



ROOT GROWTH CONDITIONS IN GREENWALL

Test method development and experiment conduction

Tommi Granroth

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TAMPEREEN AMMATTIKORKEAKOULU
Tampere University of Applied Sciences

ABSTRACT

Tampereen ammattikorkeakoulu
Tampere University of Applied Sciences
Environmental Engineering
Environmental Management

TOMMI GRANROTH:
Root Growth Conditions in Greenwall
Test Method Development and Experiment Conduction

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The final thesis was a process and product development work done for NaturVention Oy. The aim of the thesis was to develop and validate a testing method for optimizing root growth conditions in a greenwall, and to provide relevant information of the effects of the chosen factors influencing the root growth. A set of testing equipment was designed and built to simulate the growing conditions in a NaturVention's Naava -series greenwall. Two 3-4 weeks test periods were conducted during spring 2015, using Heart leaf philodendron due to it being considered as the most suitable species for the experiment. Root growth was measured by manually calculating the roots before and after the test periods.

The results of both test periods were thoroughly corrupted by root rot. Hence, profound data analysis could not be carried out and the test method could not be fully validated. However, based on the experiences gathered during the final thesis process the test method and test equipment can be developed to be more functional and reliable concerning further use.

The final thesis consists of a theory section, a section describing the conduction of the entire process, a section presenting the results, and a conclusive section where the process and results are discussed in detail and development suggestions are presented. Appendices and the contents of chapters 3 and 4 presenting the materials, methods and results are regarded as confidential information.

Key words: Root growth, greenwall, root rot, NaturVention Oy

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ABBREVIATIONS AND TERMS

CRI	A quantitative measure that expresses the ability of a light source to reveal colours in comparison to ideal light source
EC	Electric conductivity is used for measuring the amount of salts, <i>e.g.</i> nutrient amounts in a solution
Humidity	Relative humidity is the amount of water in the air compared to the theoretical maximum amount
Module	Three identical test devices that were used in this experiment and are referred to as modules (M1-3)
NASA	The National Aeronautics and Space Administration, United States government agency responsible for the civilian space program, aeronautics and aerospace research
PAR	Photosynthetically active radiation, spectral range of solar radiation that can be used in photosynthesis
pH	Potent hydrogen is the negative logarithm of the activity of a solvated hydrogen ion, in chemistry it is a measure of acidity or alkalinity
TAMK	Tampere University of Applied Sciences
Unit	A section of a module, holding 6 pots (24 seedlings), subjected to a selected combination of parameters under investigation, referred as U1-9

1 INTRODUCTION

Final thesis was a process development work for NaturVention Oy which is a young but swiftly growing player in clean tech field (Sitra News 2014), situated in Jyväskylä, Finland. Currently NaturVention employs over twenty people. They produce green walls *i.e.* vertical closed-circle hydroponic plant growing devices that function as an indoor air purifier utilizing patented Naturbo™ technology. Their main products are called Naava Original and Naava Smart that are sold worldwide (NaturVention 2014).

The aim of the thesis was to improve the efficiency of the Naava -series during a certain time period. NaturVention uses a certain set of parameters for light, air circulation and nutrients in order to maximize the root growth extent in the first few weeks period after the seedling plants are placed into the greenwall. These factors were studied experimentally at TAMK Energy and Environmental Engineering laboratories during spring and summer 2015 by simulating the conditions of the Naava -device in separate test devices. The testing equipment was designed and built for the purpose during spring 2015. The use of separate test devices enabled simultaneous comparison of more parameters than it would have been possible with actual Naava -devices. Root growth was measured by manually calculating the roots before and after the test periods.

Another aim was to validate the testing method itself. The method and devices were innovated based on NaturVention's experience and knowledge. However, it was unknown how well the testing method would work and what kind of results the experiment could provide. In any case the final thesis would provide valuable information to the company: Increasing the root growth potential by applying the results of the experiment to the Naava -series production, thus enhancing the efficiency of the process, could potentially have a positive financial effect for the company. The author, on the other hand, gained first-hand experience of vertical hydroponic systems, plant behaviour and conducting experimental research.

Many synergic factors affect to the growth of plants in general, regardless of the growing method. In this experiment the factors under investigation were limited to the three most interesting for the company: air circulation, light and nutrients. The parameter combinations selected for the experiment, do not cover all possible combinations, and consequently all possible outcomes, but it was estimated by the company and the author

that the chosen selection would provide sufficient amount of information in respect to the aim of the work. Combinations and parameter levels were chosen according to the company's knowledge and needs, and to some extent according to the technical requirements discovered during the experiment.

The final thesis begins with a presentation of the theoretical background where indoor air purification and hydroponics are discussed on a general level, Heart leaf philodendron and the Naava -series greenwall are presented and factors affecting root growth are discussed in detail. The completion of the entire process - the designing phase and carrying out of the test periods - is presented in chapter 3, where also the test equipment and arrangement as well as measurement methods are presented. The results of the root growth and the measurement results of the observed environmental factors are presented in chapter 4. The outcomes and causalities of the process are discussed in detail in chapter 5, where also a thorough error evaluation section is included. Most of the pictures included in the final thesis are presented in the appendices due to the extent of the material.

2 THEORY

In this chapter subjects considered most relevant for this thesis are presented in more or less detail and mostly from a technical viewpoint. Some interesting subjects, for example the function of roots from a biological perspective, were left out in order to limit the length of the thesis.

