewashing is very effective to decrease the temperature. Unfortunately, the reduction of light intensity may be so important that it can affect the plant development. The greenhouse are generally whitewashed before the summer and a part of the lime remains on the greenhouse in autumn, so that it continues to limit the light intake even when there is no more need of heat control. In fine, whitewashing is a good solution in the southern area, and in northern area, it can help to control the heat during the summer, but is much less interesting than a thermal screen.

3.6.4 Cooling Systems

Two systems are commonly used to actively cool down a greenhouse (Figure 18). The first system, the cool box, involve fan and pad 'evaporative cooling' where air from the outside is pulled through porous, wet pads (usually cellulose paper). Heat from the incoming air evaporates water from the pads, thereby cooling the air. Such a system is generally implemented out of the greenhouses. The advantage to cool down a greenhouse without increasing the total humidity of the air. A second system is the fogging and also use evaporative cooling. This system can be presented as a water spray within the greenhouse. The dispersion of water droplets evaporates and extract heat from the air. This system gives better uniformity since the fogging is distributed throughout the greenhouse. The smaller the droplet size, the faster each droplet evaporates, and therefore the faster the rate of cooling. Relative humidity can be increased by running fogging.

Figure 18 : Left : Coolbox ; Right: Fogg system (source: www.richel-group.com).

3.6.5 Light

Artificial lights can be used to extend the winter growing season. Various different light technologies are used in greenhouses, but the most common type is light-emitting diodes (LEDs). Unlike all other artificial lighting systems, LEDs contain no glass or gaseous components: all the components are solid state. They are therefore less fragile than other types of lamp, and can be located in places where other lamps may become damaged and pose a health and safety risk. However, the major advantage LED lighting is the low emission of radiative heat, which reduces the LED's energy consumption.

LEDs are now available with almost any wavelength between 200 and 4000 nm. The advantages of LEDs are (i) their high efficiency (light energy output/electrical energy) compared to other lighting sources; (ii) that the light emitted is directional, which reduces the amount of stray light and ensures that the maximum amount of light reaches the crop; and (iii) that the overall spectrum can be modified for different applications by changing the number and colors of LEDs installed in a lighting unit.

The objective of greenhouse lightning is to compensate for the gap between the actual daily PPFD provided by natural light and the minimal optimal daily PPFD of the crop. The Daily PPFD is about 9,72 mol m^{-2} d^{-1} for lettuce and about 22 mol m^{-2} d^{-1} for fruit plants such as tomatoes. The Figure 19 present the average monthly PPFD in Gembloux of 2018 provided by http://www.soda-pro.com. The lowest PPFD values are slightly below 5 mol m^{-2} day^{-1} occurred in January and December, the highest values are above 35 mol m^{-2} day^{-1} and occurred between may and August. The PPFD experimented by a plant within the greenhouse is depending of the light transmission of the greenhouse. The second of the table preset the PPFD within a greenhouse with a light transmission of 70%. In such greenhouse, natural light is above the minimum optimum PPFD for tomatoes between may and August, is slightly below the light requirement in April and September, and is below the plant requirement between October and March. Therefore, to maintain an optimal tomato production between October and March, grower need to provide, on average, between 10 and 19 mol m^{-2} d^{-1}. In the same greenhouse, lettuce would be in the light deficit only between November and February

	Average PPFD (mol m^{-2} d^{-1})	Average PPFD within a greenhouse of 70% transmission	Gap to reach 22 mol m^{-2} d^{-1}	Gap to reach 9.72 mol m^{-2} d^{-1}
January	4.9	3.4	18.6	6.3
February	14.8	10.3	11.7	-0.6
March	17.0	11.9	10.1	-2.2
April	29.6	20.7	1.3	-11.0
May	42.7	29.9	-7.9	-20.2
June	38.5	27.0	-5.0	-17.3
July	46.5	32.5	-10.5	-22.8
August	34.4	24.1	-2.1	-14.4
September	26.4	18.4	3.6	-8.7
October	17.0	11.9	10.1	-2.2
November	7.9	5.6	16.4	4.2
December	4.8	3.4	18.6	11.6

Figure 19 : Table presenting the average PPFD in Gembloux in 2018, average PPFD within a greenhouse of 70% transmission, the gap off PFFD to reach the requirement of tomatoes (22 mol m^{-2} d-1) and the gap off PFFD to reach the requirement of lettuce (9.72 mol m^{-2} d-1) for each month.

The light intensity of a lightning system depends on its power and the distance between the plant and the lamp. The light suppliers provide the light intensity of their product in µmol/s.m² for different distances between the plant and lamp. This enable the greenhouse designer to estimate the light requirement according to the distance between the lamp and the plant canopy. In Gembloux, to fulfill the light requirement for a tomato production, different suppliers proposed a lighting system of about 200 W/m². The lightning systems can be associated to some light sensors, so that the light is switched on when the light intensity is below a certain threshold.

The smart aquaponics model integrate both natural and artificial light to model the plant growth. It integrates the light transmittance of the greenhouse and proposes a light management based on natural light intensity.

3.6.6 CO2 Management

The rate of photosynthesis is dependent upon the availability of carbon dioxide. Fresh air contains about CO2 0.037%. Ventilating may provide sufficient CO2 during the spring, summer and autumn, but in winter, or anytime in cold climates, it will result in cold air being brought into the greenhouse. Heating will then be needed to maintain the proper temperature, which may become uneconomical. CO2 generation is therefore an effective way to increase levels in the greenhouse during the winter or in cold climates.

CO2 generators can burn various types of fuel, including natural gas (most economical) or propane. Open-flame generators also produce heat and water vapor as by-products. Therefore, hydroponic growers sometimes use CO2 generators in the winter, when the extra heat production is welcome, and bottled CO2 and dozers in the summer, since they produce no extra heat or humidity.

4 Plant Nutrition

4.1 Physiology

4.1.1 Essential nutrient elements

4.1.1.1 Overview

Plants require 16 essential nutrient elements without which they are unable to complete a normal life cycle. A plant's sufficiency range is the range of nutrient amount necessary to meet the plant's nutritional needs and maximize growth. The width of this range depends on individual plant species and the particular nutrient. Nutrient levels outside of a plant's sufficiency range cause overall crop growth and health to decline due to either a deficiency or toxicity. Plants normally obtain their water and mineral needs from the soil. In hydroponics nutrients are generally provided by inorganic commercial fertilizers. In aquaponics, the situation is complicated by the fact that the nutrient solution contains a highly complex mixture of organic and inorganic compounds originating from fish waste and fish food.

There are two major categories of nutrients: macronutrients and micronutrients (Figure 20). Both types are essential, but required in differing amounts. Much larger quantities of the six macronutrients are needed to compare with the micronutrients. The macronutrients are divided into three groups. The terms 'primary' and 'secondary' refer to the quantity, and not to the importance of a nutrient. A lack of a secondary nutrient is just as detrimental to plant growth as a deficiency of any one of the three primary nutrients, or a deficiency of micronutrients. A basic understanding of the function of each nutrient is important in order to appreciate how they affect plant growth.

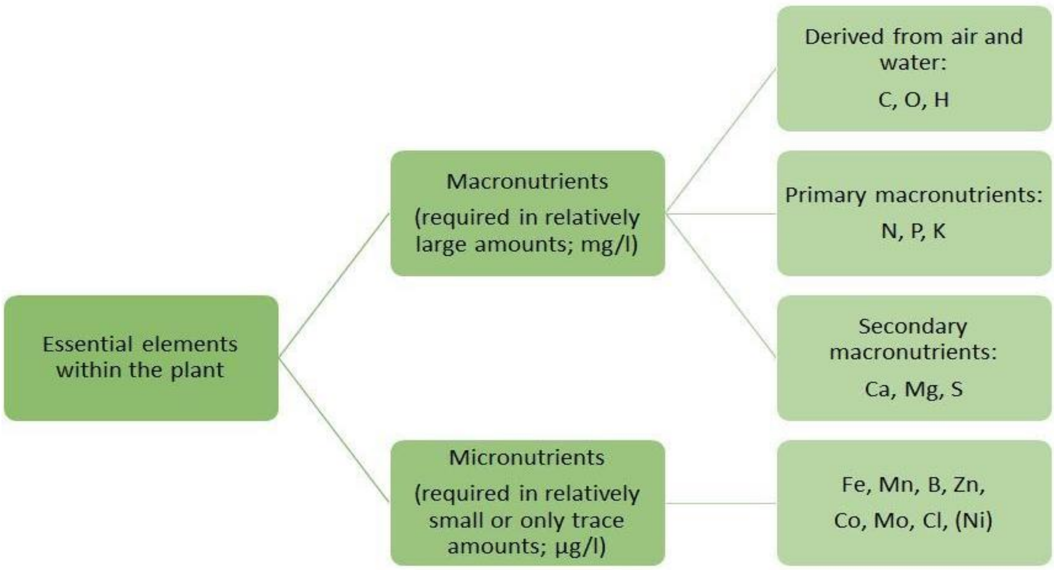

Figure 20 : Classification of essential elements (nutrients) required for plant development.

4.1.1.2 Specific role of elements

Nitrogen (N) is part of a large number of organic compounds, including amino acids, proteins, coenzymes, nucleic acids, and chlorophyll. It is essential for photosynthesis, cell growth, and metabolic processes. Usually, dissolved N is in the form of nitrates, but plants can utilize moderate quantities of ammonia and even free amino acids.

Phosphorus (P) is part of the phospholipid backbone of nucleic acids such as DNA, deoxyribonucleic, and adenosine triphosphate (ATP, the molecule that stores energy in the cells), and is contained in certain coenzymes. It is essential for photosynthesis, as well as the formation of oils and sugars, and encourages germination and root development in seedlings. As young tissues require more energy, it is particularly important for juveniles.

Potassium (K) acts as a coenzyme or activator for many enzymes. Protein synthesis requires high potassium levels. It is used for cell signalling via controlled ion flow through membranes. K also controls the opening of the stomata, and is involved in the development of flowers and fruit. It is also involved in the production and transportation of sugars, water uptake, disease resistance, and the ripening of fruits. K does not form a stable structural part of any molecules inside plant cells.

Calcium (Ca) is found in cell walls as calcium pectate, which cements together primary walls of adjacent cells. It is involved in strengthening stems, and contributes to root development. Required to maintain membrane integrity and is part of the enzyme α-amylase. It precipitates as crystals of calcium oxalate in vacuoles. Sometimes interferes with the ability of magnesium to activate enzymes.

Magnesium (Mg) is an essential part of the chlorophyll molecule. Without Mg, chlorophyll cannot capture the solar energy needed for photosynthesis. Mg is also required for activation of many enzymes needed for growth. It is essential to maintain ribosome structure, thus contributing to protein synthesis.

Sulphur (S) is incorporated into several organic compounds including amino acids (methionine and cysteine) and proteins (like photosynthetic enzymes). Coenzyme A and the vitamins thiamine and biotin also contain S.

Boron (B) is one of the less understood nutrients. It is used with Ca in cell wall synthesis and is essential for cell division. B increases the rate of transport of sugars from mature plant leaves to actively growing regions (growing point, roots, root nodules in legumes) and also to developing fruits. B requirements are much higher for reproductive growth as it helps with pollination, and fruit and seed development. Other functions include N metabolism, formation of certain proteins, regulation of hormone levels and transportation of K to stomata (which helps regulate internal water balance).

Copper (Cu) activates some enzymes which are involved in lignin synthesis and it is essential in several enzyme systems. It is also required in photosynthesis, plant respiration, and assists in plant metabolism of carbohydrates and proteins. Cu also serves to intensify flavour and colour in vegetables, and colour in flowers.

Iron (Fe) is required for the synthesis of chlorophyll and some other pigments and is an essential part of ferredoxins. Ferredoxins are small proteins containing Fe and S atoms that act as electron carriers in photosynthesis and respiration. Fe is also part of the nitrate reductase and activates certain other enzymes.

Manganese (Mn) activates one or more enzymes in fatty acid synthesis, the enzymes responsible for DNA and RNA formation, and the enzymes involved in respiration. It participates directly in the photosynthetic production of O_2 from H_2O and is involved in chloroplast formation, nitrogen assimilation and synthesis of some enzymes. It plays role in pollen germination, pollen tube growth, root cell elongation, and resistance to root pathogens.

Molybdenum (Mo) acts as an electron carrier in the conversion of nitrate to ammonium before it is used to synthesize amino acids within the plant. It is essential for nitrogen fixation. Within the plant, Mo is used in conversion of inorganic phosphorus into organic forms.

4.1.1.3 Units and notation

There are different nomenclature to express the concentration of element present in a fertilizer or a nutritive solution. Most dry fertilizer express their N P K concentration as the percentage of nitrogen, phosphoric acid (P_2O_5) or potassium oxide (K_2O). Fertilizer with the indication NPK 10-12-14 has 10% of N, 12% of P_2O_5 and 14% of K_2O. Therefore, these terms do not refer to the P and K alone.

In the context of hydroponic, most information is given for the total Nitrogen (N), total phosphorous (P) and total Potassium, which refer to the total N, P and K present in different molecules. Nevertheless, other nomenclature refers to the N present in different molecules, such as $N\text{-}NO_3$, wich refers to the nitrogen present in a nitrate molecule, while NO_3 refer to the NO_3 content. The Figure 21 presents the most common nomenclature found in the literature.

N, TIN	Total Inorganic Nitrogen, N present in NH_3, NH_4, NO_3 and NO_2
TAN	Total Amonia Nitrogen, N present in the NH_3 and NH_4
$N\text{-}NH_4$	N present in NH_4, $N\text{-}NH_4 = NH_4/1,28$
NH_4	NH_4, amonia
$N0_3$	Nitrate
$N\text{-}N0_3$	N present in NO_3, $N\text{-}NO_3 = NO_3/4.42$
$N0_2$	Nitrite, NO_2
$N\text{-}N0_2$	N present in NO_2, $N\text{-}NO_2 = NO_2/2.875$
PO_4	Phosphate
$P\text{-}PO_4$	P present in PO_4, $P\text{-}PO_4 = PO_4/2.875$
$P\text{-}PO_4$	P present in PO_4

Figure 21 : Common nomenclature found in the literature for nitrogen and phosphorous.

The quantity of elements present in nutrient solutions is generally expressed in ppm (parts per million) or ppb (parts per billion). This unit is not a concentration but a ratio. Concerning the notation, a ppm is a fraction of 10^{-6} while a ppb is 10^{-9}. This unit is used to express a mass ratio (mg/kg) or a volume ratio (µL/L). However, in solution, this unit is related to a concentration since 1 litre of water is equivalent to 1 kilogram. In this case, one ppm can then be equivalent to 1 mg/L.

4.1.1.4 Plant needs

The different nutritive elements are accessible to the plant as ions, complex molecules and in some case as organic molecules. In the case of commercial hydroponics fertilizers, most elements are provided as salts. Besides, in aquaponics and bio-ponics, some elements can also be trapped in complex organic or inorganic molecules so that they are inaccessible to the plant. Figure 22 presents the most frequent inorganic form of the element that can be absorbed by the plant.

Nutritive elements generally need to be present in different concentrations. These concentrations also vary according to the plant species and the state of developments. When elements are below or above the required concentration, this can lead to issues in the plant development. When elements are below a certain concentration, generally called minimal optimum concentration, the plant experiment some deficiency. This can result in different symptoms and/or also in a decrease of plant growth. The deficiency symptoms can differ according to the species, the element and concentration of the depleted element. Below the minimal concentration, the plant simply stops growing. Likewise, when the element is above a certain concentration, generally called maximal optimal concentration, this element becomes toxic to the plant and affect its development. Again, this result in symptoms and a lower development rate. A concentration above the maximum concentration will stop the development of the plant and eventually kill the plant.

We generally consider that the most limiting factor is the one that will limit the plant growth. In the case of nutritive elements, the limiting factor is a deficiency or an excess. For example, when an aquaponic system has a strong deficiency in iron and a small deficiency in potassium, the plant development will be very low. The plant will grow much better if we add some Iron. The plant will grow even much better if we add both iron and potassium. Nevertheless, if the solution is only completed with potassium, this will not improve the plant development.

