The potential for combining living wall and vertical farming systems with aquaponics

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Abstract

Aquaponics is a method of food production, growing fish and vegetables in a recirculating aquaculture system. Aquaponics uses the water from the fish to feed the plants in a totally natural way and like hydroponics, aquaponics is considered to be more sustainable as more plants can be grown per square metre compared to normal agriculture. However, as is the case with normal agriculture, in aquaponics plants are grown within horizontally. In aquaponics, using the UVI system, the ratio between fish tanks:filters:plant tanks is 2:1:5 which means that the plant tanks are occupying close to half of the production space. In order to reduce the spatial requirement for plants, which would make production even more sustainable, this research investigates aspects of combining living wall and vertical farming technologies in aquaponics. It is considered that by growing the plants vertically less space would be required. In this research living wall system are investigated but the main focus is on the potentials of using various inert substrates in the living wall systems for vertical aquaponics. The results showed that a pot system performs better in terms of management of the systems. With regard to substrates, horticultural grade coconut fibre and horticultural grade mineral wool outperformed other substrates.

Keywords

Aquaponics, vertical aquaponics, living wall systems, vertical farming, sustainability, growing media, substrates

1. Introduction

The overall context for this paper is the looming global food crisis. The United Nations predicts that the world population will increase from 7.2 billion in 2013 to 9 billion by

2050 (UNDESA, 2013). With this world wide population growth, the demand for both more food and more land to grow food is ever increasing (Birkby, 2016). The World Bank states that *‘the world needs to produce at least 50% more food to feed 9 billion people by 2050’* and that *‘climate change could cut crop yields by more than 25%’* (World Bank - web). There are a number of methods for increasing food production, such as using marginal lands or through genetic modifications but these are not always considered sustainable nor acceptable. Aquaponics can be seen as a promising and sustainable solution to overcome the looming food crisis. Growing more food in urban areas is seen as part of the solution and Konig *et. al.* (2016) note that as food security and infrastructure become a central issue in these urban areas, aquaponics offers one solution. Now that aquaponics is becoming more mainstream, the question that needs to be asked is, can aquaponics be made even more productive and thus more sustainable and how can this be done? This paper focuses on one aspect of aquaponics and the potential for aquaponics to be more sustainable by combining aquaponics with living wall and/or vertical farming systems to provide more sustainable food.

Most aquaponic systems such as the University of the Virgin Island (UVI) system (Figure 1), designed by Dr Jim Rakocy and his colleagues use horizontal grow tanks or beds, emulating traditional land based arable growing to produce vegetables. However, over the years new living wall and vertical farming technologies have arisen and evolved which, when linked to the aquaculture part of the aquaponics system may allow more plants to be grown in comparison to horizontal beds and thus make the systems more productive and thus more sustainable. Depending on the vegetable species the UVI aquaponic systems produce approximately 32 plants per square metre (Al-Hafedh *et. al.,* 2008), but approximately 98 plants can be grown per square meter using back-to-back elements of the *Terapia Urbana*[1] living wall system which is more than 3 times the density compared to the UVI horizontal growing system.

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[1] Terapia Urbana – (Calle Factores, 12-14 Local 4D, 41015 Sevilla, Spain) produces a living wall with sewn pockets attached to a felt backing. The pockets are then filled with a growing media. Irrigation is provided through an irrigation pipe which delivers water to the felt backing. The water then drips down the felt by gravity providing a source of water to the plant roots in each pocket. Normally the system is used singly, but in vertical aquaponics it is possible to use the system back-to-back.

This paper provides the initial results and the issues related to vertical aquaponics as assessed through investigations and trials undertaken as part of PhD studies, during 2016 at the University of Greenwich Green Roofs and Living Walls Centre.

Aquaponics – Brief Description

Aquaponics is the integration of recirculating aquaculture systems (RAS) and hydroponics in one production system (Somerville *et. al*., 2014). It is in fact a bio-integrated food production system (Diver, 2006), where water from the fish tanks pass through filters and grow beds and back to the fish tanks. Filters remove the solid waste and the filters and the surfaces of the system itself act as a means for bacteria to convert dissolved wastes into beneficial nutrients (Somerville *et. al*., 2014). Nitrifying bacteria convert ammonia (NH_3) from fish waste water, first to nitrite (NO_2) which is toxic to fish and plants and then to nitrate (NO_3), which is easily and readily acceptable by plants and not as toxic to fish at appropriate levels. Thus, fish, bacteria and plants perform together in one growing community in a symbiotic process, (Somerville, *et. al.*, 2014). Like high production hydroponic vegetable production, in aquaponics most production takes place in green houses where the microclimate can be controlled. The most common fruits, vegetables and herbs that are grown in the aquaponics include lettuce and leafy salads, herbs such as basil, pakchoi, kale, Swiss chard, arugula (rocket), mint, watercress, chives, tomato, spinach, peppers, squash, cauliflower and cabbage (Nelson and Pade, 2008). The production of quick growing vegetables and herbs such as lettuce with short life maturity cycles, (30-40 days for some soft leafed lettuce species such as Bibb [Butterhead] and basil) are more productive and the economic rate of return is higher based on repeat growing around the year. Additionally, 'cut-again' plants such as basil that can be cut and that can regrow after cutting offer the aquaponist a constant supply of the herb. Despommier (2013), reports in controlled environment conditions, eight times more produce can be achieved with indoor growing compared to outdoor growing with some leafy vegetables such as lettuce, spinach, basil and kale. The fish that grow successfully in aquaponics include tilapia, catfish, white bass, grass carp, arctic char, goldfish, koi fish and trout (Nelson & Pade – Recommended Plants and Fish for Aquaponics).