2.1 Indoor air purification

We spend most of our time indoors, according to Hussein, Paasonen and Kulmala (2012, 289–292) up to 90% of our time. Thus the quality of indoor air is a significant factor for our well-being. Indoor plants are able to effectively purify indoor air (*e.g.* Sinha 2010; Wolverton, Johnson & Bounds 1989; Wolverton 2008).

Impurities in indoor air can be classified according to their source, such as smoking, construction materials and micro toxins, or by their physical or chemical properties, such as fine particles, hydrocarbons and phthalates. Impurities can be categorized as particle-like compounds, gaseous compounds, and semi-volatile compounds in addition to (particle-like or volatile) metabolites of microbes present in water damaged structures. Exposure sources are diverse. Prevalence and potential harmfulness of exposure ranges also greatly varies. (Tuomisto 2005, 181-183)

Chemical impurities of indoor air originate both from the outside and the inside of the given space. Benzene (C_6H_6), for example, originates from traffic fumes. Indoor sources are numerous, such as construction and interior materials, detergents, clothes, utility items and humans themselves. Chemical impurities in air occur as volatile organic compounds (VOC), as semi-volatile organic compounds (SVOC) or attached to particles. Examples of potentially harmful VOC's are trichloroethylene (C_2HCl_3), aromatic compounds, halogenated hydrocarbons, alcohols, aldehydes, ketones, esters and ethers. (*Ibid.*) Formaldehyde (CH_2O) was previously considered a significant factor in indoor air problems but today it is rarely an issue (Seuri&Palomäki 2000, 45-46).

Ventilation solutions are supposed to prevent exposure to impurities but in practise this rarely happens. Hard scientific evidence and research concerning the sources, amounts and distribution of indoor air impurities is far too scarce, even though the problem is

widely acknowledged. Individual studies concerning effects of some specific compound in large amounts have been concluded, but the more significant question is the long-term effects of exposure to small doses as well as effects of combined exposure to chemical assortment. (*Ibid.*)

2.2 Hydroponic gardening

According to Encyclopaedia Britannica's definition hydroponics means the cultivation of plants in nutrient-enriched water, with or without the mechanical support of an inert medium such as sand or gravel (Britannica 2013). Soilless cultivation has been practiced for thousands of years, and its importance for food production etc. has increased during recent decades due to the demands of urbanization as well as possibilities created by technological development (Raviv & Lieth 2008, 1-6.).

Hydroponic cultivation can be arranged vertically or horizontally. The most common hydroponic cultivation methods are the drip feed technique and the nutrient film technique (NFT). Furthermore, hydroponic methods are generally divided into two types, passive and active, depending on how the irrigation and nutrient uptake is arranged. The nutrient solution is dispersed to plant clusters by an irrigation system, either directly to the roots or into a growing media. Passive methods are common in modern greenhouse food production, where plant rafts are flown on a still nutrient-enriched water bed, passively absorbing the solution. In active methods the desired amount of nutrient-enriched water is circulated through the system, usually by a pump, in a set interval. (Koivunen 2003, 132.)

2.2.1 Naava Original

The test devices designed for the thesis project are based on NaturVention's Naava Original –greenwall, which represents a technically advanced hydroponic system. The company refers to their innovative method, which combines hydroponic and aeroponic cultivation methods, as *turboponic* (NaturVention2014).



PICTURE 1. Naava Original. (NaturVention2014)

NaturVention's Naava Original, presented in picture 1, is a vertical garden unit which main purpose is indoor air purification. Its efficiency is achieved through a patented Naturbo™ technology that is based on NASA's research of active hydroponics since the 1970's. In addition to this it can be considered a decorative element. Naava Original utilizes a closed circle hydroponic cultivation method, which means that the irrigation water is pumped up from a water tank (110 litres in volume, placed on the bottom section of the system) via a pipeline and distributed by a spreader to drip through the roots of the plants and back to the tank. The plants are placed in pots that are specifically designed for this method. Plants are grown in a pH-buffered inorganic media. Naava Original's outside measures are 220 cm x 105 x 45 cm. (NaturVention 2014.)

One Naava Original habits 63 plants. It is capable of processing the air of a 100 m² room. Consequently, as the area of the room decreases the efficiency increases. In order to maintain the efficiency of the Naava Original in changing conditions, for example change

of season or placement of the Naava Original, its functions are controlled remotely by NaturboOST™ technology and adjusted automatically 24/7. (NaturVention 2014.)

The key element in NaturVention's Naava -series system, *i.e.* in Naturbo™ technology, is a natural active biological process of the microbes habiting the roots of the plants placed into the wall. Microbes break down harmful compounds from indoor air that is circulated through the system and back to the room by air fans, as presented in figure 1.

According to the company's description the air is *naturalized* and humidity increased, contrary to artificial indoor air treatment processes. Naturbo™ technology's advantage compared to other indoor air purification methods is that the microbe population is able to adjust to any given microclimate and to use chemicals present in that specific space for nutrition. It takes approximately two to eight weeks from the moment of placing the plants into the Naava Original for the process to fully activate (*Ibid.*) which is the time-frame this thesis is concentrating on.