The optimal concentration varies according to the sources, the specie and the state of development. Nevertheless, the Figure 22 shows the general optimal ranges for different nutritive elements in hydroponics. These figures show that the two forms of nitrogen that are considered in hydroponics are nitrate (NO_3) and ammonia (NH_4^+). Nitrate is generally in much higher concentration for two reasons. First the nitrate is absorbed more easily by the roots. Secondly, ammonia is toxic at a lower concentration than the nitrate. The optimal concentration of nitrate is ranging between 80 and 200 mg/l. Some deficiencies can appear when the concentration drop below 50 mg/l and toxicity above 300 mg/l. Figure 22 proposes the same information for phosphorous, potassium, calcium, magnesium, iron, copper, zinc and bore. Sodium and chloride are generally present in sufficient concentration. The issue of these elements is more to maintain them below a critical level. Ideally, we try to keep them below 30 mg/l (Na) and 50 mg/l (Cl) and severe symptoms will appear above 90 mg/l (Na) and 150 mg/l.

	Minimum	Optimum	Maximum
NO^{3-} -N	50	80-200	300
NH^{4+}-N	5	10-15	20
P	20	30-80	200
K	100	100-500	800
S		50-200	
Ca	125	150-300	400
Mg	25	50	100
Fe	1.5	6	12
Cu	0.05	1	2.5
Zn	0,05	0.05-0.5	2.5
B	0.1	0.3-0.5	0.1
Mo	0.01	0.05	0.1
Na		<30	<90
Cl		<50	<150

Figure 22 : General optimal ranges for different nutritive elements in hydroponics (mg/l) (adapted after Jones & Olson-Rutz 2016, Foucard et Tocqueville 2018, Resh 2013).

The optimal values are rather large, which lead to a certain range of concentration that is acceptable to the plant. The ideal concentration of the nutriment also differs according to the plant species and the stage of development. The leafy vegetables such as lettuce, chard or basil generally require a lower concentration of nutrients and fruit vegetables such as tomato, eggplants, cucumber or strawberries require higher concentration of nutrients. For example, the optimal nitrate concentration for lettuce is ranging from 80 to 150 mg/l when the optimal nitrate concentration of tomato is ranging from 100 to 200 mg/l. The fruit vegetables generally consume more potassium for the fructification than the leafy vegetables. Therefore the potassium concentration is general 1,5 or 2 times higher than the nitrate concentration in commercial tomato fertilizer while the potassium and nitrate concentration are generally similar in commercial lettuce fertilizer. The different hydroponic suppliers propose specific fertilizer for the different species and stages of development. They also generally propose fertilization plans including the change of concentration and fertilizers according to the stage of development. This aspect can optimize the yield in monoculture. Nevertheless, in polyculture, the objective is generally not to optimize the growing condition of one crop, but to provide an environment suitable for different plant species.

4.1.2 Nutrient availability and pH

The availability of many nutrients depends on the pH of the nutrient solution. In hydroponics, the optimal range for most plants is pH 5.3-6.8. In soil, the optimal range slightly more basic, ranging from 6 to 7.5. If the pH goes outside of this range, plants experience nutrient lockout, which means that although the nutrients are present in the water, the plants are not able to use them. Each element has its own range of availability, for example, as shown on Figure 23, N, P, K, S, Ca and Mg are more available in alkaline environment while Fe, Mg, Cu and Zn are more available in slightly acidic environment. The optimal range for the plant (5.3-6.8) is a range of value where all elements are accessible to the plant.

There is evidence that nutrient lockout is less common in mature aquaponic systems than in hydroponics, because aquaponics is an entire ecosystem, while hydroponics is a semi-sterile undertaking. Consequently, in aquaponic systems there are biological interactions occurring between the plant roots, bacteria, fungi and organic materials that may allow nutrient uptake even at higher levels than pH 7.5. However, the best course of action is to attempt to maintain a slightly acidic pH (6–7), but understand that higher pH (7–8) may also function.

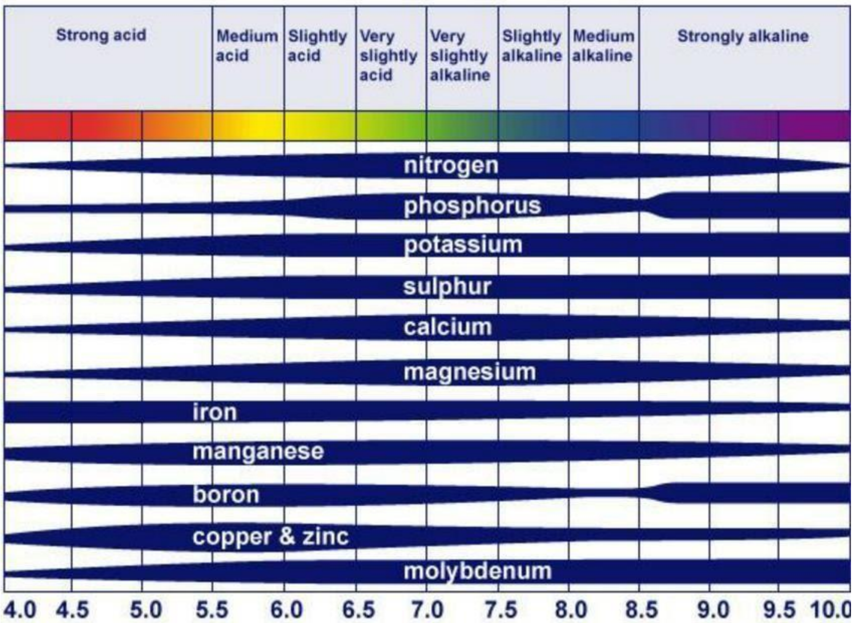

Figure 23 : The effect of pH on the availability of plant nutrients (figure from Roques et al. 2013).

Acidity also influences the equilibrium between different chemical forms. As shown in Figure 24, pH determine the equilibrium between ammonia (NH_3) and ammonium (NH_4^+). Ammonium is the most prevalent form when the pH is below 9. Ammonium is phytotoxic for plants above a certain threshold and ammonia is the volatile form of nitrogen. When ammonia evaporates from the system, it is a loss of nutrients. Ammonia is also the toxic form for the fish.

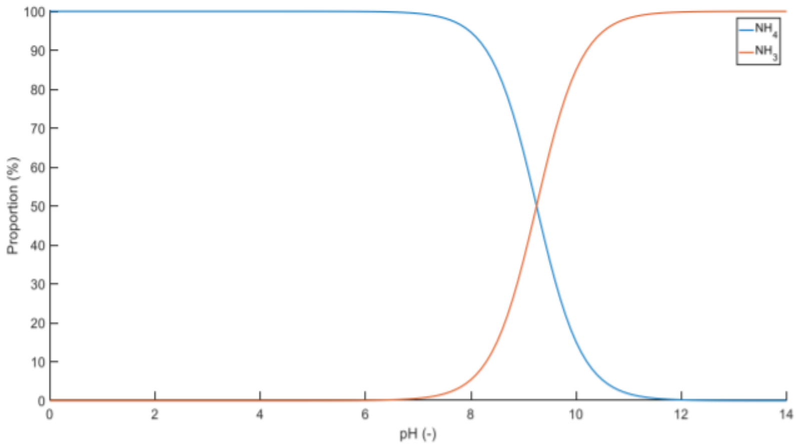

Figure 24: Percentage of NH_3 and NH_4^+ as a function of the pH of the solution (figure from Stalport, 2017)

Phosphates are found into different forms and the equilibrium between these forms is also defined by the pH. Phosphorus is found in the form phosphoric acid (H_3PO_4), dihydrogen phosphate ($H_2PO_4^{2-}$), monovalent phosphate or hydrogen phosphate (HPO_4^{2-}) and orthophosphate anion (PO_4^{3-}). At pH close to neutral (7.2), the proportion between these two forms is 50/50. $H_2PO_4^-$ is the only form present at lower pH (4-6). In contrast, at the basic pH (8), $H_2PO_4^-$ is only present at 20% while the remaining 80% is in the HPO_4^2.The form of phosphorus preferentially assimilated by the plant is $H_2PO_4^-$. However, other forms of phosphorus are sometimes present in nutrient solutions used in hydroponics.

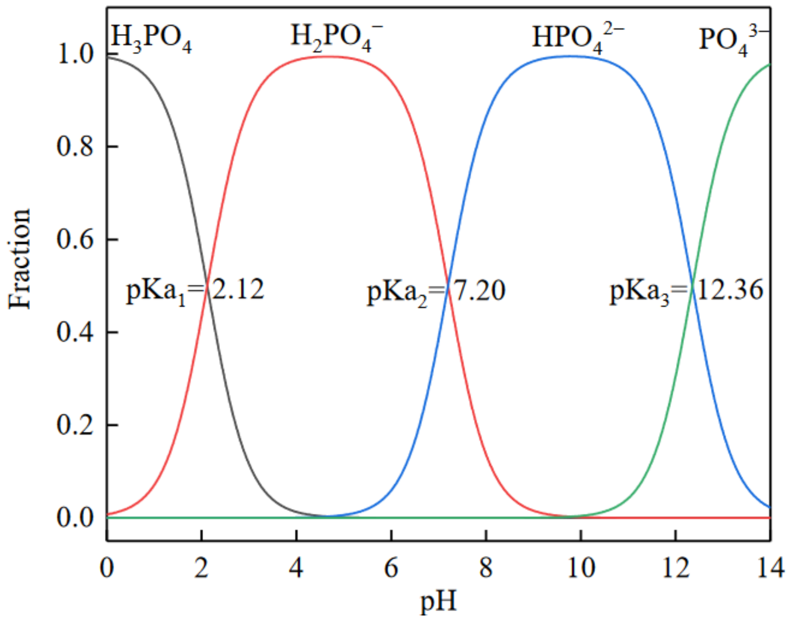

Figure 25 : Fraction of the main forms of P as a function of the pH of the solution (figure from Chen, 2021).

4.2 Electro-conductivity

Electro-conductivity, in the context of hydroponics, is used as a measure of the salt concentration and as a general measurement of the nutrients. Electro-conductivity is mostly defined by the concentration of the four cations: K^+, Ca^+, Mg^+ and Na^+, so that it is not a direct measurement of the primary essential elements such as nitrogen, phosphorous. For example, when K^+, Ca^+, Mg^+ or Na^+ are added to water, the Ec will increase, besides, the addition of nitrate or phosphate to water will not affect it's Ec. Therefore, it may seem contradictory to use Ec as a general measurement of the nutrient content of a nutritive solution, but it works pretty well on the practical aspect. Ec is the most common measurement of nutrient concentration in inorganic hydroponics and is also widely used in aquaponics

alike for the nutrient concentration, the needs of plants regarding the electro-conductivity depend on species and state development. The general view is that leafy vegetables require lower Ec level and fruit vegetables higher Ec level. For example, the lettuce's optimal range is 700 to 1800 µS/cm and tomato optimal range is 1800 to 5000 µS/cm. Practically, growers are targeting EC value of 1400- 1600 for lettuces and about 2000 to 3500 for tomato. When it is possible, the Ec is about half the target value when plantlets are transferred into hydroponic system, and then, the Ec increase gradually in order to reach the targeted value within two or four weeks. In the case of commercial hydroponic fertilizers, the supplier generally provides a fertilization plant and indicates the required Ec value according to the development stage.

4.3 Nutritional disorders in plants

A nutritional disorder is caused by either excess or deficiency of a certain nutrient. It is important to detect nutritional disorders as soon as possible, to prevent spreading of the symptoms and eventual death of the plant. However, the precise diagnosis of nutrient disorders is not easy, because many deficiencies have overlapping symptoms. To make things more complicated, there are also plant diseases that can cause similar symptoms. Water analysis also helps to identify the potential deficiencies and some companies proposes plant tissue analysis to identify the deficiencies. Nevertheless, practice is the best way to be able to distinguish these symptoms from one another.

One aspect of the diagnosis is the distinction between mobile (Mg, P, K, Zn, N) and immobile elements (Ca, Fe, S, B, Cu, Mn). All nutrients move relatively easily from the root to the growing portion of the plant through the xylem. However, mobile elements can also be repositioned from older leaves to the actively growing region of the plant (younger leaves), when the deficiency occurs. As a result, the deficiency symptoms first appear in the older leaves. Conversely, immobile elements, once incorporated into the various structures, cannot be disassembled from these structures and re-transported through the plant. Deficiency symptoms first appear on the upper young leaves of the plant. The Figure 26 describes the terminology used for the description of symptoms of nutritional disorders and the Figure 27 describe the major deficiency and toxicity symptoms for essential elements. These descriptions are general description, and the symptoms can change for the different species, varieties and environmental condition experimented by the plant.

Term	Description
Generalized	Symptoms spread over entire plant or leaf
Localized	Symptoms limited to one area of plant or leaf
Drying	Necrosis—scorched, dry, papery appearance
Marginal	Chlorosis or necrosis—on margins of leaves; usually spreads inward as symptom progresses
Interveinal chlorosis	Chlorosis (yellowing) between veins of leaves
Mottling	Irregular blotchy pattern of indistinct light (chlorosis) and dark areas; often associated with virus diseases
Spots	Discoloured area with distinct boundaries adjacent to normal tissue
Colour of leaf undersides	Often a particular coloration occurs on the lower surface of the leaves, for example, phosphorus deficiency—purple coloration of leaf undersides
Cupping	Leaf margins or tips may cup or bend upward or downward
Checkered (reticulate)	Pattern of small veins of leaves remaining green while interveinal tissue yellows manganese deficiency
Brittle tissue	Leaves, petioles, stems may lack flexibility, break off easily when touched calcium or boron deficiency
Soft tissue	Leaves very soft, easily damaged nitrogen excess
Dieback	Leaves or growing point dies rapidly and dries out boron or calcium deficiencies
Stunting	Plant shorter than normal
Spindly	Growth of stem and leaf petioles very thin and succulent

Figure 26 : Terminology used for the description of symptoms of nutritional disorders (adapted from Resh 2013).

Element	Deficiency	Toxicity
Nitrogen (N)	Reduction in protein results in stunted growth and dormant lateral buds. Stems, petioles, and lower leaf surfaces of corn and tomato can turn purple. The chlorophyll content of leaves is reduced, resulting in general pale yellow colour, especially older leaves. Flowering, fruiting, protein and starch contents are reduced.	Plants usually dark green in colour with abundant foliage but usually with a restricted root system. Can cause difficulties in flower and fruit set.
Phosphorus (P)	Poor root development, stunted growth. Reddening of the leaves. Dark green leaves (may be confused with excessive N supply, as it also leads to darker green leaves). Delayed maturity. The tips of plant leaves may also appear burnt. Deficiency symptoms occur first in mature leaves.	No primary symptoms yet noted. Sometimes Cu and Zn deficiencies occur in the presence of excess P.
Potassium (K)	Deficiency will cause lower water uptake and will impair disease resistance. Symptoms first visible on older leaves. Margins of leaves curl inward. In dicots, these leaves are initially chlorotic but soon scattered burnt spots (dead areas) develop. In monocots, the tips and margins of the leaves die first.	Usually not excessively absorbed by plants. Excess K may lead to Mg, and possibly Mn, Zn or Fe deficiency

Potassium (K)	Deficiency will cause lower water uptake and will impair disease resistance. Symptoms first visible on older leaves. Margins of leaves curl inward. In dicots, these leaves are initially chlorotic but soon scattered burnt spots (dead areas) develop. In monocots, the tips and margins of the leaves die first.	Usually not excessively absorbed by plants. Excess K may lead to Mg, and possibly Mn, Zn or Fe deficiency
Calcium (Ca)	Signs of deficiencies include tip burn on leafy plants and roots, blossom end rot on fruity plants, and improper growth of tomatoes. Young leaves are affected before old leaves.	No consistent visible symptoms.
Magnesium (Mg)	Without sufficient amounts of Mg, plants begin to degrade the chlorophyll in the old leaves. This causes interveinal chlorosis, the main symptom of Mg deficiency. Later, necrotic spots may occur in the chlorotic tissue. Growth is reduced.	No information
Sulphur (S)	Not often encountered. S deficiency can be easily confused with lack of N. Symptoms, like delayed and stunted growth, are similar. However, general chlorosis occurs on younger leaves first, whereas N deficiency symptoms are first visible on older foliage.	Reduction in growth and leaf size. Sometimes interveinal yellowing or leaf burning.
Boron (B)	Symptoms vary with species and first appear on new leaves and the growing points (which often die. The branches and the roots are often short and swollen. Leaves show mottled chlorosis, thickening, brittleness, curling, wilting. Internal tissues sometimes disintegrate or discolour. Since B helps transport sugars, its deficiency causes a reduction of exudates and sugars from plant roots, which can reduce the attraction and colonization of mycorrhizal fungi.	Yellowing of leaf tip followed by progressive necrosis starting on the leaf margin and progressing toward midrib. Unlike most nutrient deficiencies that typically exhibit symptoms uniformly across the crop, B symptoms can appear randomly within a crop.
Chlorine (Cl)	Wilting of leaves, often with stubby tips. Leaf mottling and leaflet blade tip wilting with chlorosis and necrosis. Roots become stunted and thickened near tips. Chlorine deficiency in cabbage is marked by an absence of the typical cabbage odour.	Excessive Cl can be as a major component of salinity stress and toxic to plants (Chen et al. 2010). Symptoms include scorched leaf margins, bronzing, yellowing, excessive abscission, reduced leaf size, lower growth rate. Cl accumulation is higher in older tissue.
Copper (Cu)	Natural deficiency is rare. Typically, the symptoms start as cupping of young leaves, with small necrotic spots on the leaf margins. As the symptoms progress, the newest leaves are smaller in size, lose their sheen and may wilt. The growth points (apical meristems) may become necrotic and die. Plants typically have a compact appearance as the stem length between the leaves shortens. Excess K, P or other micronutrients can indirectly cause Cu deficiency.	Reduced growth followed by symptoms of iron chlorosis, stunting, reduced branching, thickening, and abnormal darkening of rootlets.