With regards to the sustainable production of vegetables, aquaponics is seen to be more sustainable than conventional outdoor soil based agriculture. Sayara *et. al.* (2016), note that hydroponic and aquaponics systems use around 80% less water than growing in soil. Diver (2006) and Al-Hafedh *et. al.,* (2008) note that the great advantage of aquaponics are the water savings, especially in water scarce areas as the water from the fish is recycled for the production of plants and continues to be re-used for both fish and plant production. Aquaponics can also be more productive in areas where land and water is limited (Somerville, *et. al.,* 2014). Additional sustainability aspects include less fertilizer and pesticide use, more effective management and control with less waste and less contamination of land by reducing and managing the aquaculture effluents.

Living Walls and Vertical Farming Systems – Brief Descriptions

Living walls (LWs), also termed as green walls, are vertical plant growing systems that are attached to the exterior or interior walls of a building (Perini *et. al.* 2013). A variety of plant species are used in living walls depending on their hardiness and their function. LWs are not only used for aesthetic purposes but they also can have environmental, and socio-economic benefits by, for example, reducing the urban heat island effect, reducing air pollution and improving air quality, increasing biodiversity by providing food and shelter for wildlife and through the insulation of buildings (Weinmaster, 2009; Ottelé *et al*., 2010).

Vertical Farming (VF) systems, show promise as an effective means to help increase food production, maintain food security and foster sustainable urban agriculture (Besthorn, 2013). The popularity of VF among hobbyists, seasonal growers and farmers is increasing as less space is required compared to traditional agriculture. Thus the most striking aspect of vertical farming systems is that they have the capacity to produce more food per square metre and thus profitability and increased sustainability. Despommier in 2007 (reported in Besthorn *et. al.* 2013) suggested that a vertical farm acre[2], produces as much as four to six-acres using suitable technology and agro-management skills. On the other hand, an acre vertical farm, growing close cluster fruits such as strawberries can produce the equivalent amount of 30 outdoor acres. Although in most cases living walls do not recycle the excess water that drains off the system,

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[2] An acre is approximately 0.4 hectares.

vertical farming systems, like hydroponic systems re-use the water that is not taken up by the plant roots.

One key reason that VF is becoming more prevalent is because they require less horizontal space and a reduced horizontal footprint and thus, in urban areas, in particular, interest in this approach is growing (Birkby, 2016). Birkby (2016) furthermore notes all VF systems use one of three soil-free systems for providing nutrients to plants. These are hydroponic, aeroponic or aquaponic. Vertical farms come in different shapes and sizes, from simple two-level or wall-mounted systems to large warehouses several stories tall (Birkby, 2016). There are a number of commercial manufacturers who produce customized VF systems in various sizes and designs, but although the components may differ, many of VF systems use a gutter system through which run-off water is collected.

The plant growing medium is an important consideration for the success of vertical farms as well as living walls and as aquaponics systems do not normally use soil based growing media, this study investigates various types of growing media that can be best used in vertical aquaponics.

The research discussed in this paper aims to answer, at least in part, a number of fundamental questions:

- Can living walls and/or vertical farming systems be integrated into aquaponics systems effectively and will the systems be more sustainable in terms of producing more food.
- As most aquaponics systems do not use soil, what are the best media to use in the living walls/vertical farming system to grow plants?
- What are the main issues/problems associated with integrating living walls/vertical farming systems with aquaponics?
- How can these issues be overcome?

2. Materials and Methods

In order to answer the above questions, a number of considerations needed to be studied. These include:

1. The spatial arrangements of vertical versus horizontal aquaponics;

   This raises issues of:

   - Access for maintenance, management and ergonomics;
   - Lighting;
   - Pumping; and
2. Growing media suitability

This research paper concentrates on items where test experiments have been undertaken over a single growing season. Research on these areas is still in progress using modelling and spatial analysis tests and new experiments are being undertaken on growing media suitability.

In all the research undertaken to assess the benefits of growing plants vertically in an aquaponics system the horizontal UVI based system at the University of Greenwich Aquaponics Lab has been used as the control. All calculations and assessment thus use the usual set up of fish tanks and filters but then establish the differences and issues related to vertical versus horizontal aquaponics.