FIGURE 1. Indoor air is circulated through the roots of the plants and back to the room. (NaturVention 2014)

A new product called Naava Smart was launched in spring 2015 during the thesis process. It follows the same operational principles as Naava Original, although it is equipped with more hi-tech solutions regarding long-distance monitoring and settings regulation

(NaturVention 2014). In order to avoid any misunderstanding especially regarding reference material, it is worth mentioning that NaturVention rebranded their products and as a part of that changed the name of the product in March 2015 from FreshWall Original to Naava Original. These are *de facto* the same product and the latter name is used throughout this paper.

2.3 Factors affecting the plant growth

Regardless of the technique used to grow plants, grown in soil or soilless manner, they always follow the same principle of existence: Plants require light, carbon dioxide (CO₂), nutrients and water to grow. Photosynthesis is the process by which green plants transform solar energy into chemical energy. Plants use energy from light to convert carbon dioxide, water (H₂O) and minerals into oxygen (O₂) and energy-rich organic compounds, such as sugar (C₆H₁₂O₆). (Britannica 2012.)

2.3.1 Relevance of lightning

Different species of plants need different amounts and different sequences of light. Additional lighting prolongs the natural day time increasing the time for photosynthesis thus enhancing the growth. Luminous exposure is possible to extend throughout the day, but in general at least a few hours dark period is suggested. During the dark hours the plant is able to transfer the photosynthetic products from the leaves to other parts, such as roots. (Britannica 2012.)

The wavelength of the light source affects the intensity of the photosynthesis, even more so than the amount of light. Photosynthetically active radiation (PAR) which is required for abling the phenomenon and usable for the chlorophylls, is roughly in the range of 400-700 nm. Blue (~450-500 nm) and red (~650-700 nm) parts of the the spectrum are more easily absorbed than green and yellow (*Ibid.*), as presented in figure 2.

Wavelength ranges of light sources can be compared by a standard defined by the colour temperature expressed in Kelvin degrees. Colour temperature is a property of light visible to the human eye. It refers to the surface temperature of an ideal black body which emits

light corresponding to the light observed. Many light sources, such as fluorescent lights, do not emit light primarily by thermal radiation processes. Correlated colour temperature (CCT) is applied in this case meaning that the colour temperature is adapted to human colour perception. Colour temperatures over 5000 K (blue, white) are commonly called cool colours, whereas lower colour temperatures around 3000 K (yellow, red) are called warm colours. However, the more the actual wavelength spectrum of a given light source diverges from the normal distribution, less informative the given Kelvin number is. (Wyszecki 1982, 224-229.)

For the plant it is essential how much of the light energy they are able to transform into chemical energy. Green plants absorb the blue and red wavelength spectrum the best and reflect the green light back – which is why the plants can be seen green. The red and blue wavelength spectrum ranges are utilized in lighting solutions for plant cultivation in greenhouses. Blue light accelerates the basic growth of the plant, for example making the stem of the plant thicker, and red light promotes blossoming and fruit formation. (Britannica 2012.)

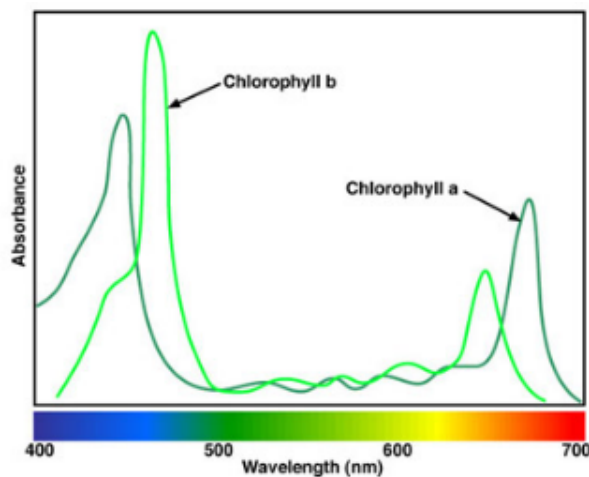


FIGURE 2. Wavelength of light vs. absorbance of the chlorophylls (Tropical fish keeping 2012).

The need of light for a plant is dependant of species and development stage. A few examples are given in irradiance units for the sake of understanding the scale: the light gazing from stars, 0.1 W/m^2 , is enough for seeds to germinate, whereas photosynthesis generally requires $100\text{-}1000 \text{ W/m}^2$. In addition to natural light, powerful sources of light such as high pressure sodium lamps and metal-halide lamps are used in modern

greenhouse production with installed capacity of 40 – 200 W/m² in Finland. (Koivunen 2003.)

The spectral distributions of the two different type of fluorescent lights used in this experiment are presented in figures 3 and 4. According to the product information given by the manufacturer Osram has a color temperature of 6500 K and a colour rendering index (CRI) over 80, where LifeLite has 5800 K and CRI of 96 respectively. (Osram 2015; Sunny LifeLite 2012.)