Iron (Fe)	Pronounced interveinal chlorosis. Similar to Mg deficiency, but here chlorosis will start at the tips of younger leaves and will work its way to older leaves. Other signs, always be coupled with the leaf chlorosis, can include poor growth and leaf loss.	Not often evident in natural conditions. Has been observed after the application of sprays where it appears as necrotic spots.
Manganese (Mn)	Leaves turn yellow and there is also interveinal chlorosis, first on young leaves. Necrotic lesions and leaf shedding can develop later. Disorganization of chloroplast lamellae. Mn may be unavailable to plants where pH is high. This is why it often occurs together with Fe deficiency, and also has similar symptoms. The symptoms of Mn deficiency are also similar to Mg because Mn is also involved in photosynthesis.	Sometimes chlorosis, uneven chlorophyll distribution. Reduction in growth.
Molybdenum (Mo)	As Mo is closely linked to N, its deficiency can easily resemble N deficiency. Deficiency symptoms start on older or midstem leaves: interveinal chlorosis, in some crops the whole leaf turns pale; leaf marginal necrosis or cupping. Leaves can be misshapen. Crops that are most sensitive to Mo deficiency are crucifers (broccoli, cauliflower, cabbage), legumes (beans, peas, clovers), poinsettias and primula.	Rarely observed. Tomato leaves turn golden yellow.
Nickel (Ni)	Ni is part of enzymes that detoxify urea. Although urea is an excellent source of nitrogen for plan), at higher concentrations it is strongly toxic to plant tissues. Typical symptoms of urea toxicity, and potentially also of Ni deficiency, are leaf burn and chlorosis.	Ni is strongly phytotoxic at higher concentration. In induces change in activity of antioxidant enzymes, and has a negative effect on photosynthesis and respiration. Excess Ni causes are chlorosis, necrosis and wilting. Cell division and plant growth are inhibited. High uptake of Ni induces a decrease in water content, which can act as an indicator for Ni toxicity in plants
Zinc (Zn)	Stunted growth, with shortened internodes and smaller leaves. Leaf margins are often distorted or puckered. Sometimes interveinal chlorosis.	Excess Zn commonly produces iron chlorosis in plants.

Figure 27 : Deficiency and toxicity symptoms for essential elements (adapted from Resh 2013).

4.4 Aquaponics

Aquaponic systems can be divided in two main categories according to the management of the fertility. The first category is named coupled aquaponics and the second decoupled aquaponics. In coupled aquaponics, the fish and plant compartment use the same water stream, so that the water from the fish compartment goes in the plant compartment, and then goes back to the fish. In decoupled aquaponic fish and plant compartment are separated, and the water from the fish is sent to the hydroponic compartment, but the plant water never goes back to the fish.

Figure 28 : Water flux in coupled (left) and decoupled aquaponics (right).

In coupled aquaponics, compared to conventional hydroponics, aquaponic water usually presents suboptimal nutrient concentrations, Ec and pH. The nutrient concentration and Ec are generally lower than the optimal value and the pH is generally higher than the optimal value. Indeed, in such a system, water quality seeks a balance between the plant and fish requirement. The fish and biofilter microorganisms prefer a low Ec, low NPK content and a neutral or slightly basic pH while plants prefer a higher EC, higher NPK content and a lower pH. In such a system, plant yield is generally lower than in conventional hydroponics. Nevertheless, some aquaponic water has been able to achieve yields similar to conventional hydroponics for lettuce and basil. Due to the high variability in the system designs, management, species and fish feed, the results presented in the literature are only applicable to specific aquaponic systems. The repeatability of these results is still an ongoing matter of discussion. In coupled aquaponics, it is also possible some fertilizer, such as micronutrients and potassium.

The Figure 29 presents the water characteristics of different coupled aquaponics systems. The global analysis shows that the most limiting factor is generally potassium, then phosphorus and then nitrogen. The low potassium concentration of fish feed is explaining the general the potassium deficiency in aquaponics systems. Phosphorous released by the fish in the aquaponic system is separated in two fractions. About 80 % of the phosphorous is stuck in fish feces and remaining 20 % is diluted in the water. One strategy to recover the phosphorous present in the fish feces is to mineralize sludge through liquid composting or vermi-composting. The liquid obtained by the mineralization is then introduced in the hydroponic compartment. The nitrogen concentration of coupled aquaponic system can be sufficient to maintain a normal growth. Iron and magnesium are two other elements are often underrepresented in coupled aquaponics systems. Again, these elements are present in very low concentration in fish feed but can be present in the water source. It is also possible to add mineral fertilizers to complement the nutrient solution with microelement and potassium.

pH	EC	$N\text{-}NO3^-$	$P\text{-}PO4^{3-}$	K	Ca	Mg	S-SO4	Na	Fe	Mn	Cu	Zn	Mo	B	Source
	ms/cm	mg/l							µg/l						
7,4	0,7-0,8	42	8	45	12	7			2500	800	50	'à	10	190	Rakocy et al. 2004
7,1	0,7-0,9	26	15	64	24	6	6	14	2500	60	30	340	10	90	Rakocy et al. 2004
8		20	10	48											Al Hafedh et al. 20
5,6-7,3		20	17												Endut et al., 2010
7,7		35	8	27	34				200		40	370			Roosta et Hamidp
		137	9	106	180	44		17							Pantanella et al., 2
		46,6-52,4	7,1-8,5		12,7-19,1	6,9-8,5	9,2-12,3	5-74,3	1580-4330	320-600	50-120	111-190	140-410	240-600	Delaide et al., 201
6,8-7,3	0,8-1,2	93	9,6	89	123	9,2	28	27	20	10	10	70	1	47	ITAVI, 2016
7,5-8,2	0,6-0,8	35	5,5	5,9	128	8,2	21	24	10	10	10	70	1	42	ITAVI, 2017
6,8-7,5	0,7-0,9	65	17	55	103	15,3	23	39,8	2000	140	272	455	109	153	ITAVI, 2018
		10,6	6,6	50,8	129,6	20,9			80		80	170	3	80	Bittsansky et al., 2
5,1-6,9		84	3,5	58	90	15			100						Nozzi et al., 2018
5-7,3		62	1,9	35	74	11			1800						
5-6,5		82	28	146	74	32			2100						

Figure 29 : Water analysis of different aquaponics systems (from Foucard and Tocqueville, 2019).

The second strategy, decoupled aquaponics consists in separating the fish and plant compartment in order to optimize the water quality of each compartment. In such a system, the fish water is transferred to the hydroponic compartment, but the hydroponics water is not sent back to the fish. Inorganic fertilizers, acid and base are added in the water of the plant compartment in order to reach conventional hydroponic standards for nutrient concentrations, EC and pH. Such system achieves yields at least as good as standard hydroponics. Delaide et al. (2016) and Goddek et al. (2018) identified higher lettuce yields in complemented aquaponics than in conventional hydroponics. For tomatoes, no yield difference was observed between those two systems in the publication of Suhl et al. (2016).

Some physiological differences between plant growing in aquaponics and conventional hydroponics have been observed: smaller leaf area in tomatoes grown in aquaponics and higher roots to shoot ratio for lettuce grown in aquaponics. Moreover, research revealed that such aquaponic water prevents the development of disease such as damping off caused by *Pythium phanumatum*. Again, such observation may be specific to each system and species, so that we still need to be cautious concerning the generalization of such observations.

The literature review highlights that aquaponic water (i) can have a positive effect on plant protection and plant development (ii) may affect the plant physiology and (iii) may not have the same effect on different species and varieties. Up to now, the scientific community does not have a perfect understanding of this phenomenon. Nevertheless, the scientific community did release evidence concerning some factors that contribute to the specific advantages of aquaponic water: microorganisms and organic matter.

Water from RAS and aquaponics systems contains dissolved organic matter (DOM) and microorganisms. DOM includes protein-like components, tryptophan and humic acids. In soils, amino acids are absorbed by the roots and may interact with the rhizosphere. Other organic elements may be present in DOM. These observations lead to the hypothesis that some DOM components contribute to the positive effect of aquaponics on plant development. Concerning the microorganisms, different research highlighted the presence of microorganisms involved in different process. First, microorganisms in the aquaponic water protect the seedlings through a competition of ecological niches that prevent pathogens development. Second, microorganisms present in aquaponic water have an active mechanism on the pathogens. Thirdly, some microorganisms promote the plant development by releasing some compounds such as hormones that fosters the development of the plant. Fourthly, microorganisms support the plant for the assimilation of elements, such as observed in soil rhizosphere.

The presence of microorganisms, organic material and different forms of inorganic elements confers different advantages to aquaponics. Besides the advantages presented above, it worth noting that in aquaponic systems, plants are able to develop in nutritive solution with lower nutrient concentration or higher pH than required in standard hydroponics.

4.5 Modeling

Smart Aquaponics is modeling different interactions between the nutrient solution and plant development. Two main categories of interactions can be distinguished: First, the nutrient uptake from the nutrient solution by the plant and secondly, the limitation of the plant development when the nutrient solution parameters are not optimal for the plant development. Smart Aquaponics model predict the concentration of different nutrient and the electro-conductivity, but provide no modeling of pH.

The Smart Aquaponics Model is based on the hypothesis that the nutrient uptake by the plant is equal to the element accumulated in the different organs of the plant. Two organs are considered in the Smart Aquaponics model, (i) the vegetative organs, which consists in shoot, roots, leaves and (ii) the fruits. The mineral composition of the vegetative organs and the fruits are stored in the database presented in Figure 30 and Figure 31. This database is used compute the mineral composition of the different organs. Elements taken into account in the model are sodium, nitrogen, phosphorous, potassium, magnesium, calcium, iron, sulfur. At each simulate time step, the actual computed plant growth associated with the composition of the different parts enables the calculation of the dissolved nutrient uptake from the water. For example, the sodium concentration of lettuce is 0,00048 g of sodium per g of fresh lettuce. Therefore, when a lettuce fresh mass increase of 10 g, the model remove 0,0048 g of the nutrient solution. This is the same for the other elements. Concerning the Nitrogen, the Smart Aquaponics Model uses a simplification, assumes that plants only absorb $N0_3$ and do not absorb ammonia.

	Vegetative organs							
	N (g/g)	Na (g/g)	P (g/g)	K (g/g)	MG (g/g)	Ca (g/g)	Fe (g/g)	S (g/g)
lettuce	0.00059	0.00048	0.00036	0.00277	0.00021	0.00084	0.00001	0.00100
tomato	0.00065	0.00012	0.00037	0.00407	0.00037	0.00185	0.00003	0.00390
basil	0.00113	0.00012	0.00056	0.00295	0.00064	0.00235	0.00002	0.00890
mint	0.00136	0.00031	0.00073	0.00569	0.00080	0.00243	0.00005	0.00280
coriander	0.00468	0.00046	0.00048	0.00521	0.00026	0.00067	0.00008	0.00130
pepper	0.00079	0.00120	0.00040	0.00662	0.00055	0.00126	0.00020	0.00540
eggplant	0.00094	0.00110	0.00040	0.00485	0.00130	0.00494	0.00650	0.00051
cucumber	0.00052	0.00100	0.00072	0.00360	0.00073	0.00485	0.00006	0.00450

Figure 30: Mineral composition of the vegetative organs (g/g) used by the Smart Aquaponics Model.

	Fruits							
	N (g/g)	Na (g/g)	P (g/g)	K (g/g)	MG (g/g)	Ca (g/g)	Fe (g/g)	S (g/g)
tomato	0.00054	0.00005	0.00024	0.00237	0.00011	0.00010	0.00000	0.00660
pepper	0.00154	0.00004	0.00026	0.00211	0.00012	0.00007	0.00000	0.02400
eggplant	0.00143	0.00002	0.00024	0.00229	0.00014	0.00009	0.00000	0.00014
cucumber	0.00152	0.00002	0.00024	0.00147	0.00013	0.00016	0.00000	0.00864

Figure 31: Mineral composition of the fruits (g/g) used by the Smart Aquaponics Model.

The water electro-conductivity is computed according to a simple model developed for hydroponics by Carmassi et al. (2003). The proposed equation describing the relationship between the EC and the concentration of the four most influencing cations (K, Ca, Mg and Na) is the following:

$$EC=0.78\ [Na]+0.28\ [K]+0.04\ [Mg]+0.06\ [Ca]$$

where the concentrations are expressed in (meq/l) and the resulting water electro-conductivity is given in (µS/cm).

Acidity is a very complex variable and no reliable pH model is available for aquaponics. Therefore, within the Smart Aquaponics Model, the pH of the different components of an aquaponics system is defined either by the user either by the sensors present in the aquaponic system.

The limiting factor of plant development used by the Smart Aquaponics Model is O_2 concentration, T°, Ec, pH, and N, P, K, Na content of the nutrient solution. The plant development is defined by the most limiting factor system, as described in the section 1.2. For the pH and Ec, plants are not growing below the minimum value, the plant is growing equally well between the minimum optimal value and the maximal optimal value. For nitrate, phosphorous and potassium, plant are not growing below a minimum value, and grow equally well the parameter is above the minimum optimal value. There is no maximum value taken into account for these parameters. Plants are growing equally well when the sodium concentration is below a maximal optimal value and stop growing when the sodium concentration is above the maximum optimal value. The different values minimal, optimal and maximal value were identified in the scientific literature.