Spatial Arrangements for Horizontal and Vertical Aquaponics – Issues of Space, Light and Pumping:

Space

Aquaponics systems have a number of key components including fish culture tanks, filtration tanks which include clarifier tanks, mineralization tanks and a degassing tank and then the vegetables grow beds (Figure 1). The horizontal vegetable growing beds are normally of 3 types:

- Floating Raft (this is used in the University of Greenwich system);
- Gravel or other granular material; and
- NFT (nutrient film technique).

Water flows by gravity through the filtration tanks on through the grow beds and back towards the fish tanks where the water is then pumped back up to the fish tanks, usually via an electrical pump or by 'air-lift' pump[3] from a sump. An air blower provides air and thus oxygen to both the fish and plants. The ratio between the different components of the aquaponics unit using the UVI system at the University of Greenwich (Figure 1) as an example is as follows:

- Fish tanks – 3.0m wide x 2.4m long (7.2m^2);
- Filtration tanks – 3.0m wide x 1.2m long (3.6m^2); and
- Plant tanks – 3.0m wide x 6.0m long (18m^2). [4]

Thus the ratio between fish tanks: filtration tanks: plant tanks is 2:1:5 (Figure 1).

The above arrangement shows that the horizontal vegetable grow beds thus occupy more than 50% of the fish production volume of aquaponics unit and this is essentially the case for the raft, gravel and NFT systems. It must be noted that space in greenhouses which are climate controlled is an expense which needs to be calculated and using the same space to grow more vegetables must be more economical and thus essentially more sustainable. This is particularly relevant in urban areas where land values are expensive and raising productivity levels in urban areas may make aquaponics that much more economically viable. VF and LW systems, on the other hand, have an advantage over horizontal systems as the systems can be placed back to back and thus two sides of the living wall / VF system can be used to produce food which in principle decreases the space requirement. The Terapia Urbana LW system has 49 plant pockets per square metre and thus utilising both sides the system can produce 98 plants per square metre whereas the horizontal grow bed only can produce approximately 42 plants per square meter (Al-Hafedh *et. al*., 2008; UVI). The UVI system plant ratio compared to the back to back Terapia Urbana system is 1: 2.42 which is a substantial increase. However, the number of plants one can produce per square metre also needs to include the access pathways that are required for management, between the horizontal grow tanks and between the VF / LW systems. Only then can a proper comparison be made. In the University of Greenwich Aquaponics Lab, the plant area of 6 metres x 3 metres which is 18 square metres accommodates 324 plants. This

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[3] Air lifts are sometimes used as they are more economical and because when using an airlift only a blower is required thereby reducing the need for the water pump.

[4] Note these areas include access paths and spaces between tanks which are at a minimum.

only equates to 18 plants per square metre as this includes the access paths (0.4 m wide x 6 metres long) between the plant tanks as well as small areas of 'lost space' between tanks and the sides of the greenhouse.

The potential for increasing plant production using VF and LW systems thus needs to take account more than the maximum number of plants that can placed in each square metre of the system but the calculation needs to account for the need for access by people between the rows of VF/VL systems and also lighting.

The method for calculating the optimum space for vertical aquaponics compared to horizontal aquaponics needs to be calculated taking account of the two main issues of 1) ergonomics and systems management procedures (for planting, harvesting, cleaning etc.) and 2) lighting. (Figure 1).

Lighting

Growing plants on horizontal beds has the advantage that natural light is theoretically transmitted from all sides in a free-standing greenhouse without any blockages from other equipment and system components and where lighting is required, these lighting systems can be readily located immediately above the plants without any interference. However, with vertical aquaponics lighting is an issue as natural light from above will be greater towards the upper part of a vertical wall compared to the bottom and the vertical elements themselves will block light that is entering the green house and blocking light from lighting systems spreading over the whole system. The questions that thus need to be asked and which require answers include:

- What types of lighting would be suitable for vertical aquaponics systems?
- How much space would be required to accommodate these systems? and
- How much power would be required to run these systems?

Whereas a horizontal flow system only uses pumping or an air-lift to pump water back to the fish tanks, additional pumping is required to lift water to the top of the VF/LW systems which adds additional power requirements and this has an impact on sustainability.

Growing Media Suitability: Whereas in horizontal aquaponics, plants are grown directly in deep water, shallow water or ebb and drain water flows, in VF and LW systems water needs to be delivered to the top of the system, or to each row of plants or to each individual plant initially through pumping and then the water passes into the growing media which then supports root and plant growth.