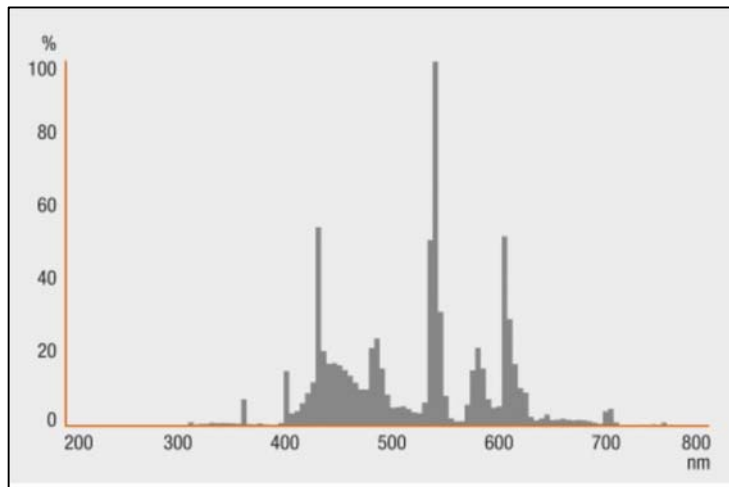


FIGURE 3. Osram Lumilux HE 21W/865 Cool daylight fluorescent lamp spectral distribution. (Osram 2015)

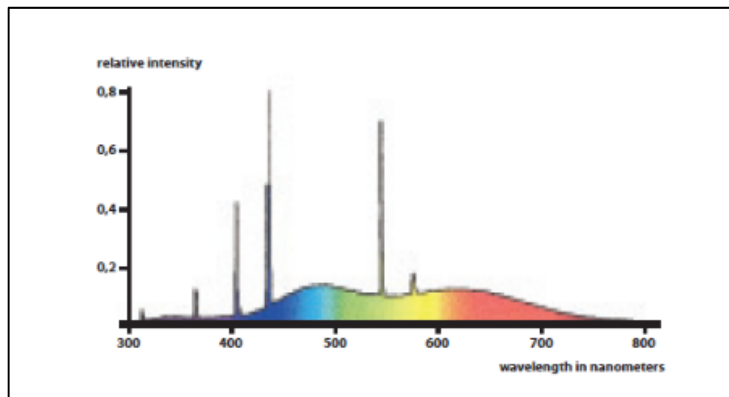


FIGURE 4. Sunny LifeLite Full Spectrum Daylight fluorescent lamp spectral distribution. (Sunny LifeLite 2012)

Several units are used for measuring illumination. The most commonly used are 1) candela (cd) that is the SI base unit of luminous intensity i.e. the emitted light to a certain direction, being approximately the amount of light emitted by a common candle, 2) lumen

(lm) that is SI derived unit of the luminous flux i.e. the total amount of emitted light and 3) lux (lx) that is the SI derived unit of luminance and luminous emitting, measuring luminous flux (lumens) per square meter. (Ryer 1997.)

Due to the differences in wavelength spectrum and efficiency of different lamps, all mentioned units are more or less inadequate measures taking the actual needs of plants into account. For example lux and cd are weighted measurements that approximate the human eye response, and thus overweight wavelengths of 550-600 nm and underweight wavelengths below 500 nm and above 650 nm. These measurements are, nevertheless, the ones by which lightning solutions are usually concerned. PAR measurements, on the other hand, are by far the best when green plants are in question. Quantum sensors, *i.e.* PAR-meters, are specifically designed for use by the horticulture industry. PAR, or Quantum, is usually expressed in Photosynthetic Photon Flux (PPF). The unit of the PPF being $\mu\text{mol m}^{-2} \text{s}^{-1}$. (Apogee Instruments 2015.)

2.3.2 Relevance of nutrients

Plants grown in a soilless manner require nutrient input in order for them to be able to intake nutrients normally found in the soil. Plants absorb numerous elements through their roots. Over 50 different elements have been discovered from various plants, but only 20 of these elements are considered essential, *i.e.* the ones that are required for the normal life cycle of a green plant and that cannot be replaced by another element. Essential elements are exclusively inorganic and are usually classified as macro- and micronutrients. (Raviv & Lieth 2008, 292-294.)

Macronutrients are required in larger amounts; carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), calcium (Ca), sulphur (S), potassium (K) and magnesium (Mg). Micronutrients are required in smaller amounts; for example chlorine (Cl), iron (Fe), manganese (Mn), boron (B), zinc (Zn), copper (Cu), sodium (Na) and selenium (Se). Silicon (Si) is not considered an essential but has a significant role in the resistance to stress and some diseases. (*Ibid.*)

The essential nutrients are absorbed by the roots, except for carbon and oxygen that are predominantly absorbed from the air by the canopy. Carbon is also absorbed by the roots in form of HCO_3^- and oxygen is also absorbed as gaseous O_2 and with hydrogen

molecules. Most of the nutrients absorbed by the roots are taken up as cations and anions (concerning nitrogen in both forms; NH_4^+ and NO_3^-). Nutrient solutions are composed of mineral salts, acids and bases. (*Ibid.*)

2.3.3 Relevance of air circulation

Plants are able to move the surrounding air by their natural ability to evaporate water through the stomas on leaf surface. Air currents occur when the temperature difference between the surrounding air and the leaf is significant and the plant evaporates. Water is transferred swiftly from the growing media towards the upper parts of the plant and air sinks down to the root area, thus increasing the amount of oxygen and nitrogen, as well as any compounds present in the air mass, for the roots to utilize. (Wolverton 2008, 16-17.)

The roots of the plants are able to remove harmful compounds from indoor air, as stated in chapter 2.1, and the ability to move air is important in this respect also. Especially in automatically air conditioned spaces the humidity of the air is low, but the evaporation of plants helps the air with its impurities to sink to the root level, where microbes break down and utilize them (*Ibid.*). This process can be accelerated by applying air fans to suck the influent air through the plant *i.e.* the growing media, and push the effluent air back into the room. Several studies have indicated that for example VOC removal is efficient in bio filter systems where air is circulated through growing media consisting of inorganic compounds and microbes. (*e.g.* Wolverton *et.al.* 1984; Wolverton *et.al.* 1989; Orwell *et.al.* 2004; Kesselmeier & Staudt 1999; Orwell *et.al.* 2006; Wood *et.al.* 2006.)