As described in the section 4.4, aquaponic water provides some advantage to the pant development, so that plants are able to have a good development even when the pH, Ec and nutrient concentration are not in their optimal range. Therefore, the Smart Aquaponics Model proposes some minimal, optimal and maximal value for aquaponics. These values are less restrictive than the hydroponics value. For example, plants can grow equally well in aquaponics when the nitrate concentration is 34 mg/l and when the nitrate concentration is 67 mg/l in hydroponics. Unfortunately, specific minimal, optimal and maximal values for Ec, pH, and nutrient concentration are not available in the scientific literature. Therefore, the value used in the model are approximations and not based on specific scientific experiments. The minimal, optimal and maximal values for Ec, pH, and nutrient concentration used by Smart Aquaponics are presented in the figures.

	pH							
	Aquaponics				Hydroponics			
	Minimum	Minimum optimum	Maximum optimum	Maximum	Minimum	Minimum optimum	Maximum optimum	Maximum
lettuce	5	6.5	7.6	9	4	5.3	6.8	8
basil	5	6.5	7.6	9	4	5.5	6.5	7
mint	5	6.5	7.6	9	4	6	7	8
coriander	5	6.5	7.6	9	4	5.5	6.5	8
tomato	5	6.5	7.6	9	4	5.3	6.8	8
pepper	5	6.5	7.6	9	4	5.3	6.7	7.5
eggplant	5	6.5	7.6	9	4	5.3	6.8	7.8
cucumber	5	6.5	7.6	9	4	5.5	6.3	7.3

Figure 32 : Minimum, minimum optimum, maximum optimum, maximum value of pH used by the Smart Aquaponics Model.

	eC (µS/cm)							
	Aquaponics				Hydroponics			
	Minimum	Minimum optimum	Maximum optimum	Maximum	Minimum	Minimum optimum	Maximum optimum	Maximum
lettuce	200	600	2000	6000	400	700	2500	6000
basil	200	400	2000	6000	950	1800	2500	6000
mint	200	400	2000	6000	1000	1800	2500	6000
coriander	200	400	2000	6000	900	1800	2500	6000
tomato	200	400	2000	6000	1000	1800	5000	7000
pepper	200	400	2000	6000	1300	2300	2800	6000
eggplant	200	400	2000	6000	1300	2300	3800	6000
cucumber	200	400	2000	6000	900	1500	2700	6000

Figure 33: Minimum, minimum optimum, maximum optimum, maximum value of eC used by the Smart Aquaponics Model.

	NO_3 (mg/l)				P-PO_4 (mg/l)			
	Aquaponics		Hydroponics		Aquaponics		Hydroponics	
	Minimum	Minimum optimum	Minimum	Minimum optimum	Minimum	Minimum optimum	Minimum	Minimum optimum
lettuce	0	20	0	80	0	10	0	20
basil	0	20	0	80	0	10	0	20
mint	0	20	0	80	0	10	0	20
coriander	0	20	0	80	0	10	0	20
tomato	0	35	0	100	0	20	0	40
pepper	0	35	0	100	0	20	0	40
eggplant	0	35	0	100	0	20	0	40
coriander	0	35	0	100	0	20	0	40

Figure 34 : Minimum, minimum optimum value of NO_3 and P-PO_4 used by the Smart Aquaponics Model.

	K (mg/l)				Na (mg/l)	
	Aquaponics		Hydroponics			
	Minimum	Minimum optimum	Minimum	Minimum optimum	Maximum optimum	Maximum
lettuce	0	27	0	100	120	1725
basil	0	27	0	100	120	1725
mint	0	27	0	100	120	1725
coriander	0	27	0	100	120	1725
tomato	0	27	0	144	120	1725
pepper	0	27	0	144	120	1725
eggplant	0	27	0	144	120	1725
coriander	0	27	0	144	120	1725

Figure 35 : Minimum, minimum optimum of K and maximum optimum, maximum value of Na used by the Smart Aquaponics Model.

5 hydroponics

5.1 Introduction

5.1.1 The principles of hydroponics

Hydroponics is a method for growing crops without the use of soil, in such a system, a nutritive solution consisted of water and divers nutrients achieve the nutrition function of the soil and diverse kinds of substrates support the anchoring of the plant s and support the development of the roots.

The main differences between traditional in-ground growing techniques and soil-less techniques concern the relative use of water and fertilizer, and overall productivity. Soil-less agriculture is also typically less labor-intensive, supports monocultures better than in-ground agriculture, and can be used on non-arable land.

Hydroponics systems are generally constituted by different elements (Figure 36). The main element is the production system that contains the plants. This production system is generally associated with a sump, which is a big tank containing the nutritive solution. One or several pumps transfer the nutritive solution into the different compartment of the system. A ferti-irrigation stations generally used to control the nutrient content and the acidity of the hydroponic system.

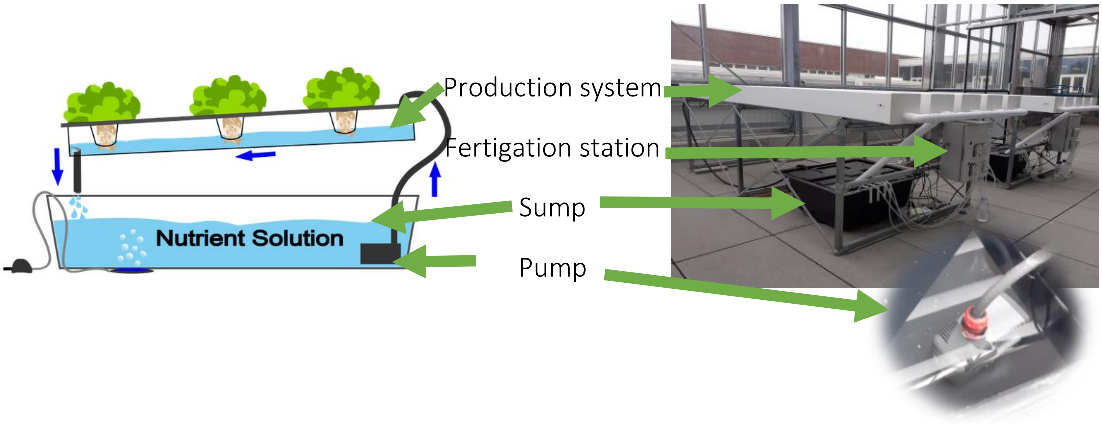

Figure 36 : Illustration of an hydroponic system (Sketch source: https://www.nosoilsolutions.com).

5.1.2 Advantages and disadvantages of hydroponics

Hydroponics allows the farmer to monitor, maintain and adjust the growing conditions of the plants, ensuring optimal real-time nutrient balances, water delivery, pH and temperature. In addition, there is no competition from weeds, and the plants benefit from higher control of pests and diseases. It is said that a plant grown using hydroponics uses 90% less water than would be used to grow the same plant in soil. In hydroponics the water used is the minimum needed for plant growth, while in-ground agriculture loses water through evaporation from the surface, percolation into the subsoil, runoff, and weed growth. Hydroponics therefore offers great potential for crop production in areas where water is scarce or expensive and in area where soil is inaccessible or unusable, such as cities or polluted areas.

Since the nutrients necessary for plant growth are in a solution that is delivered directly to the roots, the solution can be tailored to the plant's needs at a particular growth stage. With in-ground agriculture, on the other hand, farmers cannot fully control the delivery of nutrients to the plants because of the complex processes occurring in the soil, and some fertilizer may be lost to runoff, which not only decreases efficiency, but also causes environmental concerns. Because hydroponically grown plants dip their roots directly into the nutrient solution, they obtain what they need much more easily than plants grown in soil, so they usually have smaller root systems and can divert more energy into leaf and stem growth. As a result, hydroponic culture can achieve between 5 and 25% higher yields than soil-based culture.

However, there are also some limitations to hydroponic systems. One issue is the high financial and ecological cost of the setup. Secondly, an hydroponic system is vulnerable to power outages, as the electrical-driven devices such as the water pump, greenhouse management or nutrient solution management. Another aspect is the systematic use of inorganic fertilizers. The ammonia can come from the Haber-Bosch process that fixes nitrogen with hydrogen. Such process has a high energy demand. Phosphate, potassium or nitrate generally comes from mining industries, so that they are limited resources. Moreover, many mining industries are very questionable concerning social and environmental impacts.

Hydroponic system operators need specialized skills and knowledge to produce high yields of crops; they must learn the proper amounts of nutrients and lighting, manage complex nutritional problems.

5.2 Production systems

There is a wide range of production systems commonly us for hydroponic and aquaponics (Figure 37). The most commonly used systems are deep water culture (DWC) also named floating rafts, nutrient film techniques (NFT), drip system and media bed also named ebb and flow. In deep water culture (DWC) or floating raft systems the plants are rooted in tank with a deep-water layer. In NFT the plants grow with their roots in wide pipes supplied with a trickle of water. In media bed hydroponics the plants grow in a tank filled with a substrate regularly immersed in water. In drip system, plants are rooted in a small volume of the substrate and irrigated with a small amount of water so that the substrate is never immersed in water. Other systems and hybrid systems are also available. Within these systems, plants are rooted in a variable volume of the substrate. Each substrate and system type has its advantages and disadvantage which are discussed in more detail below.

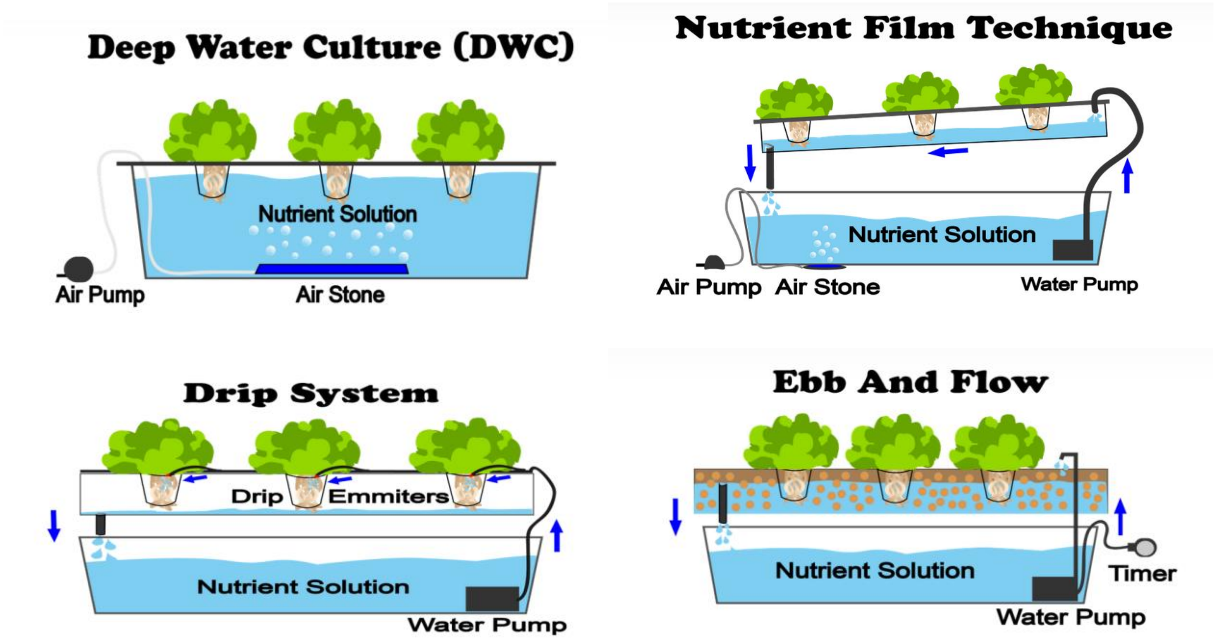

Figure 37 : Schematic representation of 4 types of hydroponic system (source: https://www.nosoilsolutions.com).

The evidence is somewhat contradictory in terms of the relative yields of the different in hydroponics and aquaponic systems. Lennard and Leonard (2006) compared the three hydroponic systems for lettuce production and found the highest production in gravel media beds, followed by DWC and NFT. However, subsequent studies by Pantanella et al. 2012 and the University of Liege found that NFT performed as well as DWC, while media bed consistently underperformed in terms of yield.

As for the role of the design of the hydroponic component of the overall performance and water consumption of aquaponic systems, a literature review by Maucieri et al. 2018 found that NFT is less efficient than media bed or DWC hydroponics, although the results were not unequivocal. The hydroponic component directly influences water quality, which is essential for fish rearing, and is also the main source of water loss by plant evapotranspiration. The design of the hydroponic component therefore influences the sustainability of the entire process, either directly in terms of water consumption and/or indirectly in terms of system management costs. The choice of the hydroponic component of an aquaponic system will also influence the design of the entire system. For example, in media bed systems the substrate usually provides enough surface area for bacteria growth and filtration, while in NFT or DWC the surface area is insufficient and additional biofilters will need to be installed.

5.2.1 Deep water culture (DWC)

Deep water culture (DWC) or floating raft system is a type of hydroponic system in which the plants have the roots are submerged in deep nutrient solution present in a tank and the plant are supported by a floating raft (Figure 38). DWC is very popular both in hobbyist and in professional systems.

Figure 38: Left : DWC at L'Écho-Village (Santes, Fr); Right : DWC at Gembloux Agro Bio-Tech (Gembloux, Be).

The tank is either consisted of a plastic tank or made out of a rigid material such as wood or brick, covered with a plastic layer that ensures the waterproofing of the system. The raft is generally consisted of a floating material such as polystyrene foam. Nevertheless, other materials can be used, such as any rigid and flat material where we can drill holes.

The length of the canals is not an issue, and they can range from one to several tens of meters. The recommended depth is 30 cm to allow for adequate plant root space, although small leafy greens such as lettuce only require a depth of 10 cm or even less. The system can be large too, nevertheless, most systems are designed in order to make all floating raft accessible by the plant grower, so that the tank is generally less than 2m wide.

The flow rate of the water entering each canal is relatively low, and generally each canal has a retention time (the amount of time it takes to replace all the water in the raft) of 1-4 hours in a small system up to one day in long systems of several tens of meters. This allows for adequate replenishment of nutrients, although the volume of water and the amount of nutrients in deep canals is sufficient to nourish the plants over longer periods. On the other hand, additional aeration might be required when the raft length exceeds several meters, because the flow rates are not high enough to provide sufficient oxygen for all the length of the raft (Figure 39).

Figure 39 : Bubbles from aerator in a raft at L'Écho-Village (Santes, Fr).

DWC is adapted for the production of most vegetable types and is one of the most common methods for commercial aquaponics systems growing multiple crops. It is very convenient to grow leafy greens (typically lettuce, salad leaves or basil), in such a situation, the plant pots are directly inserted in the raft, and the grower can easily move the raft according to his needs. The major adaptation that has to be done to grow different species are changing of holes densities or hole size of the raft. For the fruit vegetable productions, the raft cannot generally support the plant weight. Therefore, for these productions, the grower needs to create structure to hold the plants.

The major advantages of DWC are its simplicity in terms of design and management and therefore, its cost. Indeed the conception of such system requires few materials and competences. Concerning the management, RAFT is very flexible, indeed, the same tank can be used to grow nearly any type of vegetables.

Another advantage of the raft is its thermal inertia, indeed, the volume of water is quite important compared to other systems and the material used to build the raft, such as wood, brick and polystyrene are quite insulating. Therefore, compared to systems such as NFT, the DWC systems do not heat up easily, which may be very inserting in aquaponics systems using cold-water fishes.

The main disadvantage of DWC is the weight of the system. Such system is generally too heavy to be implemented on a rooftop greenhouse. Besides, although it is possible to install DWC on a table or other type of support, most of DWC systems are set up at the ground level.

5.2.2 Nutrient Film Technique (NFT)

Nutrient film technique (NFT) is a system of solutions culture where a thin film (two to ten millimeters depth) continually flows along the base of small channels in which the root systems sit. With NFT, the objective is that root create a mat in the nutrient flow, but the other roots are suspended above this in the moist air, accessing oxygen without being submerged. NFT is very popular both in hobbyist and in professional systems.

Figure 40 : NFT system at Gembloux Agro Bio-Tech (Gembloux, Be).

The channels are often in the form of pipes with a rectangular section or possibly rounds section. The width is generally larger than the height, as this means that a larger volume of water hits the roots. Larger fruiting vegetables and polycultures (growing different types of vegetables) require larger pipes than those needed for fast-growing leafy greens and small vegetables with small root masses. Indeed, root systems of tomatoes or other fruit plants can easily clog small pipes. The length of the pipe can vary, but it is worth bearing in mind that nutrient deficiencies can occur in plants towards the end of very long pipes because the first plants have already stripped the nutrients. White pipes should be used as the color reflects the sun's rays, thereby keeping the inside of the pipes cool. The channels must be positioned on a slope so that the nutrient solution flows at a good flow rate, which for most systems is around one l/minute. NFT systems do not require any aeration system.

NFT systems is adapted for most vegetables. Nevertheless they are mostly used for producing rapid-turnover crops such as leafy green lettuce, herbs, strawberries, green vegetables, fodder, and microgreens. Nevertheless, it is also suitable for fruit vegetables. It can be particularly interesting in polyculture system in order to grow on the same structure leafy greens during the winter and fruit vegetables in summer.