The type of growing media that is used in LW and VF systems is a key factor for the successful operation of these systems. Choosing the appropriate growing medium that the plants will be growing in, is one of the most crucial parts of the system which determines plant establishment and growth and hence the success of the operation and its profitability. Whereas different LW and VF use soil based media or other inert media such as mineral wool, in most instances, aquaponics systems do not use any soil[5]. In normal aquaponics there is no need for soil based media as the system is essentially hydroponic and there is the issue that some media can leach chemicals and other elements into the aquaponics systems which can be toxic to fish. The use of inert media helps to overcome the issue of leaching and/ or introduction of unwanted organic matter into the systems. This research investigated some of the most commonly used inert growing media used in the horticulture industry which includes mineral wool (Cutilene[6]), perlite and vermiculite, coconut fibre and some alternatives including sphagnum moss and pond grown algae. Three experiments were undertaken using different types of media over the summer and autumn of 2016. Determining the best media to use in the vertical aquaponics system is not only based on the performance of the plants in the media but also on how the plant roots interact with the media and the plant container, the ease of management (planting, watering, harvesting) and the sustainability credentials of the product.

Living Wall (LW) and Vertical Farming (VF) Systems Suitability – There are numerous types of LWs and VF systems, but the key question here is what types or system would be best suited to integrate with aquaponics? Based on the growing medium, LW systems can be categorised into two types; with or without growing

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[5] The authors know of a case in northern Germany where plants are introduced from a nursery in pots with soil into an aquaponics system to increase their size and then returned to the nursery for sale, without any detriment to the fish.

[6] http://www.cultilene.com

media, i.e. ones which include some type of media (mainly soil based, but which would include percentages of coconut fibre, vermiculite, perlite etc.) and those where the plants are grown in mineral wool. Cunningham (2015), noted that LW systems have three basic layers, the anterior layer where plants are grown, a middle layer where water is retained to keep the growing medium wet and supply nutrients to the plants and the posterior laminated layer which prevents the support structure or back wall to become wet. Frames or a support structure which are mainly made of stainless steel or wood are bolted or screwed into existing walls to support the LW. Loh & Stav (2008) classified living wall systems into three types as which include: 1) a panel system, 2) a felt pocket system and 3) a container and/ or trellis systems. However, 4 different types of LW can be identified and these are readily available in the EU as follows:

1. Panel systems with planting holes ('Biotecture'[7] type) – these systems use mineral wool located between a perforated front plastic façade and a solid back facade;
2. Pocket systems with extruded rigid pockets ('Mobilane'[8] type) uses soil based media with a water wicking system from a water trough concealed in the system below or with soft woven material soil based pocket system ('Terapia Urbana'[9] type) with a geotextile pocket holding the media backed with an absorbent material where water drains down from the top;
3. Pot or trough systems with individual plant pots ('Nemec'[10] type) or Green Vertical Garden Company ('GVGC' type)[11] using soil based media in individual pots where water is sucked up by capillary action from troughs under each layer of pot or plants planted in troughs within media ('Treebox'[12] type); and not relevant to this study.
4. Container systems which use soil based media to grow climbers on trellises or steel wires.

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[7] http://www.biotecture.uk.com/living-walls (UK based)

[8] http://mobilane.co.uk/products/livepanel (Netherlands based but with UK operations)

[9] https://www.terapiaurbana.es/fytotextile-vertical-garden/?lang=en Spanish based but with UK operations)

[10] http://www.cascadegarden.nemec.eu (Czech based)

[11] http://greenverticalgarden.com

[12] http://www.treebox.co.uk/products/easiwall-green-wall.html

All types of living wall systems require support structures and irrigation systems. Most systems have a damp proof layer which stops water from entering the supporting wall.

At the outset of this research, two different LW systems were chosen as they were considered to be the most suitable for linking with aquaponics. The choice was based mainly on the flexibility and ease of erection, but additional analysis is required to determine costs and sustainability. The two LW systems chosen were the Terapia Urbana system (Figure 2), and the Green Vertical Garden Company (GVGC) system (Figure 3).

Three LW experiments using the two different types of LW were carried out to determine 1) the performance of plants using different non soil based media and 2) to determine any issues relating to the day-to-day management of the systems.

Experiment 1:

This externally located living wall, (facing East), comprised $1m^2$ Terapia Urbana consisting of 49 flexible pockets of *'industrially produced flexible multilayer modules'* (Terapia Urbana) in which 49 plants were planted on the 30th of June, 2016. The system was suspended from a constructed frame of scaffolding poles (Figure 2). Seven of each of the following plants were established from seedlings grown in the Aquaponics Lab: Perpetual spinach (*Beta vulgaris*) from here on referred to as spinach, basil (*Ocimum basilicum*) chicory (*Cichorium intybus 'castelfranco'*), asparagus pea (*Lotus tetragonolobus*), lettuce (*Lactuca sativa 'mazur'*,) mint (*Mentha viridis*) and tomato (*Solanum lycopersicum*)[13]. Whereas each plant species was arranged vertically in columns the growing medium was placed horizontally in rows (Figure 2). The plant media included: Horticultural grade mineral wool, vermiculite, charcoal, coconut fibre, sphagnum moss, pond grown algae and straw[14]. In this instance, the rationale behind planting the same species of vegetables vertically instead of horizontally is that it would identify variable plant growth performance based on different growing media. Water

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[13] The selection of the plants was based on the availability of seedlings in the greenhouse.