The optimal level of air circulation is completely case-specific. For example temperature, irrigation conduct and irrigation sequence affect to evaporation rate, hence the air circulation should be set in respect to those factors. Llewelyn, Darlington and Dixon have studied specifically the role of air circulation and temperature within a system with very similar operating principles as in NaturVention's system. Factors were studied in respect to VOC removal efficiency etc. They have reached the conclusion that the air flow should be as high as possible without causing any undesired side-effects, such as additional cost of dehumidifying the effluent stream (2002).

2.3.4 Electric conductivity, acidity, temperature and humidity

The acidity (pH) level usually considered optimal for hydroponics is around 6.5 because a slightly acidic solution is best for nutrients to dissolve into water. Concerning NaturVention's purposes, optimum pH range is a bit wider, from 6 to 7.5, although the low end of the range, 6.2-7, is most suitable for the inorganic growing medium. However, the nutrients used are pH-buffered, meaning that they help to keep the pH closer to the optimum pH range of plants since tap water is usually a bit alkaline. (NaturVention, undated.)

Electric conductivity (EC) is a suitable method in determining fertilizer solution strength i.e. nutrient levels when applied in hydroponics, where the environment is quite easily controlled. The higher the EC is the more there are nutrients (salts) present in the irrigation water (Practical Hydroponics & Greenhouses 2013). The EC unit commonly used is either mS/cm or μ S/cm.

In general most plants are grown in between 18-24 °C temperature. Small changes around plant-specific optimum are not dangerous, and most plants enjoy lower temperatures at night time. Hot or cold air flows are, however, detrimental. The humidity of the air is important for the plants well-being. Ideal relative humidity is 35-60%, for both human and plants. Humidity of the air is dependent on the temperature of the surrounding air; the higher the temperature, the faster the relative humidity decreases. Plants are natural air humidifiers; the dryer the surrounding air, the more the plants evaporate. (Wolwerton2008, 30-31.)

2.3.5 Root rot

Root rot is usually caused by *Pythium*, which is a root-parasitic fungus. It is a common problem in agriculture in general and especially in hydroponics. It lives in air and water, hence the sources of contamination are numerous and difficult to trace. Under favorable conditions; high moisture levels, temperature between 20 and 30 °C, poor oxygenation of the water and high pH levels; *Pythium* spreads very fast and can be extremely destructive. *Pythium* can be described as a "secondary infection", because it only attacks already damaged (sick or wounded tissues) plants or plants in poor growing conditions. It

liberates microscopic spores that infect the roots and deprive the plant of nutrition. Seeds and seedlings are most prone to be attacked, larger plants are more resistant. (Kehdi, undated.)

Pythium attack causes seedlings to get soggy stems and collapse. Leaves wilt, turn yellow and curl downwards. These clear signs of the plants ill-being may easily be mixed with nutrient deficiency symptoms. On root level the infection starts at the tip of the root slowly disintegrating root hairs and the fine lateral roots which are critical for nutrient uptake. Healthy white roots turn brown and finally black. The lower portion of the stem can turn slimy and black if the infection is severe. (*Ibid.*) Examples of healthy and rotted roots of a Heart leaf are presented in pictures 2 and 3.



PICTURE 2. Healthy roots of a Heart leaf seedling.



PICTURE 3. A complete root rot destruction; even the tip of the stem has turned black.

The most effective way to tackle root rot is to prevent it. Healthy plants are able to resist the infection. Concerning hydroponics, the following elements are required to keep the plants healthy: A clean environment and clean equipment, good water quality, optimal oxygenation of the nutritive solution, good ventilation, adequately drained substrate, adequate temperature and humidity levels and suitable fertilizer programs. Active measures for fungi prevention include wetting agents and chlorination of the nutritive solution, UV light, hydrogen peroxide and ozone. These methods may, however, interfere with the nutritional balance. Or, as for example in case of adding hydrogen peroxide to irrigation water, destroy all microbes including those that are favorable. (*Ibid.*)

2.4 Heart leaf philodendron

NaturVention uses many different species of plants in their greenwalls. Heart leaf philodendron (*Philodendron scandens*, also known as the Sweetheart plant, “herttaköynnösvehka” in Finnish) is presented in picture 4. Heart leaf was chosen by the company to be used in this experiment due to its suitable properties; mainly the shape and the manner of its root growth. The roots of the Heart leaf (presented previously in picture 2) are somewhat thick, grow strong and mainly in length and produce cross-sections in an easily observable manner (Järvinen 2015).

Philodendron includes hundreds of species of herbs and climbers originating from tropical America. Many species of *Philodendron* are commercially exploited, Heart leaf being one of the most popular amongst them. Heart leaf is fast to grow and a climber by its growing manner, although it is easy to restrain its growth in length by simply pinching it shorter. It is common to place several cuttings into a common pot in order to make the appearance of the plant more luscious. (Koti kukkii 1981, 278-280.)

The ideal temperature for the Heart leaf is 16-21 °C. The temperature should never drop under 13 °C or rise above 24 °C. Too moist or cold growing conditions might cause root rot. Shadowy light conditions are well suited for it. (Wolverton 2008, 90.)