Different strategies can be implemented to save space with NFT systems. Some professional farms use mobile pipes. In such systems, the distance between the pipe is small at the beginning of the plant development and then increase along with the plant development. Another strategy is to use the vertical space and to place the pipes above each other's or on a triangular structure.

5.2.3 Drip Systems

Drip system is a system where plants are rooted in a substrate and nutrient solution is provided by a drip system. The drip irrigation is not continuous and is generally activated 3 times per day to 3 times per hour. The nutrient solution is absorbed by the substrate and plant and the excess of the solution is leaking from the substrate, collected, and recycled in the system. In drip system, the substrate and roots are regularly soaked by nutrient solution, but, contrary to DWC, NFT and ebb and flow, they are never completely immersed in water.

Figure 41 : Left: Tomato production using drip system at Tomato Masters (Deinze, Be); Right: Detail of a drip system at PTI (Kortrijk, Be).

Plants are generally germinated or grafted in a small cube (about 10 cm large) of substrate (rockwool or cocopeat). Then after, this cube is inserted in a larger substrate bag (about 10 L). The bag is designed in order to let the excess of nutrient solution leak in the recovery system.

Drip system is the most common system in professional structure producing fruit vegetables only. It is also possible to grow other types of vegetables. Nevertheless, it is not very interesting because drip system is not flexible in terms of plant density. Plant density required for fruit vegetables is much lower (2-3 plant /m³) than for leafy greens (8-15 plants/m²).

5.2.4 Media bed hydroponics

Media bed Hydroponics consists into tanks filled with a substrate continuously flooded by a stream of nutrient solution (Figure 42). The substrate generally consists of clay balls or gravel like material. Such a system is very similar to DWC in terms of design and structure except that the tank is filled with a substrate and that a raft does not cover the system. Due to the lack of oxygenation, the length of the media bed system is limited. Ebb and flow systems is a variation of the media bed where the media is alternatively flooded and drained. This alternative flooding drastically improve the oxygenation issue, but increase the complexity of the set up. Media bed and ebb and flow are very popular in hobbyist aquaponics.

Figure 42 : Ebb and flow at Don Bosco (Bruxelles, BE).

Depending on the type of substrate, it will occupy roughly 30-60 percent of the volume. The depth of the media bed is important because it controls the amount of root space volume in the unit, which in turn determines the types of vegetables that can be grown. Large vegetables such as tomatoes will need a substrate depth of 30 cm to allow sufficient root space and to prevent root matting and nutrient deficiencies. Small leafy green vegetables only require 15-20 cm of substrate depth.

The media bed also serves as a biological and physical filter within the hydroponic sub-systems, media beds have an efficient biological filtration because of the large surface area. The substrate also captures the solid and suspended fish waste and other floating organic particles, although the effectiveness of this physical filter will depend on the particle and grain size of the substrate, and the water flow rate. Over time, the organic particles are slowly broken down by biological and physical processes into simple molecules and ions that are available for the plants to absorb.

Ebb-and-flow (or flood-and-drain) causes the media beds to be periodically flooded with water which then drains back to a reservoir Figure 43). The alternation between flooding and draining ensure that the plants have fresh nutrients and adequate air flow in the root zone, which replenishes the oxygen levels. It also ensures that enough moisture is in the bed at all times so the bacteria can thrive in their optimal conditions. Some aquaponists introduce worms in order to improve the degradation of organic matter. The nature of an ebb-and-flow media bed creates three separate zones which are differentiated by their water and oxygen content. The firs top 2-5 cm is the dry zone, which functions as a light barrier, minimizing evaporation and preventing the light from directly hitting the water which can lead to algal growth. It also prevents the growth of fungus and harmful bacteria at the base of the plant stem, which can cause collar rot and other diseases. Secondly, the dry/wet zone has both moisture and high gas exchange. This is the 10-20 cm zone where the media bed intermittently floods and drains. If not using ebb-and-flow techniques, this zone will be the path along which the water flows through the medium. Most of the biological activity occurs in this zone. Third, the wet zone is the bottoms 3-5 cm of the bed which remains permanently wet. The small particulate solid wastes accumulate in this zone, and therefore the organisms that are most active in mineralization are also located here, including heterotrophic bacteria and other micro-organisms which break down the waste into smaller fractions and molecules that can be absorbed by the plants through the process of mineralization. The alternation between flooding and draining are generally achieved in a system with (i) a constant water (intake achieved by a pump for example) and (ii) a mechanical system, such as a siphon bell, that evacuate the water once it rise above a certain level. In some case, the evacuation is achieved a pump activated by a sensor. Another alternative is a system with a pump which is alternatively active and inactive. Therefore, the water level rises up when the pump is active and decrease when the pump stops.

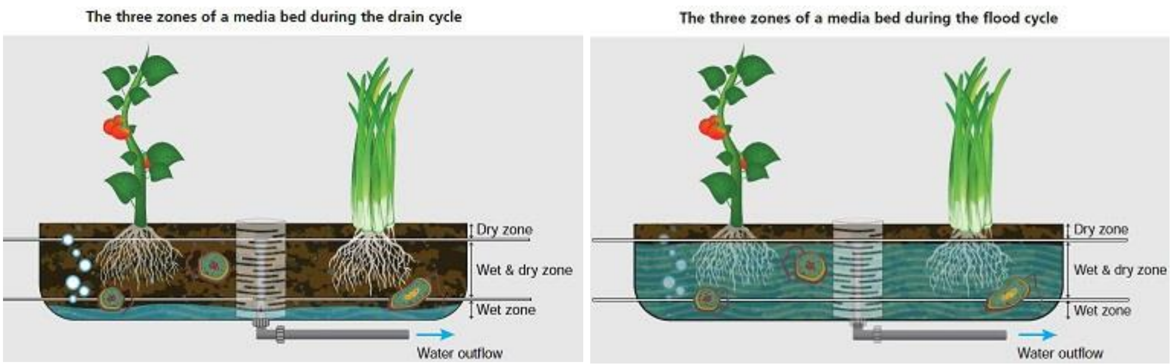

Figure 43 : Ebb and flow (figure from Carruthers, S. 2015).

5.2.5 Substrate

The substrate may be organic, inorganic, natural, or synthetic and it needs to have an adequate surface area while remaining permeable for water and air, thus allowing bacteria to grow, water to flow, and the plant roots to breathe. It must be non-toxic, have a neutral pH so as not to affect the water quality, and be resistant to mold growth. It must also not be so lightweight that it floats. Water retention, aeration and pH balance are all aspects that vary depending on the substrate. Water is retained on the surface of the particles and within the pore space, so water retention is determined by particle size, shape, and porosity. The smaller the particles, the closer they pack, the greater the surface area and pore space, and hence the greater the water retention. Irregular-shaped particles have a greater surface area and hence higher water retention than smooth, round particles. Porous materials can store water within the particles themselves; therefore, water retention is high. While the substrate must be capable of good water retention, it must also be capable of good drainage. Therefore, excessively fine materials must be avoided so as to prevent excessive water retention and lack of oxygen movement within the substrate. All substrates need to be cleaned periodically.

The substrates can also be classified as either granular or fibrous. Granular substrates include light expanded clay aggregate, gravel, vermiculite, perlite, and pumice. Fibrous substrates include rockwool and coconut fibre. Water is mainly held in the micropore space of a substrate, while rapid drainage and air entry is facilitated by the macropores. An adequate combination of large and small pores is therefore essential. Granular substrates have high macroporosity (air availability) but comparatively low microporosity (water availability), while fibrous substrates have high microporosity but comparatively low macroporosity.

In the context of aquaponics, the substrate used in an hydroponics production system can act as a biofilter. As described in the fish chapter, the nitrifying bacteria will attach to the surface of the biofilter media and the quantity of nitrifying bacteria is directly correlated to the specific area of a biofilter. Therefore the specific area of a substrate (area of surface per volume, m^2/m^3), associated to the volume of substrate, define the ability of a material to achieve the bio filtration. The Smart Aquaponics Model compute the biofitration achieved by the substrate present in the hydroponic system.

Light expanded clay aggregate (LECA) is very lightweight compared with other substrates, which makes it ideal for rooftop aquaponics. It comes in a variety of sizes; the larger sizes with diameters of 8-20 mm are recommended for aquaponics. Larger pore spaces (macroporosity) mean better percolation of solutions through the substrate and better air supply, even when biofilms cover the surfaces. However, LECA has small micropores, and thus does not have good water holding capacity. Its specific area is about 250-300 $m2/m^2$.

Volcanic gravel (tuff) has a very high surface area to volume ratio which provides ample space for bacteria to colonize, and it is almost chemically inert, except for small releases of microelements such as iron and magnesium and the absorption of phosphate and potassium ions within the first few months. The recommended size of volcanic gravel is 8-20 mm in diameter. Smaller gravel is likely to clog with solid waste, while larger gravel does not offer the required surface area or plant support. Its specific area is about 300-400 $m2/m^2$.

Limestone gravel is not recommended as a substrate, although it is sometimes used. Limestone has a lower surface-to-volume ratio than volcanic gravel, it is comparatively heavy, and it is not inert. Limestone is composed primarily of calcium carbonate ($CaCO_3$), which dissolves in water. This will increase the pH, and it should therefore only be used where water sources are very low in alkalinity or acidic. Nevertheless, a small addition of limestone can help to counterbalance the acidifying effect of nitrifying bacteria, which can offset the need for regular water buffering in well-balanced aquaponic systems. Its specific area is about 150-200 $m2/m^2$.

Vermiculite is a mineral which expands when heated above 1000 ºC. The water turns to steam, forming small, porous, sponge-like kernels. Vermiculite is very light in weight and can absorb large quantities of water. Chemically, it is a hydrated magnesium-aluminium-iron silicate. It is neutral in reaction with good buffering properties, and has a relatively high cation exchange capacity and thus can hold nutrients in reserve and later release them. It also contains some magnesium and potassium, which is available to plants.

Perlite is a siliceous material of volcanic origin, mined from lava flows. It is heated to 760 ^{o}C, which turns the small amount of water into steam, thereby expanding the particles to small, sponge-like kernels. Perlite is very lightweight and will hold three to four times its weight of water. It is essentially neutral, with a pH of 6.0–8.0, but with no buffering capacity; unlike vermiculite, it has no cation exchange capacity and contains no minor nutrients. It should not to be used on its own, but rather mixed with another substrate in order to improve drainage and aeration and thereby prevent nutrient build-up and subsequent toxicity issues while providing an oxygen-rich environment for the roots to thrive in.

Pumice, like perlite, is a siliceous material of volcanic origin and has essentially the same properties. However, it is the crude ore after crushing and screening, without any heating process, and therefore it is heavier and does not absorb water as readily, since it has not been hydrated. Its specific area is about 200-300 m2/m².

Rockwool is made from basalt rock that is molten in furnaces at a temperature of 1500 ^{o}C. The liquid basalt is then spun into threads and compressed into wool packets which are cut into slabs, blocks, or plugs. Most of the rapid expansion of the greenhouse industry over the past two decades has been with rockwool culture. However, in recent years concerns have been raised about its disposal, as it does not break down in landfills.

Coconut fibre (or coir) is an organic substrate derived from frayed and ground coconut husks. It is close to pH neutral and retains water while allowing for a good amount of oxygen for the roots. Its specific area is about 200-400 m2/m².

5.2.6 Modeling

The smart aquaponics model is able to integrate some specificities of different production systems. It is possible to (ii) add blowers into DWC, (ii) integrate the aeration of the water stream in the NFT system, (iii) the biofiltration achieved by the substrates of the different production systems. Nevertheless, the Smart Aquaponics Model cannot properly model the drip system and the effect of the timing of watering on yield. Smart aquaponics does not propose yield differences according to the different production systems.

5.3 Fertigation

Fertigation is the use of fertilizers in the appropriate combination, concentration and pH. Two aspects are important considering the fertigation. The first aspect is associated with the selection of chemicals (fertilizers, base and acid) and the water quality required by plants. The second is associated with the devices used to add these chemicals in the hydroponic system.

The section Plant Nutrition present the details of plant needs in terms of nutrients concentration, eC and pH. Nevertheless, management of an hydroponic or aquaponic farm, the grower uses commercial fertilizers to fulfill the nutrients needs and evaluate the nutrient needs using eC value. The pH is adapted using acid or base.

Commercial fertilizers are generally well balanced, so that the grower does not manage the balance between the chemical elements. The companies providing commercials fertilizers sometime provide a grow schedule including the EC target and additives. Commercial fertilizers are available in the form of liquids or as powder concentrates that are then diluted with water according to the EC. Nutrients are available in different formulas that, when mixed together, provide all the essential elements. Usually, most liquid commercial fertilizer stored in two separate solutions, namely, the solution A and solution B. The calcium containing compounds are kept separate from the phosphate and sulfate compounds. Indeed, in high concentrations, the calcium will combine with the phosphates and sulfate to form insoluble precipitates. Solutions A and B are added simultaneously in the hydroponic system.

Some professional growers prefer to prepare their own nutrient recipes based on different salts. For example, nitrogen may come from potassium, calcium nitrate, ammonium sulfate or ammonium nitrate. These different chemicals also provide other elements such as potassium, calcium or sulfur. As described in the section Units and notation, it is important to take into account the chemical form of the element when preparing the solution. For example, one Kg of potassium nitrate contains 0,1385 Kg of nitrogen. HydroBuddy is an open source program for the calculation of nutrient solutions for hydroponics. The program enables one to find the amount of salt weights necessary for the preparation of the nutrient solution with a given composition or, conversely, to determine nutrient concentrations within a solution based on a given fixed weight of salts. While the database contains pre-defined formulations, the program can be customized to allow the addition of other preparations.

Acidity is controlled by adding basic or acid compounds. Calcium hydroxide or potassium hydroxide, or as calcium carbonate and potassium carbonate are commonly used to increase the pH.. The choice of the buffer depends on the price of the available chemical and on the plant type being cultivated: leafy vegetables may need more calcium, while fruiting plants may need more potassium. Sulfuric acid and phosphoric acid are commonly used to decrease the pH of an hydroponic system. Alike the base described above, these acids provide elements required by plants.

5.3.1 Fertigation & Aquaponics

In coupled aquaponics, the principle is generally to introduce few or no chemical to the system. For instance, the only input of some hobbyist system is fish feed. In such systems, the limiting factors are generally iron, magnesium, calcium and potassium.

Iron is the most common and severe limiting factor since it is absent from the fish feed and water source. In many systems, the lack of iron completely hamper the plant development. In such a situation, leaves become light green or white. In general, iron is added, as chelated iron (EDDHA) to reach concentrations of 2 mg /l (Figure 44). Commercial products dedicated to this purpose is easily available on different web shop. It is important to take into account the iron concentration of the commercial product, which is generally ranging from 4 % to 12 %. For example, if your system is 2m³ big, and the commercial product contains 5 % of iron, you have to add 80 g of your product to the system to reach the 2mg/l. We recommend complementing with iron two or three times a year or as soon as the first deficiency symptoms appear. Once that Iron is added to the system, plant generally restart their development and all new organs have no sign of deficiency. Since iron is a non-mobile element in the plant, all the organs that experiment the deficiency remain light green or white.

Figure 44 : Left : lettuce with iron deficiencies. Right: The same lettuce 2 weeks after the EDTA addition, the new leaves do not show sign of deficiencies.

In coupled aquaponics, most of the magnesium and calcium are provided thought the water source. Therefore, Mg or Ca deficiencies are generally associated with a specific area. The local water services generally provide the water analysis, including magnesium and calcium. It may happen, in some areas that magnesium and calcium deficiencies are as severe as iron deficiencies. When the magnesium or calcium concentration are very critical or below the optimal value presented in the section, salts can be added to the system. Ca complementation can also be integrated with the pH control, as calcium hydroxide or potassium carbonate. Some companies propose microelement mix including all microelements such Fe, Mg Ca. Some authors such as Foucard et al proposes to avoid micro-element deficiencies through the systematic addition of microelement mixes.