[14] It should be noted that the unusual choice of charcoal, pond algae and straw was due to the aspiration to investigate common sustainable materials that were not usually used. It should also be noted the coconut fibre used was not horticultural grade but obtained from the lining for hanging baskets.

was pumped up to an internal drip irrigation pipe from a surrogate aquaponics tank[15] with added hydroponic nutrients. The water then flowed down the back of the panel where it was made available to the substrate and the demand of the plant roots. Excess water dripped from the bottom of the living wall panel into a gutter and then back to the water tank (Figure 2).

Experiment 2:

This 2nd experiment was set up adjacent to Experiment 1, (externally facing east), on the 1st of August 2016 using the Green Vertical Garden Company (GVGC) pot system. The individual plant pots were attached to a stainless steel reinforcing mesh panel supported by the scaffolding support system used for experiment 1 over 1m^2 using 40 pots with 5 horizontal rows and 8 vertical columns of pots (Figure 3). In this experiment, only one herb bush basil (*Ocimum minimum*) was used across the whole living wall with different growing media used in the vertical columns (Figure 4). Two columns of each of the following media were used: Hydroleca, vermiculite, mineral wool and coconut fibre[16]. This strategy aimed to identify the best inert growing media. The system was irrigated using an irrigation pipe to supply nutrient rich water into the top row of pots and then the water flowed through each pot to the next via a small irrigation tube from a hole located at the bottom of each pot.

Experiment 3:

Experiment 3 comprised of an offshoot of Experiment 2 using the GVGC system and single species of Chicory (*Cichorium intybus*) with two vertical columns each of hydroleca, vermiculite, mineral wool, and coconut fibre (Figure 5).

For all three experiments the following activities were carried out:

- Irrigation was provided at approximately litres 373 litre per hour to each 1 square metre of planting using a submersible pump from a 60 litre water tank. Hydroponic solution was added when water was topped up – the reason for this large water flow is to simulate aquaponic conditions where the roots of the

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[15] This tank contained 60 litres of water with added hydroponic solution manufactured by Canna

[16] Horticultural grade vermiculite, mineral wool and coconut fibre were used.

plants need to take up the nutrients in the water and to cleanse the water for the fish;

- Daily visual checks were carried out to identify any operational issues;
- Plant growth measurements, growth performance and visual quality data were taken every week according to the methods described by Zollinger *et. al.* (2006) and Martensson *et. al.* (2014); and
- Visual characteristics were monitored and light meter readings were taken once it was realised that light intensity could be playing a significant part in the growth parameters of the plants.

Results

Experiment 1:

This living wall was planted on the 30th of June, 2016 and plant length was recorded on the 2nd of July 2016. The plants were then measured again on the 8th of August 2016 with the following results – (Figure 6):

- Mineral wool and vermiculite were by far the best performing media, with an average growth per plant of 14.7cm and 13.7cm respectively (Figure 7);
- Charcoal, sphagnum moss and straw were middle performers with an average added growth of 9.6cm, 8.7cm, and 8.9cm respectively; and
- Coconut fibre and pond algae were the worst performing media and growth in the plants of 5cm and 6cm respectively although the spinach and basil grew much better than the other species. (It must be noted that the coconut fibre used was not horticultural grade and this is most likely to have affected the results).

Whilst initial growth across the LW was good it became apparent that light and exposure to wind were significant factors affecting plant performance (Figure 6). The perpetual spinach, did well overall, but the other plants were greatly affected by light and especially by overshadowing, e.g. the top tomatoes cascading down and overshadowing the lower tomato plants.

Experiment 2:

This experiment which used bush basil across the living wall was planted on the 1st of August 2016 and growth was monitored on the 20th of October 2016. The results are as follows:

- The average growth in length of each basil plant was 21.1 cm.
- The best performing row which used horticultural grade coconut fibre as the substrate had an average growth per plant of 24.2cm.
- Overall the plants in coconut fibre did the best (Figures 4 and 7) but differences were recorded between the two columns where the 1st column had an above average plant growth increase of 28.6cm, whilst the 2nd column had a below average growth rate of 19.6cm.
- The mineral wool substrate performed 2nd best but there was a similar difference in the two planted columns with an above average growth of 26.8cm in the 1st column and a below average growth rate of 14.0cm in the 2nd column.
- Overall there was a much greater evenness in growth across the living wall but with a preponderance of good growth towards the top and right hand side (north facing) edges (Figure 4).

Experiment 3:

This living wall was planted on the 3rd of September 2016 and growth on height and diameter was recorded on the 8th of September, 2016 and the final measurements were recorded on the 29th October, 2016 (Figure 5). The following results were noted during the experiment:

- Chicory planted within the coconut fibre grew very well compared to those planted within mineral wool, vermiculite and hydroleca where the average length of chicory within the coconut fibre medium was 12.6 cm (Figure 9). Coconut fibre was the best medium compared to hydroleca, vermiculite and mineral wool. Mineral wool was the 2nd best medium in this experiment in terms of length with an average plant height of 10.8cm at the end of the experiment.
- The hydroleca medium did not perform well where an average length within the hydroleca was 8.8cm (Figure 9).