It is considered an especially well suited species for indoor air quality improvement and also suitable for hydroponic cultivation. When comparing plant species suitable for this

use, Wolverton gives Heart leaf a general grade of 6.3 (on a scale of 1-10) in terms of combined efficiency of chemical gas removal, easiness of care, pest tolerance and moisture evaporation. (*Ibid.*) However arbitrary this sort of grade might seem, it is given by one of the most distinguished researcher in this field, thus is worth mentioning.



PICTURE 4. Vivid Heart leaf specimen placed on a stool.

3 MATERIALS AND METHODS (CONFIDENTIAL)

Contents of this chapter are ruled confidential and removed as a whole from the published version of the final thesis.

3.1 Test devices

3.2 Test arrangement

3.3 Procedure

3.3.1 Preparatory work

Design phase

Setup phase

During the test periods

3.3.2 Planting of the seedlings

3.3.3 Adjustment of the parameters

Airflow intensity and irrigation sequences

Lighting

Nutrients

3.4 Measurement methods

3.4.1 Electric conductivity, acidity, temperature and humidity

3.4.2 Root growth

4 RESULTS (CONFIDENTIAL)

Contents of this chapter are ruled confidential and removed as a whole from the published version of the final thesis.

4.1 Electric conductivity, acidity, temperature and humidity

4.2 Root growth

5 CONCLUSIONS AND DISCUSSION

As the case often is in research and development projects, several adversities of mostly technical (but also humane) nature were encountered and are discussed in more detail in chapter 5.1. Some of these setbacks might have been enough to corrupt the data on their own, but were undone by the arch enemy of hydroponic cultivation: root rot. Root-parasitic fungus *Pythium* thoroughly contaminated practically all plants for both test periods leaving both qualitative and quantitative comparison and analysis of the root growth results, *i.e.* the effects of different parameter values and combinations, somewhat irrelevant and too prone to misinterpretation. Consequently, validation of the test method remains ambiguous; without successful completion of a test period in respect to valid results it cannot be downright assured that the method works.

The test arrangement was perhaps a bit ambitious; taking into account the synergic ways the plants are affected as living entities, limiting the number of potential cross-effects of factors and their parameters could benefit and simplify the interpretation of the results, when valid for interpretation. On the other hand, the test arrangement and devices were specifically designed to gain as much data as possible *at the same time*. Concerning further research this aspect of test arrangements should be taken into consideration. Test devices have their benefits, but using actual Naava devices would undoubtedly be more reliable. Nevertheless, all flaws of the test devices rest upon the designers' shoulders; devices worked as well as they were designed to.

The methods for measuring the root growth were experimental. There was no previous experience, at least in this scale, or known (specific) references for the methods validity. Manually calculating the roots proved to be difficult and, to some extent, prone to humane inaccuracy. However, according to the author's experience and assessment, it could work as an indicator of the root growth if a certain level of roughness is accepted in respect to results, if the process is conducted with due care and, most of all, if root rot does not ravish the roots into uncountable state. Unfortunately this was almost the situation in this experiment. One possible method for improving the accuracy of root calculations could be pre-staining the roots in order to ease the distinguishing of new root growth (Schumacher *et.al.* 1983). For example using neutral red dye could be considered, as it would fit into the desired pH range and has been proven not to disturb the root growth when staining is done by using very low concentrations (*Ibid.*).

According to the statistical results the only significant increase, actual growth, was the number of the primary roots during the first test period. 10-60% growth seems enormous in respect to decrease of same level with roots' cross-sections. This was, according to the author's estimation, completely due to the increased number of small, hair-like, beginnings of roots, previously presented for example in picture 32. Hence no significant growth in the total surface area of the roots, which ultimately was the desired outcome, took place. This phenomenon could be a result of the plants desire to survive and grow new roots when the old ones are rotting useless. Strange enough, on the second test period similar growth did not occur. Some units showed a small increase concerning primary roots, but this increase fitted into the error margin. In order to avoid misinterpretation the root calculation method should be developed so that the small knots and/or hair-like beginnings of roots are calculated in separate categories.

None of the roots showed any growth in length, but cutting the roots to a standard length surely helped root rot to spread, hence the roots should not be cut in future. Some of the seedlings used showed early stage of root rot, especially on the tips of the roots, and these contaminated parts were simply cut off when the root length was standardized. In order to minimize the root rot hazard seedlings that are already damaged should not be used at all.

Heart leaf philodendron seemed to be a fit choice for the test method. Perhaps some other species with similar root qualities might be more prone to resist root rot, but this is a mere speculation of the author. Witnessing the steady, fatal decline of the plants from healthy, fresh and green to sloppy and dried, yellowing, browning, and even greying eyesore of plants could have been more informative. Unfortunately there was no significant difference between the test periods, modules, units and pots concerning the state of the leaves. For a while it seemed that the second test period would have been more successful, but it was only a hopeful illusion.

Plants were photographed regularly during the test periods. The condition of the leaves gives a good indicator of the roots' condition. Hence the condition of the visible parts of the plants should be documented in future also. Photographing the roots was not as easily arranged as one might think. Photographing the roots one seedling at a time was ruled as too time-consuming and irrelevant, but arranging the seedlings in units to fit in one picture was not the perfect solution either, as can be seen in the appendix 2. TAMK greenhouse

hardly provided a studio environment concerning lightning etc., nor did the mobile phone camera used. Improving the arrangement and using decent equipment surely would provide more value to documentation.