The next limiting factor in coupled aquaponics is generally the potassium. In a well-balanced aquaponics system with a good iron, magnesium and calcium management, potassium is generally a limiting factor. Indeed, the fish feed contains low concentration of potassium compared to nitrogen and phosphorous. In coupled aquaponics, low potassium concentration is scarcely as deleterious as iron deficiencies, but can result in a yield decrease of 20 to 50 % compared to an optimal potassium concentration. The usage or the non usage of potassium complementation in an aquaponic system is sometimes the result of different ethical considerations. Therefore, potassium can be added in as a salt or in the pH control, as potassium hydroxide, or potassium carbonate. Some companies also proposes organic potassium fertilizers dedicated to aquaponics.

In the case of complemented aquaponics, the farms generally use similar fertilizers as standard hydroponics system (either commercial formulation or salt based fertilizers) and use the RAS water as a water source. This RAS water is then complemented in order to reach a target EC and pH value. Such a system is efficient and is generally reported achieving yields similar to above the inorganic hydroponics. The complementation of the fertilizer according to the element (NPK) content of RAS water is a matter of discussion in the aquaponic network. To our knowledge, no professional farm is using this strategy.

5.3.2 Monitoring and control tools

5.3.2.1 Electroconductivity and pH

Most of professional systems use a fertigation station to monitor water quality and adjust the EC and acidity by adding different chemicals to the water. The grower introduces the minimal threshold and the target value of EC and pH. When the EC or pH drop below the threshold, the station add a small amount of chemical. The station will add chemicals until the EC or pH reach the target value. The station generally wait few minutes between two successive chemical additions in order to let the chemical mix with the water. Generally, the quantity of chemicals provided at each addition can be defined by the grower. For example, for a lettuce production, the EC target value can be 1450 $\mu S/cm$ and the threshold value 1400 $\mu S/cm$. When the EC value drop below 1400, the station will add identical quantity of solution A and B, wait few minutes and then evaluate the EC. If the EC is below 1450, the station adds an additional quantity of solution A and B. The station will stop adding fertilizer once the EC rise above 1450. The price of such station is ranging from 1 000 € for small station up to 100 000 for professional station dedicated to large commercial farms.

Some small-scale professional farmers and most home gardeners do not invest in a fertigation station. In such case, the uses handheld pH and EC sensors and manually add the chemical up to a target value. In such a situation, alike for the fertigation station, it is recommended adding successive small quantity of chemicals. Some companies proposing fertilizer to home gardeners also proposes some dilutions of their fertilizer, so that the hydroponic gardener does not have to work with EC. For example, they propose to dilute 10ml of fertilizers in 10 L of water.

5.3.2.2 Nutrient concentration

Up to now, nitrogen phosphorous and potassium probes are too expensive to be used in commercial farms. These elements can be measured accurately using a spectrophotometer. The spectrophotometers present in some professional fish and aquaponic farms can provide accurate measurement of the macro elements (nitrogen, phosphorous and potassium), including the different nitrogen forms (nitrate nitrite, and ammonia). Professional spectrophotometers cost about 2 000 euros. The analysis requires different chemicals. The macro element analysis cost about 3 to 5 € of chemical reactive. Public laboratories also proposes macro and micro nutrient analysis. Recently, some companies developed portative spectrophotometers, such device generally analyzes the concentration of only one element, but are much cheaper. Such sensors can be very interesting to monitor ammonia, for example.

Macronutrients analysis presented above is accessible to commercial farms but may represent an important cost to the hobbyist. In such case some aquarium kits enable monitor some elements such as nitrogen, phosphorous, potassium, iron or calcium. Measurements of such a system are not very accurate but is enough to identify or exclude some issue causes in the context of nonprofessional systems.

Some companies propose another approach to evaluate if the quality of the plant nutrition. These companies analyze the plant tissues and propose a diagnostic associated with the plant nutrition/deficiencies.

5.3.3 Modeling

The Smart Aquaponics Model only is modeling flux of nitrogen, phosphorous, potassium, magnesium, calcium, iron and sulfur in the system. This includes their presence in the fish feed and their final location, such as water, sludge, plant or fish. The element cycle is modeled in any type of aquaponics system. The only limiting factor factors in terms of nutrients for the plant are nitrogen, phosphorous, potassium and sodium. Therefore, within the Smart Aquaponics Model, these four elements are the focus for the fertigation.

The fertigation station can be simulated in the Smart Aquaponics model. One of the most critical step is to define the macro element concentration of the fertilizer. The concentration of macronutrients and elements contributing to the EC (sodium, potassium, Mg and Ca) are the most important element of the fertilizer description and are generally well described for commercial products.

Unfortunately, Smart Aquaponics Model cannot model the pH. The pH value of each tank is pre defined by the user does not change during the simulation. Therefore, within the Smart Aquaponics Model, the addition of a base or an acid in a tank will not change the pH but may increase the concentration of elements present in the acid or base.

6 Plants

More than 150 different vegetables, herbs, and flowers have been grown successfully in aquaponic systems. Plants suited to aquaponic systems are typically fast growing, have shallow root systems, and a low nutrient demand, such as leafy greens and herbs. Fruiting vegetables, such as tomatoes, cucumbers and peppers, also do well but they have higher nutrient demands and are more appropriate for established systems with adequate fish stocks. But there are some plants that don't grow well, some that don't make sense in terms of economics, and some that probably won't work well due to space restrictions. Root crops, such as potatoes, sweet potatoes, turnips, onions, garlic, and carrots, typically do better in traditional culture, though they can be grown successfully in deep media beds.

When building a new farm, crop choice impacts sales, space, and technique. There are two types of cropping system: monocrop (or monoculture) is a system with a single plant type or variety; polycrop (or polyculture) is a system with different plant types and varieties. The choice between a variety of crops or a single plant type must be made with an eye on logistics, sales, experience, and pest control. The biggest advantage in favour of monocropping is simplicity. It can beat polycropping in terms of environment optimization, yield, management and ease of sales. If you are growing a single crop, you'll only ever need to prepare and ship your product in a single fashion. However, monocropping opens up the possibility of exhausting demand and, if combined with poor pest control, runs the risk of losing the entire yield at once. Polycropping gives farmers the possibility to meet a variety of demand, and is inherently more robust and resistant to pest outbreaks as there is a lower chance of the entire operation being compromised. It also enable different business model, since producer can propose a larger range of products, it can access shorter food supply chain and therefore higher prices.

6.1 Lettuce

Lettuce (Lactuca sativa) takes up relatively little space, and has a short growing cycle when it is healthy: 5-6 weeks from transplant, or 9-11 weeks from seed (Figure 45). It can be grown in media bed, NFT and DWC systems with 9-25 heads/m^2. Many varieties can be grown in aquaponic systems, including iceberg lettuce which is ideal for cooler conditions, Romaine lettuce which is slow to bolt, and loose leaf lettuce which has no head and can be sown directly onto media beds and harvested by picking single leaves without collecting the whole plant. The most common pests and diseases affecting lettuce are aphids, leaf miners, and powdery mildew.


Figure 45: Left: lettuces in NFT at PCG (Kruishoutem, Be), Right: lettuces in homemade DWC at the University of Lubumbashi (Lubumbashi, RDC)

The seeds take between 3 and 7 days to germinate at 13-21ºC. Plant hardening, through exposing the seedlings to colder temperatures and direct sunlight for 3-5 days before transplanting, also results in higher survival rates. The seedlings can be transplanted into the hydroponic unit after 3 weeks, when the plants have 2-3 true leaves. When transplanting lettuce in warm weather, place light sunshade over the plants for 2-3 days to avoid water stress (Figure 46).

For head growth, the night temperature should be 12-18ºC, with a day temperature of 18-26ºC. The generative growth is affected by photoperiod and temperature: extended daylight and warm conditions (>18ºC) at night cause bolting. Water temperatures above 26ºC may also cause bolting and leaf bitterness. Some varieties are more tolerant of heat than others. When air and water temperatures increase during the season, use bolt-resistant (summer) varieties. If growing in media beds, plant new lettuces where they will be partially shaded by taller plants. To achieve crisp, sweet lettuce, grow plants at a fast rate by maintaining high nitrate levels. The plant has low nutrient demand, though higher calcium concentrations in the water help to prevent tip burn in the summer. While the ideal pH is 5.8-6.2, lettuce still grows well with a pH as high as 7, although some iron deficiencies might appear owing to reduced bio-availability of this nutrient above neutrality.

	minimum	minimum optimum	maximumm optimim	maximum
Plant density (plants/m^2)	/	0	9	20
Day temperature (C°)	3.5	18	26	41
RH (%)	0	30	90	150
PPFD (mol/m^2.day)	1.296	9.72	22.68	32.4
Light Duration (h)	7	17	19	24
Water temperature (C°)	10	17	26	35
Dissolve Oxygen concentration (mg/l)	1	5	/	/
pH aquaponics	5	6.5	7.6	9
pH hydroponics	4	5.3	6.8	8
ec aquaponics (µS/cm)	200	600	2000	6000
ec hydroponics (µS/cm)	400	700	2500	6000
N-NO_3 aquaponics (mg/l)	0	20	/	/
N-NO_3 hydroponics (mg/l)	0	80	/	/
P-PO_4 aquaponics (mg/l)	0	10	/	/
P-PO_4 hydroponics (mg/l)	0	20	/	/
K aquaponicS (mg/l)	0	27	/	/
K hydroponics (mg/l)	0	100	/	/
Na (mg/l)	/	/	120	1725

Figure 46 : Summary of the lettuce parameters used by the Smart Aquaponics Model.

6.2 Coriander

Coriander (Coriandrum sativum) is an interesting crop for the colder seasons. Indeed, it bolts very easily, especially in hot conditions. It prefers cooler temperatures (5-24ºC) and low salts (Figure 47 and Figure 48Figure 50). The preference for cool temperatures extends to germination as well; temperatures of 15-20ºC will result in the best germination rates. If bolting is triggered, which makes the flavor of the herb more bitter, the bolts should be trimmed and the environmental conditions adjusted. Growers can purchase slow bolting seeds to minimize the potential for crop failure. Two of the most common diseases of coriander in hydroponics are bacterial leaf spot and powdery mildew. Coriander is also vulnerable to Pythium, which can become problematic in systems with inadequate aeration around the roots.

Figure 47: Coriander in NFT at Urban Farmers (The Hague, NL)

Coriander seeds germinate in 7-10 days, with leaves ready to harvest 40-48 days later. From seeds to harvest, coriander takes 50-55 days. Coriander can be harvested fully or partially, requiring very little maintenance like trimming. If using a partial harvest, the first harvest will take place at about 5 weeks after transplant and the second at about 8 weeks after transplant. The second harvest will be lower than the first. Coriander may be packaged in various ways depending on the farmer and, even more importantly, market preference.

	minimum	minimum optimum	maximumm optimim	maximum
Plant density (plants/m^2)	/	0	20	125
Day temperature (C°)	0	4	24	28
RH (%)	20	30	70	150
PPFD (mol/m^2.day)	1.296	22	30	41
Light Duration (h)	7	17	19	24
Water temperature (C°)	3	4	24	28
Dissolve Oxygen concentration (mg/l)	7	9	/	/
pH aquaponics	5	6.5	7.6	9
pH hydroponics	4	5.5	6.5	8
ec aquaponics (µS/cm)	200	600	2000	6000
ec hydroponics (µS/cm)	900	1800	2500	6000
N-NO_3 aquaponics (mg/l)	0	20	/	/
N-NO_3 hydroponics (mg/l)	0	80	/	/
P-PO_4 aquaponics (mg/l)	0	10	/	/
P-PO_4 hydroponics (mg/l)	0	20	/	/
K aquaponics (mg/l)	0	27	/	/
K hydroponics (mg/l)	0	100	/	/
Na (mg/l)	/	/	120	1725

Figure 48 : Summary of the coriander parameters used by the Smart Aquaponics Model.

6.3 Mint

Mint (Mentha spicata) is one of the easiest crop to grow (Figure 49). It is easy to plant, grows quickly, and easy to harvest. Mint is also tolerant of low EC and some temperature variation (Figure 50). Nevertheless it doesn't do well when heat spikes above 26^{o}C. It struggles less with pests than many of the herbs, although verticillium wilt and powdery mildew can become problematic. Mint can be grown from seed, but using cuttings or rootstock is much quicker, especially on a commercial scale. Stem cuttings can be made by removing healthy green sprigs and setting them in water. Roots will form and the plants will grow to maturity within a few weeks. Mint can be harvested by cutting about 5 centimeters from the surface of the system. A second harvest will be ready in only 2-3 weeks, once it has grown out to about 20 centimeters.

Figure 49: Mint and other herbes grown in a vertical system at Urban Farmers (The Hague, NL)

There are dozens of types of mint, but the main varieties are spearmint (Mentha spicata), peppermint (Mentha x piperita), and pennyroyal mint (Mentha pulegium); some of the other mints like lemon mint (Monarda citriodora) are actually not mint at all.

	minimum	minimum optimum	maximumm optimim	maximum
Plant density (plants/m^2)	/	0	25	40
Day temperature (C°)	6	17	23	28
RH (%)	20	60	90	150
PPFD (mol/m^2.day)	1.152	8.64	20.16	28.8
Light Duration (h)	6	15	18	24
Water temperature (C°)	10	17	26	31
Dissolve Oxygen concentration (mg/l)	7	9	/	/
pH aquaponics	5	6.5	7.6	9
pH hydroponics	4	6	7	8
ec aquaponics (µS/cm)	200	600	2000	6000
ec hydroponics (µS/cm)	1000	1800	2500	6000
N-NO_3 aquaponics (mg/l)	0	20	/	/
N-NO_3 hydroponics (mg/l)	0	80	/	/
P-PO_4 aquaponics (mg/l)	0	10	/	/
P-PO_4 hydroponics (mg/l)	0	20	/	/
K aquaponics (mg/l)	0	27	/	/
K hydroponics (mg/l)	0	100	/	/
Na (mg/l)	/	/	120	1725

Figure 50 : Summary of the mint parameters used by the Smart Aquaponics Model.

6.4 Basil

Owing to the higher nitrogen uptake, basil (Ocimum basilicum) is an ideal plant for aquaponics. However, if mint is one of the easiest herbs to grow, then woody herbs like basil are at the other end of the scale. Although basil isn't needy in terms of water and pH, it does require pruning to achieve full yields. Many cultivars of basil have been tried and tested in aquaponic systems, including Genovese basil (sweet basil), lemon basil, and purple passion basil (Figure 51).

Figure 51: Different varieties of Basil at ECF Farm (Berlin, Ge)

Basil seeds need a reasonably high and stable temperature to initiate germination (20-25^{o}C), and should germinate within 6 to 7 days. The seedlings should be transplanted to the aquaponic system when they have 4-5 true leaves. Once transplanted, basil grows best in warm to very warm conditions (18-26C°), with full exposure to the sun (Figure 52). However, better quality leaves are obtained through using slight shading. Basil can be affected by various fungal diseases, including Fusarium wilt, grey mould, and black spot, particularly under suboptimal temperatures and high humidity conditions. Air ventilation and water temperatures higher than 21^{o}C help to reduce plant stress and incidence of diseases.

Basil has been bred to be a single-stemmed plant growing upward (apical growth). For most growers, a bushier plant is better. A pruned plant looks better, yields more, and can be easier to transport depending on the growing method. To change the way that basil grows, growers can trigger a secondary type of growth that moves outward and up instead of straight up (lateral growth). A young basil plant (12-25 centimetres tall) has lateral buds on the side of the stem that will only grow if the main stalk gets badly damaged or removed. This means that if growers clip the stem right above those lateral buds (1 centimetre or so), the buds will be triggered to grow out. By pruning basil this way, growers can increase the production of that branch and control the shape of the plant. The plant should be cut above the second pair of buds so that the growth fans out and doesn't stop airflow or light penetration. Correct pruning will result in increased yield in each of the first three harvests (around weeks 5, 8, and 11).