- There was considerable growth difference in terms of diameter of the chicory on different media. The diameter of chicory on coconut fibre was 22.6cm compared to hydroleca at 16.6 cm (Figure 10).
- The average chicory diameter on perlite medium was 17.8 cm (Figure 10) and average height was 9.2 cm placing it in 3rd position in terms of both height and diameter.
- The average chicory diameter was 20.5cm on the mineral wool medium (Figure 10) and thus the 2nd best in terms of diameter performance.

Discussion

Experiment 1, (Figures 2, 6 and 7):

Analysis of the data from Experiment 1 showed that spinach in mineral wool had the highest growth (32cm after 34 days from planting). The spinach in vermiculite achieved the 2nd highest growth (28cm) whereas the lowest growth was in straw (13cm). The 2nd lowest growth for spinach is recorded in the sphagnum moss (14cm). The conclusion is that the mineral wool medium performed best with spinach and vermiculite performing the 2nd best. On the whole both perpetual spinach and tomatoes have grown very well in this experiment. On the other hand, the asparagus peas had grown very poorly. At the end of the experiment, all the asparagus peas were poor, whereas lettuce, basil, chicory and mint grew well in the top layer and the peripheral areas of the living wall. Tomato and spinach grew best on the top row of the living wall. It is expected that this is due mainly to the additional natural light received especially in comparison to the other rows where light levels were less and caused by overshadowing of the above plants. Thus the experiment showed that the top and peripheral vegetables grew very well and that light intensity, in this instance has determined the higher growth of the plants compared to the plants growing more centrally within the living wall. The variation in growth could also be to greater nutrient availability in the top layer, but if this is the case then all the plants on the periphery and those located at the bottom would not grow very well. This was not the case. Post-harvest root and growing media analysis showed that roots within the mineral wool, vermiculite and sphagnum moss spread widely into the growing media and the back wall regardless of the plant type. This indicated the superiority of these media compared to the charcoal, algae and coconut fibre and straw substrates. As noted previously horticultural grade coconut fibre was not used in the 1st experiment and the lack of root penetration is likely due to the poor quality of the medium. Good root penetration into the medium indicates a healthy plant which is well nourished. The main issue with this type of LW is that plant roots readily invade the structure of the LW and it is difficult to remove the plants at harvest (Table 1). If cut again species were used over a long period of time where replanting was not going to occur then this would be less of an issue.

Experiment 2, (Figures 3, 4 and 8):

In Experiment 2 the basil grew best on the coconut fibre compared to hydroleca and mineral wool and vermiculite media with an average height of 43.5cm for the coconut fibre, 42cm for the hydroleca and 39.6cm for the mineral wool. The vermiculite performed least well and grew to an average height of 35.6cm. The plants did appear to perform better towards the top of the living wall and towards the edges which indicated that there may have been some overshadowing effect on the inner most plants which did not perform as well. Some irrigation problems occurred where the small sized irrigation pipe leading from one pot to the lower point became blocked by the media. This occurred a number of times with the coconut fibre and vermiculite substrates. These can be readily unblocked through sucking out the clogged material but this could not be done at a large scale. In the 2nd experiment root penetration on the coconut fibre was excellent all over the medium (Figure 11). This even distribution is evidence that the water and nutrients were mixed well in the media and supported the plant well. The advantages of the mineral wool and coconut fibre substrates over the other media in this experiment was that they were very easily harvestable, being easily removed from the plant pots. The hydroleca and vermiculite materials were more difficult to work with as the material was easily displaced at planting and at harvest. Mineral wool is considered the best substrate when it came to harvesting as the whole block with roots was readily removed, but then there is an issue with recycling, whereas coconut fibre and the roots within could be readily composted. The 2nd best root penetration was observed within the vermiculite medium, but the roots did not occupy the vermiculite and pushed it aside (Figure 12). The roots within the hydroleca was superficial staying within the upper regions or middle regions on the media but penetrating through and within the clay balls (Figure 13). Although the basil grew reasonably well within the hydroleca substrate, there were issues with seedling stability at the time of planting as the plants would not readily be supported by the coarse grained oval material. The root penetration through the mineral wool was very good but the roots mainly passed through the substrate and collected at the bottom of the pot (Figure 14).

Experiment 3,

The overall best growth of chicory both in terms of length and diameter was recorded using the coconut fibre substrate reaching an average length of 12.6 cm and a diameter of 22.6 cm. The second highest growth was recorded on the mineral wool reaching an average length and diameter of 10.8 cm and 20.5 cm respectively. Hydroleca and vermiculite did not perform well in terms of growth but root penetration within and through the vermiculite was excellent but again largely pushed through the media (Figure 15). The root penetration and holding ability of the plants in hydroleca was not strong and this resulted in poor growth (Figure 16). There was strong root growth and good penetration within the coconut fibre medium (Figure 17). The plants in the mineral wool substrate showed average performance but root growth was good although concentrated at the bottom of the pot (Figure 18). Lighting was considered an issue in the middle of the living wall with greater plant growth towards the edges. In this experiment, coconut fibre was the best growing medium for this living wall and the growing conditions compared to the hydroleca, mineral wool and vermiculite substrates.