The duration of the test periods (three weeks for the first period and four weeks for the second) seemed to have no significant effect on the results. Measured indicators of conditions (pH, EC, temperature (water and air) and humidity) mostly stayed within reasonable limits, although a more stable environment especially concerning temperature variations would increase possibilities to carry out a successful experiment. The variety of measured indicators should provide sufficient information of the general conditions.

Some of the reasons behind the relative failure of the experiment are on the author's responsibility, but some of them were simply beyond control. These flaws and misfortunes, as well as other factors that may have influenced the process, are discussed further in chapter 5.1.

5.1 Error evaluation

Due to their confidential nature some technical details concerning for example the structure of the test devices are left unpublished in this chapter.

Washing was done as far as possible according to the instruction sheet, but it is possible that too much manual force and too high water pressure was applied, causing the uppermost layer of the roots to peel off. This along with the cut-surfaces of the root tips, as the length was standardized, surely lured root rot to attack even more fiercely. Rough indication of the level of soil removal after the washing can be seen in appendix 1. Error in the planting process was minimized by following the company's instructions and organizing the work phases (the author was assisted; one person executed for example pre-washing phase etc.). Naturally the author executed all the root calculations.

Calculating the roots proved to be both time-consuming and challenging; it required strict focus and patience, as well as delicacy, for the roots were often mixed up to each other making it difficult to avoid damage. Root calculation before the test period (initial calculation) was, of course, easier as the roots were relatively healthy and intact. But

calculating the rotten roots was frustrating as they disintegrated easily, thus increasing the error even more. Arbitrary estimation of human error in calculations is 5-10% for initial calculation and 10-15% for final calculation.

Due to a human error the water levels were not checked before the weekend April 24th-27th. This resulted in the water level of M3 dropping below the pump. Thus M3 was dried up but luckily the pump was not broken. The air fan of M2 was mysteriously broken during another weekend (April 17th-20th). The fan and related electrics were examined by the author and TAMK physics department staff, but the reason for malfunction was not defined. The fan was replaced as soon as possible.

The lights worked very well the whole experience. Unfortunately a PAR-meter was not available during the test periods; hence the Full spectrum daylight lamp's PAR values could not be measured, and later on proved to differ significantly from the Cool daylight lamps' PAR values. This could have influenced the results. The error of the PAR-meter is $\pm 2\%$ (Apogee Instruments 2015) but the measurement results vary depending on the specific spot on the front panel (height and width) where the probe is placed, as well as the probes direction, hence the PAR measurements were standardized as far as feasible by using for example duct tape to hold the probe in position.

For the second test period M1 and M2 were set on exactly the same parameter values, except that M2 had Full spectrum lamps. After a few days it was discovered that M1 was alright (although probably yet too moist in retrospect) with the set irrigation interval, but all M2 units were completely dried after only 70% shorter irrigation cycle. Only distinction was the difference in the spectrum of light. Leaves in M2 turned yellow and dry from the very beginning of the test period. All equipment, for example timers, were checked and re-checked but no explanation was discovered.

The author failed to find any literature references supporting the dramatic effect of the spectrum differences, on the contrary, the differences within the used spectrum and lightning power should not make any difference (*e.g.* Physics Stack Exchange 2015; Rama Das 2004, 47-56). Too intense lighting can be harmful to plants and theoretically lead to evaporation, as the pots in M2 were dried up. In nature, most plants absorb higher levels of solar energy than they can utilize in photosynthesis and have to process the excess light somehow. The amount of excess energy is also related to the spectral

distribution of the light; when the ratio of PPF (PAR) density is high, there is a lot of excess energy. Processing the excess energy is referred to as *photoprotection*, and it includes several methods. One of these methods is thermal dissipation of energy (Rama Das 2004, 47-56). However, the intensity of light applied in this experience was merely 15-35 $\mu\text{mol m}^{-2} \text{s}^{-1}$ (PAR). Even at intensities around 100 $\mu\text{mol m}^{-2} \text{s}^{-1}$ nearly 80% of the absorbed energy can be utilized in photosynthesis. As a reference value, full sunlight provides 2000 $\mu\text{mol m}^{-2} \text{s}^{-1}$ where the utilization is only 10% (*Ibid.*). Hence the final answer to the peculiar phenomenon was left undiscovered.

During the first test period the temperature of the greenhouse (outside) generally stayed between 18-30 °C, with only a few peaks. During the second test period there was a bit more fluctuation. Temperature inside the light frame (inside) followed the same tendency, although was slightly lower for the second test period due to the Full spectrum lamp type. Manually measured temperature (inside) varied between units and modules only approximately one °C. As discussed in chapter 2.4 the ideal temperature for Heart leaf is 16-21 °C, and the temperature should never drop under 13 °C or rise above 24 °C (Wolverton 2008, 90). The upper boundaries were broken daily. According to Wolverton too moist or cold growing conditions might cause root rot (*Ibid.*), but apparently too warm conditions do not prevent it either. Perhaps adjusting the day/night period in a way that the dark sequence would have took place in the warmest hours of the day and *vice versa* the temperature fluctuations would have been smaller.