The harvest of leaves starts when plants reach 15 cm in height and continues for 30-50 days. Basil needs to be handled gently, as bruising can increase the rate of deterioration. It should not be stored in a chiller, where the temperature is usually kept at 5-7^{o}C, as it is a warm weather crop and does not have the cellular machinery to deal with those temperatures, and will decay rapidly. To extend its shelf life, it should be stored above 13°C (preferably at a temperature of 16°C). At this temperature, it can attain a shelf life of 12 days.

	minimum	minimum optimum	maximumm optimim	maximum
Plant density (plants/m^2)	/	0	25	40
Day temperature (C°)	8	18	26	31
RH (%)	20	60	90	150
PPFD (mol/m^2.day)	1.296	22	30	41
Light Duration (h)	7	16	19	24
Water temperature (C°)	10	17	26	31
Dissolve Oxygen concentration (mg/l)	5	7	/	/
pH aquaponics	5	6.5	7.6	9
pH hydroponics	4	5.5	6.5	7
ec aquaponics (µS/cm)	200	600	2000	6000
ec hydroponics (µS/cm)	950	1800	2500	6000
N-NO_3 aquaponics (mg/l)	0	20	/	/
N-NO_3 hydroponics (mg/l)	0	80	/	/
P-PO_4 aquaponics (mg/l)	0	10	/	/
P-PO_4 hydroponics (mg/l)	0	20	/	/
K aquaponics (mg/l)	0	27	/	/
K hydroponics (mg/l)	0	100	/	/
Na (mg/l)	/	/	120	1725

Figure 52 : Summary of the basil parameters used by the Smart Aquaponics Model.

6.5 Tomato

Tomato (Solanum lycopersicum) is one of the major cash crop in polyculture but is mostly grow in monoculture (Figure 53). Given their high nutrient demand, especially for potassium, the number of plants per unit should be planned according to the fish biomass in order to avoid nutrient deficiencies. Tomatoes prefer warm temperatures, with full sun exposure. The optimal daytime temperature is 22-28°C, while night time temperatures of 13-16°C encourage fruit set (Figure 54).

Figure 53: Left: Tomato plants at at ECF Farm (Berlin, Ge); Right: Tomato plants at Tomato Masters (Deinze, Be).

Seeds will germinate in 4-6 days at 20-30ºC. Stakes or plant supports should be set before transplanting to prevent root damage. Seedlings can be transplanted to the aquaponics systems 3-6 weeks after germination when the seedlings are 10-15 cm high and when night time temperatures are constantly above 10ºC. The growth time is 50-70 days until the first harvest, and fruiting continues for 90-120 days in bush varieties and as long as the environmental condition are good for vining varieties. For best flavour, harvest tomatoes when they are firm and fully coloured. Fruits will continue to ripen if picked half ripe and brought indoors. Fruits can be easily maintained for 2-4 weeks at 5-7ºC under 85-90 percent relative humidity.

Pruning is crucial for tomato production, as it ensures proper utilization of energy for the growth of fruits and the main stem. Once the tomato plants are around 60 cm tall, the growing method (bush or single stem) can be determined by pruning the unnecessary upper branches. Vining tomatoes can grow up to a height of 16m in heated greenhouses, while 2-3m is a normal height in tunnel greenhouses. Pruning is required for vining tomatoes, as 50 percent of tomato yield is reduced without pruning and trellising. Both bush and vining varieties should be grown with a single stem (double in case of high plant vigour) by removing all the auxiliary suckers. Hand removal of suckers 2 to 2.5 mm in length once a week is the best method. At this size, the suckers can be easily broken off without injuring the main stem. Tomatoes rely on supports that can either be made of stakes (bush varieties) or bound to vertical plastic/nylon strings that are attached to iron wires pulled horizontally above the plant units (vining varieties). It is also important to remove the leaves from the lower 30 cm of the main stem to favor a better air circulation and reduce fungal infection. The best way to remove them is to bend them upward first and then pull down in order to prevent peeling of the skin on the stem. Remove the leaves covering each fruit branch soon before ripening to favor nutrition flow to the fruits and to accelerate maturation.

Tomatoes are normally wind pollinated or pollinated by bees when grown outside. In greenhouses, however, air movement is insufficient for flowers to pollinate themselves. Pollination is generally achieved by using bumble bees (Bombus sp.). It is important to maintain the correct population levels of bumble bees, as overpopulation may result in the bees overworking the tomato flowers.

	minimum	minimum optimum	maximumm optimim	maximum
Plant density (plants/m^2)	/	0	3	20
Day temperature (C°)	8	24	28	40
RH (%)	10	40	65	120
PPFD (mol/m^2.day)	1.296	22	30	41
Light Duration (h)	7	17	19	24
Water temperature (C°)	10	17	26	31
Dissolve Oxygen concentration (mg/l)	7	9	/	/
pH aquaponics	5	6.5	7.6	9
pH hydroponics	4	5.3	6.8	8
ec aquaponics (µS/cm)	200	600	2000	6000
ec hydroponics (µS/cm)	1000	1800	5000	7000
N-NO_3 aquaponics (mg/l)	0	35	/	/
N-NO_3 hydroponics (mg/l)	0	100	/	/
P-PO_4 aquaponics (mg/l)	0	20	/	/
P-PO_4 hydroponics (mg/l)	0	40	/	/
K aquaponicS (mg/l)	0	27	/	/
K hydroponics (mg/l)	0	144	/	/
Na (mg/l)	/	/	120	1725

Figure 54 : Summary of the tomato parameters used by the Smart Aquaponics Model.

6.6 Peppers

Peppers (Capsicum annuum) include a wide range of interesting varieties, with a wide range of size and color (green, yellow, red, purple, Black).They require rather high temperature but slightly lower than tomatoes (19-23ºC). Alike other fruit plants, they require high P and K fertilization during the fruit production (Figure 55 and Figure 56).

Figure 55: Pepper at Urban Farmers (The Hague, NL)

Seeds will germinate in 8-12 days at 22-30ºC. The seedlings can be transplanted as soon as the night time temperature settles above 10ºC, and when they have 6-8 true leaves. Bushy, heavy yielding plants need to be supported with stakes or vertical strings hanging from iron wires pulled horizontally above the buckets. The first few flowers that appear on the plant should be picked in order to encourage further plant growth, and the number of flowers should be reduced in the event of excessive fruit setting to favour the growing of fruits to reach adequate size.

Because of a pepper's unique growth patterns, pruning is essential in ensuring a successful crop. Pruning will reduce production cost, increase yield and reduce disease susceptibility. Sweet pepper pruning is different from tomato pruning because peppers do not produce side shoots like tomatoes. After pinching (removal of the plant tip), the top two nodes start to grow.

The growth time is 60-95 days. Like tomatoes, peppers also need to be pollinated either manually or by introducing a bumble bee hive to the greenhouse. For sweet red peppers, the green fruits should be left on the plant until they ripen and turn red or yellow. Harvesting should begin when the peppers reach marketable size, and continue throughout the season to favour blossoming, fruit setting and growth. Peppers can be easily stored fresh for 10 days at 10ºC with 90-95 percent humidity.

	minimum	minimum optimum	maximumm optimim	maximum
Plant density (plants/m^2)	/	0	3	20
Day temperature (C°)	10	17	25	31
RH (%)	10	40	65	120
PPFD (mol/m^2.day)	1.152	8.64	20.16	28.8
Light Duration (h)	6	14	18	24
Water temperature (C°)	10	17	27	31
Dissolve Oxygen concentration (mg/l)	7	9	/	/
pH aquaponics	5	6.5	7.6	9
pH hydroponics	4	5.3	6.7	7.5
ec aquaponics (µS/cm)	200	600	2000	6000
ec hydroponics (µS/cm)	1300	2300	2800	6000
N-NO_3 aquaponics (mg/l)	0	35	/	/
N-NO_3 hydroponics (mg/l)	0	100	/	/
P-PO_4 aquaponics (mg/l)	0	20	/	/
P-PO_4 hydroponics (mg/l)	0	40	/	/
K aquaponics (mg/l)	0	27	/	/
K hydroponics (mg/l)	0	144	/	/
Na (mg/l)	/	/	120	1725

Figure 56 : Summary of the pepper parameters used by the Smart Aquaponics Model.

6.7 Cucumber

Cucumber (Cucumis sativus) comes in three sexual breeds: a half-and-half mix of male and female flowers (monoecious); a seventy-thirty mix of female to male flowers (gynoecious); and entirely female flowering plants (parthenocarpic). Planting only female flowering plants will ensure a flowering fruit with each plant, and therefore a crop that can fruit without pollination. However, the pollen transmitted by bees and other pollinators can corrupt parthenocarpic plants, so it will be necessary to keep potential pollinators out of the greenhouse. Cucumbers can be grown in media bed units as they have a large root surface, and on DWC floating rafts, although in grow pipes there could be a risk of clogging owing to excessive root growth (Figure 57).

Cucumbers require large quantities of nitrogen and potassium, so the decision on the number of plants to grow should take into account the nutrients available in the water and the fish stocking biomass. They grow best with long, hot and humid days, with ample sunshine and warm nights. Optimal growth temperatures are 24-27°C during the day, with 70-90 percent relative humidity, and a night time temperature of 18-20°C. They are highly susceptible to frost. Full sunlight and a temperature of the substrate of about 21°C are also optimal for production. A higher potassium concentration will favour higher fruit settings and yield.

Seeds will germinate after 3 to 7 days at a temperature of 20-30°C. The seedlings can be transplanted at 2-3 weeks when they have developed 4-5 leaves. Once transplanted, cucumbers can start producing fruit after 2-3 weeks. In optimal conditions, plants can be harvested 10-15 times. Harvesting every few days will prevent the fruits from becoming overly large, and favour the growth of the following ones. Cucumber plants grow very quickly and it is good practice to limit their vegetative vigour and divert nutrients to the fruits by cutting their apical tips when the stem is two meters long; removing the lateral branches also favours ventilation. Further plant elongation can be achieved by leaving only the two furthest buds coming out from the main stem. Plants are encouraged to further production by regular harvesting of fruits of marketable size. Cucumber plants need support for their growth, which will also provide them with adequate aeration to prevent foliar diseases like powdery mildew and grey mould.

	minimum	minimum optimum	maximumm optimim	maximum
Plant density (plants/m^2)	/	0	3	20
Day temperature (C°)	11	18	26	31
RH (%)	20	60	90	150
PPFD (mol/m^2.day)	1.296	22	30	41
Light Duration (h)	7	17	19	24
Water temperature (C°)	10	17	26	31
Dissolve Oxygen concentration (mg/l)	7	9	/	/
pH aquaponics	5	6.5	7.6	9
pH hydroponics	4	5.5	6.3	7.3
ec aquaponics (µS/cm)	200	600	2000	6000
ec hydroponics (µS/cm)	900	1500	2700	6000
N-NO_3 aquaponics (mg/l)	0	35	/	/
N-NO_3 hydroponics (mg/l)	0	100	/	/
P-PO_4 aquaponics (mg/l)	0	20	/	/
P-PO_4 hydroponics (mg/l)	0	40	/	/
K aquaponicS (mg/l)	0	27	/	/
K hydroponics (mg/l)	0	144	/	/
Na (mg/l)	/	/	120	1725

Figure 57 : Summary of the cucumber parameters used by the Smart Aquaponics Model.

6.8 Aubergine

Aubergine (Solanum melongena) is a greedy crop, thriving at high temperatures (24-33 C°) and requiring a lot of space between each plant(Figure 58 and Figure 59).. Aubergine has high nitrogen and potassium requirements, so careful management choices are required regarding the number of plants to grow in order to avoid nutrient imbalances. It enjoys warm temperatures with full sun exposure. Aubergine plants are highly susceptible to frost.

Figure 58: Auberines at Urban Farmers (The Hague, NL)

The seeds will germinate in 8-10 days in warm temperatures (24-32ºC) and the seedlings can be transplanted in springtime, when temperatures are rising, when they have 4-5 leaves. Towards the end of summer, new blossoms should be pinched off to favour the ripening of existing fruit. Event though plants can be grown without pruning, management of the branches can be facilitated with pruning and the use stakes or vertical strings. The growth time is 90-120 days. Like tomatoes and peppers, in huge greenhouse, aubergines also need to be pollinated by introducing a bumble bee hive to the greenhouse. Harvesting should begin when the fruits are 10-15 cm long, using a sharp knife to cut the fruit from the plant, leaving at least 3 cm of stem attached to the fruit. The skin should be shiny; dull and yellow skin is a sign that the fruit is overripe. Delayed harvest makes the fruits unmarketable owing to the presence of seeds inside. Plants can produce 10-15 fruits for a total yield of 3-7 kilos.

	minimum	minimum optimum	maximumm optimim	maximum
Plant density (plants/m^2)	/	0	3	20
Day temperature (C°)	15.5	24	33	40
RH (%)	20	50	90	150
PPFD (mol/m².day)	1.296	22	30	41
Light Duration (h)	7	17	19	24
Water temperature (C°)	10	17	26	31
Dissolve Oxygen concentration (mg/l)	7	9	/	/
pH aquaponics	5	6.5	7.6	9
pH hydroponics	4	5.3	6.8	7.8
ec aquaponics (µS/cm)	200	600	2000	6000
ec hydroponics (µS/cm)	1300	2300	3800	6000
N-NO_3 aquaponics (mg/l)	0	35	/	/
N-NO_3 hydroponics (mg/l)	0	100	/	/
P-PO_4 aquaponics (mg/l)	0	20	/	/
P-PO_4 hydroponics (mg/l)	0	40	/	/
K aquaponics (mg/l)	0	27	/	/
K hydroponics (mg/l)	0	144	/	/
Na (mg/l)	/	/	120	1725

Figure 59 : Summary of the pepper parameters used by the Smart Aquaponics Model.

7 References

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Abtew, W., & Melesse, A. (2012). Evaporation and evapotranspiration: measurements and estimations. Springer Science & Business Media.

Baxter, I. 2015. Should we treat the ionome as a combination of individual elements, or should we be deriving novel combined traits? Journal of Experimental Botany 66 (8), 2127-2131.

Bhalerao, S.A., Sharma, A.S. & Poojari, A.C. 2015. Toxicity of nickel in plants. International Journal of Pure and Applied Biosciences 3 (2), 345-355.

Bittsanszky, A., Uzinger, N., Gyulai, G., Mathis, A., Junge, R., Villarroel, M., Kotzen B. & Kőmíves, T. 2016. Nutrient supply of plants in aquaponic systems. Ecocycles 2 (2), 17-20.

Boyd, C.E. 2015. Overview of aquaculture feeds: Global impacts of ingredient use. In D.A. Davis (ed.) Feed and Feeding Practices in Aquaculture, pp. 3-25. Woodhead Publishing Series in Food Science, Technology and Nutrition, Sawston.

Bryson, B. 2003. A Short History of Nearly Everything. Doubleday, London.

Burgin, A.J. and Hamilton, S.K. 2007. Have we overemphasized the role of denitrification in aquatic ecosystems? A review of nitrate removal pathways. *Frontiers in Ecology and the Environment* 5 (2), 89-96.

Buzby, K.M. & Lin, L.S. 2014. Scaling aquaponic systems: Balancing plant uptake with fish output. *Aquacultural Engineering* 63, 39-44.

Carruthers, S. (2015). Small-scale aquaponic food production. *Practical Hydroponics and Greenhouses*, (152), 42-46.

Chen, W., He, Z.L., Yang, X.E., Mishra, S. & Stoffella, P.J. 2010. Chlorine nutrition of higher plants: progress and perspectives. Journal of Plant Nutrition 33 (7), 943-952.

Chen, R. F., Liu, T., Rong, H. W., Zhong, H. T., & Wei, C. H. (2021). Effect of organic substances on nutrients recovery by struvite electrochemical precipitation from synthetic anaerobically treated swine wastewater. Membranes, 11(8), 594

da Silva Cerozi, B. & Fitzsimmons, K. 2016. The effect of pH on phosphorus availability and speciation in an aquaponics nutrient solution. Bioresource Technology 219, 778-781.

Da Silva, J.F. & Williams, R.J.P. 2001. The Biological Chemistry of the Elements: The Inorganic Chemistry of Life. Oxford University Press, Oxford.

Davis, P. 2015. Lighting: The Principles. Agriculture and Horticulture Development Board Technical Guide. Davidson, J., Good, C., Barrows, F.T., Welsh, C., Kenney, P.B. & Summerfelt, S.T. 2013. Comparing the effects of feeding a grain-or a fish meal-based diet on water quality, waste production, and rainbow trout Oncorhynchus mykiss performance within low exchange water recirculating aquaculture systems. Aquacultural Engineering 52, 45-57.