Conclusions

The results of the above three experiments indicate that vertical farming and the use of living wall technologies is a promising area to be integrated into the aquaponics. Whereas horizontal aquaponics, apart from gravel systems, uses direct water flows, LW and VF technologies need to use media to hold the plant roots in place. Thus it is essential to ascertain the most suitable substrates and in these three experiments coconut fibre was found to be the best growing medium and mineral wool was found to be second best. There are advantages and disadvantages of both these substrates. Coconut fibre and the roots within can be readily composted but when coconut fibre is used with smaller irrigation pipes, blockages can occur. Horticultural grade mineral wool performs well, but cannot be readily recycled and thus is likely to be considered to be less sustainable. The research also found that with some plants the stability of seedling plants was an issue for example with course grained media such as hydroleca. Issues that arose through the management of the research indicate that not all LW are the same and that plant root penetration through the substrate is a key factor. If the roots can penetrate the material of the LW this will cause problems in harvesting. Irrigation is also an issue that is key to the success of vertical aquaponics. Whereas horizontal aquaponics is characterised by free flows of water, vertical aquaponics requires pumping as well as additional piping which can become blocked because of residues or from substrates. Additional filtration may be required and suitable pipe sizing to stop clogging will be necessary with some LW systems. The experiments undertaken on the roofs of University of Greenwich Green Roofs and Living Walls Centre has illustrated that vertical aquaponics is possible. But what still needs to be shown is that difficulties can be overcome and that more plants can be grown in less space thus making vertical aquaponics more economical and more sustainable than conventional aquaponics. The spatial and energy components of this research are ongoing and the results will be published at a later date, but what we can show here is that there are solutions to solving those problems that arise specifically as part of vertical aquaponics. These are as follows:

- Homogenous artificial or natural light is essential over the whole of the living wall. Recent advances in LED lighting makes this area even more interesting.
- Most vertical aquaponic systems will be located indoors but if outdoors, microclimate and especially wind will affect production. (In these experiments there was some water loss through wind blow). Ventilation is an important consideration in all greenhouses and the arrangement of vertical growing units need to take account of an adequate supply of free flowing air.
- A constant flow of nutrient rich water is necessary for the successful operation of the VF or LW. Additional filtration may be required and irrigation needs to be checked every day for blockages. This may be achieved through automatic

sensors. Additionally, the media needs to allow for enough flow of water to flow back to the fish.

- An appropriate inert media such as coconut fibre and mineral wool is necessary to integrate the living wall systems with aquaponics. Plant roots need to establish readily within the media. These need to be assessed with regard to their carbon footprints and their sustainability.
- The container (pot or pocket) in which the plants will grow needs to be impervious to roots to allow for easy extraction of the plant and easy disposal of the roots and substrate which could be composted.

As noted the next steps in affirming the validity of vertical aquaponics is the study of the spatial requirements for vertical aquaponics and the pumping and lighting requirements. These studies will look at the spatial requirements relative to the energy requirements and calculate the energy required per metre squared of planting.