Temperature of the water stayed between 15 and 21.5 °C. Temperatures much higher than 20 °C could cause trouble, but for example algae filaments were not discovered. EC adjusting was successful and the amount of nutrients was sufficient, although the rotting of the roots did probably influence this; plants could not uptake all the available nutrients. Optimum pH range for NaturVention's purposes is 6-7.5 (NaturVention, undated). During the first test period pH dropped slightly below 6, probably due to the root rot prevention chemical, but stayed slightly below 7 for the second test period. Available pH meter was calibrated frequently.

Humidity levels rose significantly for the second test period and the stunning fluctuations did not follow any clearly defined pattern, as for example time-relation to irrigation sequences. Explanation for fluctuation from 17% to 97% was difficult to find. Perhaps water was splashed from the air fans directly to the outside probe, but this explanation

still lacks relation to the infrequent irrigation sequences. Protecting the probe from direct splashes should be done in the future. The measuring equipment could have been the source of error but seems unlikely for the device is robustly built and proved reliable. Then again, so was the mysteriously broken air fan. Timers were checked and re-checked and seemed to work flawlessly, although digital timers have proven unreliable by NaturVention's experience.

One possible explanation for the strange humidity levels could have been the air conditioning of the greenhouse. According to TAMK technical maintenance staff the air conditioner operates with full power on weekdays between 7-16, and half power on evenings and weekends. It warms/cooling incoming air to 19 °C but does not control humidity. Intake air (from outdoors) was initially warmer due to the progressing spring, and as the air is warmer its relative humidity is higher, thus containing more water even after cooling to 19 °C. Humidity graphs were also compared to weather statistics of June at the nearest weather station, but no consequent and direct correlation between the graphs can be seen, as presented in figure 11.

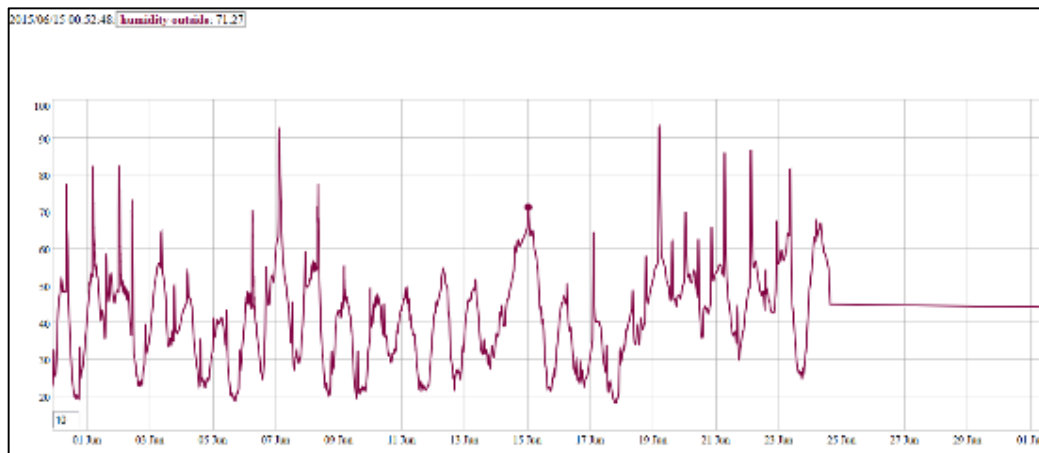
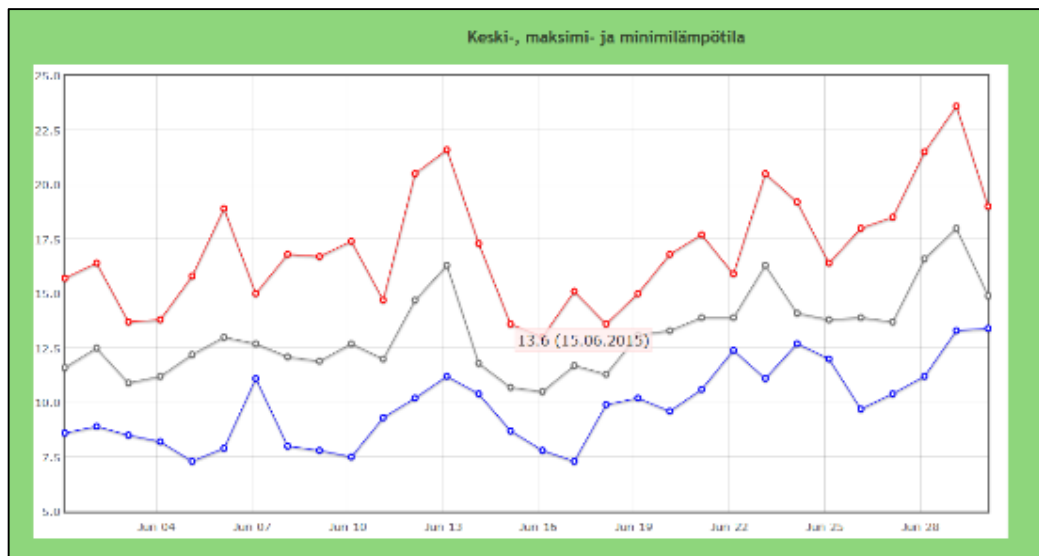


FIGURE 11. Weather statistics of June and relative humidity of the greenhouse of the corresponding period. (Ilmatieteenlaitos Avoin Data, 2015, modified and NaturVention 2015, modified)

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6 APPENDICES

Contents of this chapter are ruled confidential and removed as a whole from the published version of the final thesis.