Delaide, B., Delhaye, G., Dermience, M., Gott, J., Soyeurt, H. & Jijakli, M.H. 2017. Plant and fish production performance, nutrient mass balances, energy and water use of the PAFF Box, a small-scale aquaponic system. Aquacultural Engineering 78, 130-139.

Drzal, M.S., Keith Cassel, D. & Fonteno, W.C. 1999. Pore fraction analysis: A new tool for substrate testing. Acta Horticulturae 481, 43-54.

Fernandez, D. 2016. HydroBuddy v1.62: The First Free Open Source Hydroponic Nutrient Calculator Program Available Online.

Foucard, P., & Tocqueville, A. (2019). *Aquaponie: associer aquaculture et production végétale*. Quae.

Francis-Floyd, R., Watson, C., Petty, D. & Pouder, D.B. 2009. *Ammonia in Aquatic Systems*. University of Florida, IFAS Extension. Publication #FA 16.

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L.A., Seitzinger, S.P. & Sutton, M.A. 2008. Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. *Science* 320 (5878), 889-892.

Ganguly, A., & Ghosh, S. (2011). A review of ventilation and cooling technologies in agricultural greenhouse application. *Iranian (Iranica) Journal of Energy & Environment*, *2*(1).

Gay, S.W. & Knowlton, K.F. 2009. *Ammonia Emissions and Animal Agriculture*. Virginia Cooperative Extension (VCE) Publications, No. 442-110.

Goddek, S., Delaide, B., Mankasingh, U., Ragnarsdottir, K. V., Jijakli, H., & Thorarinsdottir, R. (2015). Challenges of sustainable and commercial aquaponics. *Sustainability*, *7*(4), 4199-4224.

Goddek, S., Schmautz, Z., Scott, B., Delaide, B., Keesman, K.J., Wuertz, S. & Junge, R. 2016. The effect of anaerobic and aerobic fish sludge supernatant on hydroponic lettuce. *Agronomy* 6 (2), 37.

Godfrey, M. 2018. *How to Minimize Downtime Between Hydroponic Crop Cycles*. Upstart University.

Raviv, M. & Lieth, J.H. 2007. *Soilless Culture: Theory and Practice*. Elsevier.

Graber, A., & Junge, R. 2009. Aquaponic systems: Nutrient recycling from fish wastewater by vegetable production. *Desalination* 246 (1-3), 147-156.

Gruda, N. (2005). Impact of environmental factors on product quality of greenhouse vegetables for fresh consumption. *Critical reviews in plant sciences*, *24*(3), 227-247.

Hu, B.L., Zheng, P., Tang, C.J., Chen, J.W., van der Biezen, E., Zhang, L., Ni, B.J., Jetten, M.S., Yan, J., Yu, H.Q. & Kartal, B. 2010. Identification and quantification of anammox bacteria in eight nitrogen removal reactors. *Water Research* 44 (17), 5014-5020.

Hu, Z., Lee, J.W., Chandran, K., Kim, S., Brotto, A.C. & Khanal, S.K. 2015. Effect of plant species on nitrogen recovery in aquaponics. *Bioresource Technology* 188, 92-98.

Jamaludin, Z., Rollings-Scattergood, S., Lutes, K. & Vaneeckhaute, C. 2018. Evaluation of sustainable scrubbing agents for ammonia recovery from anaerobic digestate. *Bioresource Technology* 270, 596-602.

Jones, C. & Olson-Rutz, K. 2016. *Plant nutrition and soil fertility*. Montana State University Extension, Nutrient Management Module No. 2.

Khemira, H., Sanchez, E., Righetti, T.L. & Azarenko, A.N. 2000. Phytotoxicity of urea and biuret sprays to apple foliage. *Journal of Plant Nutrition* 23 (1), 35-40.

Junge, R., Antenen, N., Villarroel, M., Griessler Bulc, T., Ovca, A., & Milliken, S.(Eds.) (2020). Aquaponics Textbook for Higher Education. Zenodo. http://doi.org/10.5281/zenodo.3948179
Körner, O., Gutzmann, E. & Kledal, P.R. 2014, Modelling the symbiotic effects in aquaponics. European Aquaculture Society conference, Donastia/San Sebastian, Spain, October 2014.
Lee, S. & Lee, J. 2015. Beneficial bacteria and fungi in hydroponic systems: Types and characteristics of food production methods. *Scientia Horticulturae* 195, 206-215.
Lennard, W.A. & Leonard, B.V. 2006. A comparison of three different hydroponic sub-systems (gravel bed, floating and nutrient film texhnique) in an aquaponics test system. Aquaculture International 14 (6), 539-550.Li, Q., Li, X., Tang, B. & Gu, M. 2018. Growth responses and root characteristics of lettuce grown in aeroponics, hydroponics, and substrate culture. Horticulturae 4 (4), 35.
Mattson, N. & Peters, C. 2014. A Recipe for Hydroponic Success. Inside Grower.
Mattson, N. & Krug, B. 2015. Identifying Boron Deficiency and Corrective/Preventative Actions. Cornell University Cooperative Extension/University of New Hampshire Cooperative Extension.
Maucieri, C., Nicoletto, C., Junge, R., Schmautz, Z., Sambo, P. & Borin, M. 2018. Hydroponic systems and water management in aquaponics: A review. *Italian Journal of Agronomy* 13: 1012.
Montanhini Neto, R. & Ostrensky, A. 2015. Nutrient load estimation in the waste of Nile tilapia *Oreochromis niloticus* (L.) reared in cages in tropical climate conditions. *Aquaculture Research* 46 (6), 1309-1322.
Nozzi, V., Graber, A., Schmautz, Z., Mathis, A., & Junge, R. (2018). Nutrient management in aquaponics: comparison of three approaches for cultivating lettuce, mint and mushroom herb. *Agronomy*, *8*(3), 27.
Pantanella, E. 2012. *Aquaponic System Design Parameters: Basic System Water Chemistry.* Aquaponic Solutions.
Pantanella, E., Cardarelli, M. & Colla, G. 2012. Yields and nutrient uptake from three aquaponics sub-systems (floating, NFT and substrate) under two different protein diets. World Aquaculture Society Meeting, Prague, 1-5 Sept 2012.
Polacco, J.C., Mazzafera, P. & Tezotto, T. 2013. Opinion–nickel and urease in plants: still many knowledge gaps. *Plant Science* 199, 79-90.
Pratt, C.W. & Cornely, K. 2014. *Essential Biochemistry* (3rd edition). John Wiley and Sons Inc., MA.
Resh, H.M. 2013. *Hydroponic Food Production: A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower*. CRC Press, Boca Raton.
Raviv, M., Wallach, R., Silber, A. & Bar-Tal, A. 2002. Substrates and their analysis. In Passam, H. & Savvas, D. (eds.) *Hydroponic*
Resh, H.M. 2013. *Hydroponic Food Production: A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower* (7th edition). Newconcept Press, Mahwah, SA.
Roosta, H.R. & Hamidpour, M. 2011. Effects of foliar application of some macro-and micro-nutrients on tomato plants in aquaponic and hydroponic systems. *Scientia Horticulturae* 129 (3), 396-402.
Roques, S., Kendall, S., Smith, K., Newell Price, P. & Berry, P. 2013. *A review of the non-NPKS nutrient requirements of UK cereals and oilseed rape*. Research Review No. 78. HGCA, Kenilworth.
Rorabaugh, P.A. 2015. *Introduction to Controlled Environment Agriculture and Hydroponics*. Controlled Environment Agriculture Center, University of Arizona, Tucson.Singh, H. & Dunn, B. 2017. *Pruning Hydroponic Crops*. Oklahoma Cooperative Extension Service.
Sato, S., Peet, M. M., & Gardner, R. G. (2004). Altered flower retention and developmental patterns in nine tomato cultivars under elevated temperature. *Scientia Horticulturae*, *101*(1-2), 95-101.
Shamshiri, R. R., Jones, J. W., Thorp, K. R., Ahmad, D., Man, H. C., & Taheri, S. (2018). Review of optimum temperature, humidity, and vapour pressure deficit for microclimate evaluation and control in greenhouse cultivation of tomato: a review. *International agrophysics*, *32*(2), 287-302.
Schachtman, D.P., Reid, R.J. & Ayling, S.M. 1998. Phosphorus uptake by plants: from soil to cell. *Plant Physiology* 116 (2), 447-453.
Schmautz, Z., Loeu, F., Liebisch, F., Graber, A., Mathis, A., Bulc, T.G. & Junge, R. 2016. Tomato productivity and quality in aquaponics: Comparison of three hydroponic methods. *Water* 8 (11), 533.
Schneider, O., Sereti, V., Eding, E.H. & Verreth, J.A.J. 2005. Analysis of nutrient flows in integrated intensive aquaculture systems. *Aquacultural Engineering* 32 (3-4), 379-401.
Seawright, D.E., Stickney, R.R. & Walker, R.B. 1998. Nutrient dynamics in integrated aquaculture–hydroponics systems. *Aquaculture* 160, 215–237.
Somerville, C. et al. 2014a. Plants in aquaponics. In Somerville, C., Cohen, M., Pantanella, E., Stankus, A. & Lovatelli, A. *Small-Scale Aquaponic Food Production – Integrated Fish and Plant Farming*. FAO Fisheries and Aquaculture Technical Paper No. 589. Food and Agriculture Organization of the United Nations, Rome, pp. 83-102.
Somerville et al. 2014b. Design of aquaponics units. In Somerville, C., Cohen, M., Pantanella, E., Stankus, A. & Lovatelli, A. *Small-Scale Aquaponic Food Production – Integrated Fish and Plant Farming*. FAO Fisheries and Aquaculture Technical Paper No. 589. Food and Agriculture Organization of the United Nations, Rome, pp. 35-74.
Somerville, C. et al. 2014b Management and troubleshooting. In Somerville, C., Cohen, M., Pantanella, E., Stankus, A. & Lovatelli, A. *Small-Scale Aquaponic Food Production – Integrated Fishand Plant Farming*. FAO Fisheries and Aquaculture Technical Paper No. 589. Food and Agriculture Organization of the United Nations, Rome, pp. 123-139.
Somerville et al. 2014c. Appendix 1 – Vegetable production guidelines for 12 common aquaponics plants. In Somerville, C., Cohen, M., Pantanella, E., Stankus, A. & Lovatelli, A. *Small-Scale Aquaponic Food Production – Integrated Fish and Plant Farming*. FAO Fisheries and Aquaculture Technical Paper No. 589. Food and Agriculture Organization of the United Nations, Rome, pp. 169-181.
Somerville et al. 2015a. Additional topics on aquaponics. In Somerville, C., Cohen, M., Pantanella, E., Stankus, A. & Lovatelli, A. *Small-Scale Aquaponic Food Production – Integrated Fish and Plant Farming*. FAO Fisheries and Aquaculture Technical Paper No. 589. Food and Agriculture Organization of the United Nations, Rome, pp. 141-155.
Sonneveld, C. & Voogt, W. 2009. *Plant Nutrition of Greenhouse Crops*. Springer, Springer Netherlands.
Stalport, B., 2017. Modélisation et développement d'un système aquaponique avec surveillance métrologique pour l'étude du cycle de l'azote.Sterner, R.W. & Elser, J.J. 2002. *Ecological Stoichiometry: The Biology of Elements from Molecules to the Biosphere*. Princeton University Press.
Storey, A. 2016a. *Best Conditions and Methods for Growing Parsley in Hydroponics*. Upstart University.
Storey, A. 2016b. *Everything You Need to Know About Growing Chard Without Soil.* Upstart University.

Storey, A. 2016c. *Farmer Tip #1 – How to Make a Planting Schedule*. Upstart University.
Storey, A. 2016d. *Get the Scoop on How to Grow Fennel in Hydroponics*. Upstart University.
Storey, A. 2016e. *Growing or Selling Basil? Read this First.* Upstart University.
Storey, A. 2016f. *Harvesting and Handling Lettuce for a Longer Shelf Life*. Upstart University.
Storey, A. 2016g. *Get the Tips and Guidelines on Growing Mustard Greens*. Upstart University.
Storey, A. 2016h. *Growing Oregano in Hydroponics? Read This First!* Upstart University.
Storey, A. 2016i. *Here's What You Need to Know About Growing Bok Choy in Hydroponics.* Upstart University.
Storey, A. 2016j. *How to Grow Classic Rosemary in Hydroponics.* Upstart University.
Storey, A. 2016k. *How to Grow Hydroponic Cabbage: The Beginner's Guide.* Upstart University.
Storey, A. 2016l. *How to Grow Hydroponic Strawberries*. Upstart University.
Storey, A. 2016m. *How to Grow Mint in Hydroponics – All You Need to Know*. Upstart University.
Storey, A. 2016n. *So You Want to Grow Chives? Read this First!* Upstart University.
Storey, A. 2016o. *10 Tips for Farmers on the Post-harvest Care of Herbs*. Bright Agrotech.
Storey, A. 2016p. *The Beginner's Guide to Growing Kale in Hydroponics*. Upstart University.
Storey, A. 2017a. *Are You Growing Cilantro in Hydroponics? Read This First!* Upstart University.
Storey, A. 2017b. *Everything You Need to Know About Growing Nasturtiums in Hydroponics*. Upstart University.
Storey, A. 2017c. *The Beginner's Guide to Hydroponic Tomatoes*. Upstart University.
Storey, N. 2018. Why You Need to Be Careful About Zinc in Aquaponics. Upstart University.
Strauch, S., Wenzel, L., Bischoff, A., Dellwig, O., Klein, J., Schüch, A., Wasenitz, B. and Palm, H. 2018. Commercial African catfish (Clarias gariepinus) recirculating aquaculture systems: Assessment of element and energy pathways with special focus on the phosphorus cycle. Sustainability 10 (6), 1805.
Strous, M., Fuerst, J.A., Kramer, E.H., Logemann, S., Muyzer, G., van de Pas-Schoonen, K.T., Webb, R., Kuenen, J.G. & Jetten, M.S. 1999. Missing lithotroph identified as new planctomycete. Nature 400 (6743), 446.
Tacon, A.G. & Metian, M. 2008. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects. Aquaculture 285 (1-4), 146-158.
Thorarinsdottir, R. (ed.) 2015. Aquaponic Guidelines. EU Lifelong Learning Programme.
Treadwell, D., Taber, S., Tyson, R. & Simonne, E. 2010. Foliar-applied micronutrients in aquaponics: A guide to use and sourcing. University of Florida IFAS Extension, HS1163.
Valdez, J. 2017a. The Best Plants for Bato Buckets. Upstart University.
Valdez, J. 2017b. The Best Plants for Raft Systems (DWC). Upstart University.
Winogradsky, S. 1892. Contributions à la morphologie des organismes de la nitrification. Arch. Sci. Biol. 1, 87–137.
Wongkiew, S., Hu, Z., Chandran, K., Lee, J.W. & Khanal, S.K. 2017. Nitrogen transformations in aquaponic systems: A review. Aquacultural Engineering 76, 9-19.
Yang, H., Menz, J., Häussermann, I., Benz, M., Fujiwara, T. & Ludewig, U. 2015. High and low affinity urea root uptake: involvement of NIP5; 1. *Plant and Cell Physiology* 56 (8), 1588-1597.
Yavuzcan Yildiz, H., Robaina, L., Pirhonen, J., Mente, E., Domínguez, D. & Parisi, G. 2017. Fish welfare in aquaponic systems: its relation to water quality with an emphasis on feed and faeces—a review. *Water* 9 (1), 13.
Yogev, U., Barnes, A. & Gross, A. 2016. Nutrients and energy balance analysis for a conceptual model of a three loops off grid, aquaponics. *Water* 8 (12), 589.
Zou, Y., Hu, Z., Zhang, J., Xie, H., Liang, S., Wang, J. & Yan, R. 2016. Attempts to improve nitrogen utilization efficiency of aquaponics through nitrifies addition and filler gradation. *Environmental Science and Pollution Research* 23 (7), 6671-6679.

Website resource:

https://www.flickr.com/photos/145301455@N07/29979758460, last visit: 20/08/2021

https://richel-group.com/produits/cooling/, last visit: 21/11/2022

http://www.soda-pro.com, last visit: 24/10/2020

https://www.nosoilsolutions.com, last visit: 07/11/2022