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Figures

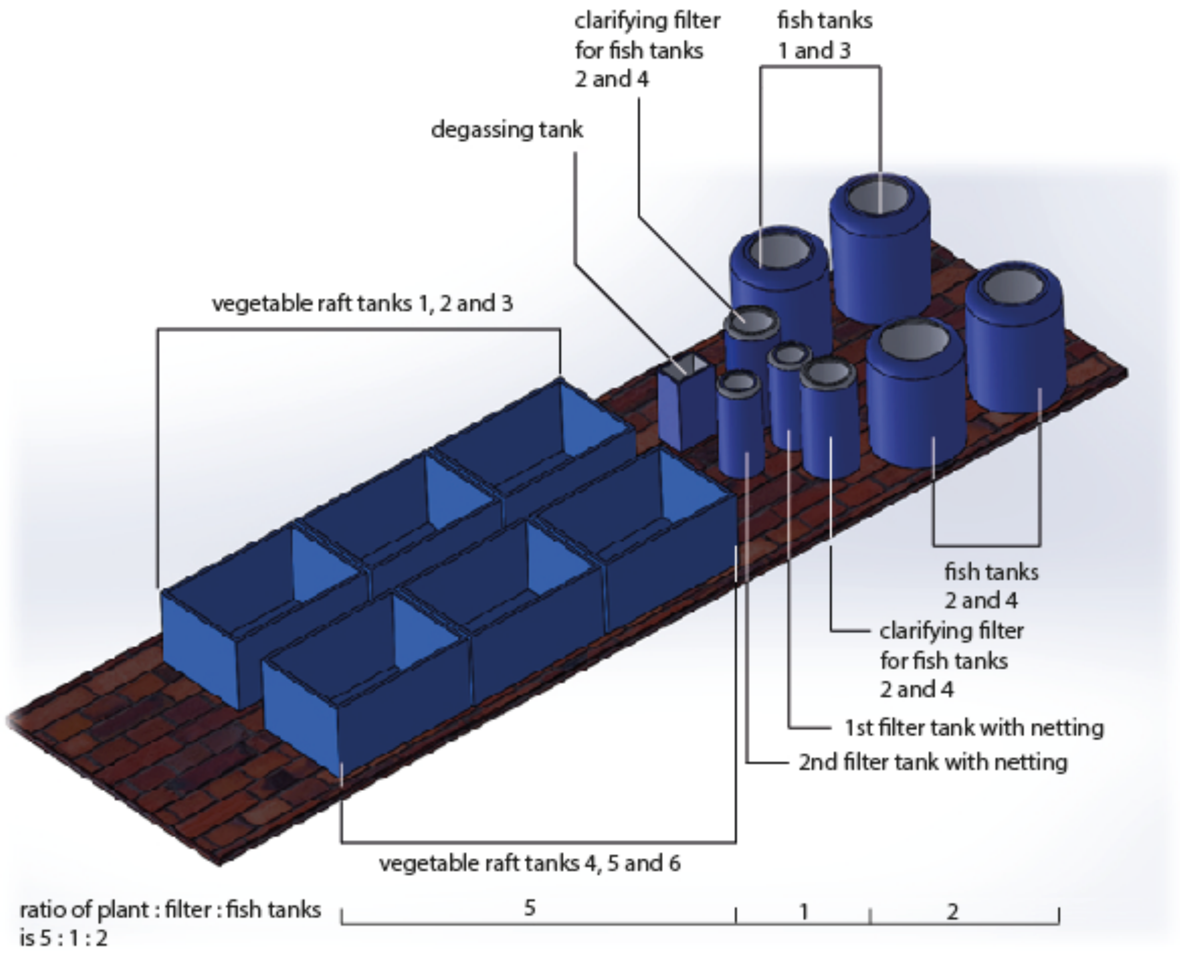

Figure 1. Spatial arrangement of the UVI system as set up at the University of Greenwich Aquaponics Lab

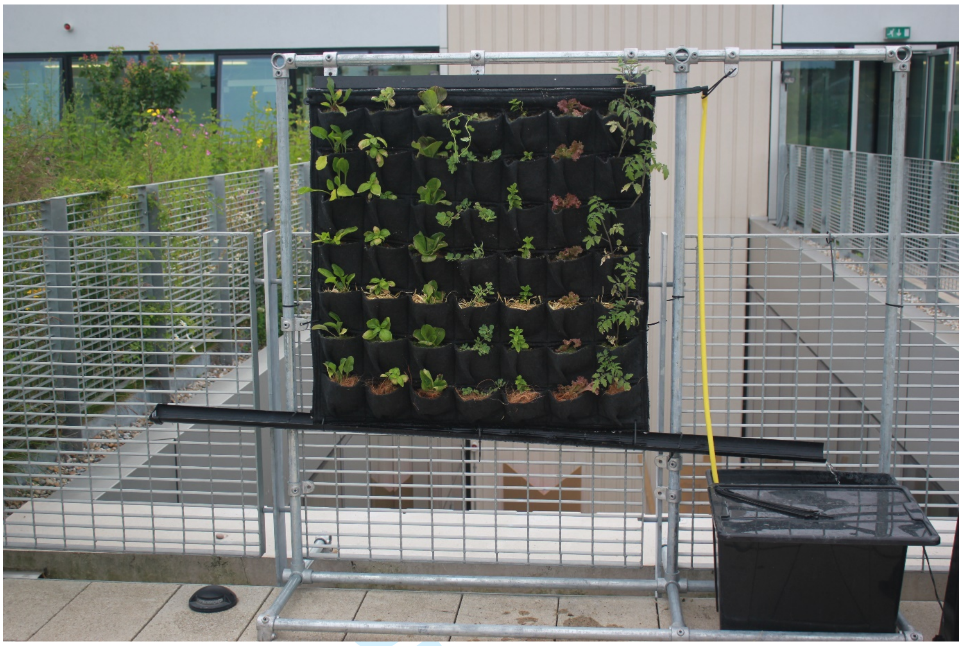

Figure 2. Experiment 1: Terapia Urbana system with a gutter system through which run-off water is collected and then pumped back to the top of the wall

Figure 3. Experiment 2: Basil plants within the pot system living wall manufactured by GVGC, photo taken on 10/08/2016

Figure 4. Experiment 2: Mature basil plants within the pot system

Figure 5. Experiment 3: Chicory growing on different media

Figure 6: Experiment 1: Various vegetables in full growth on

29.07.2016

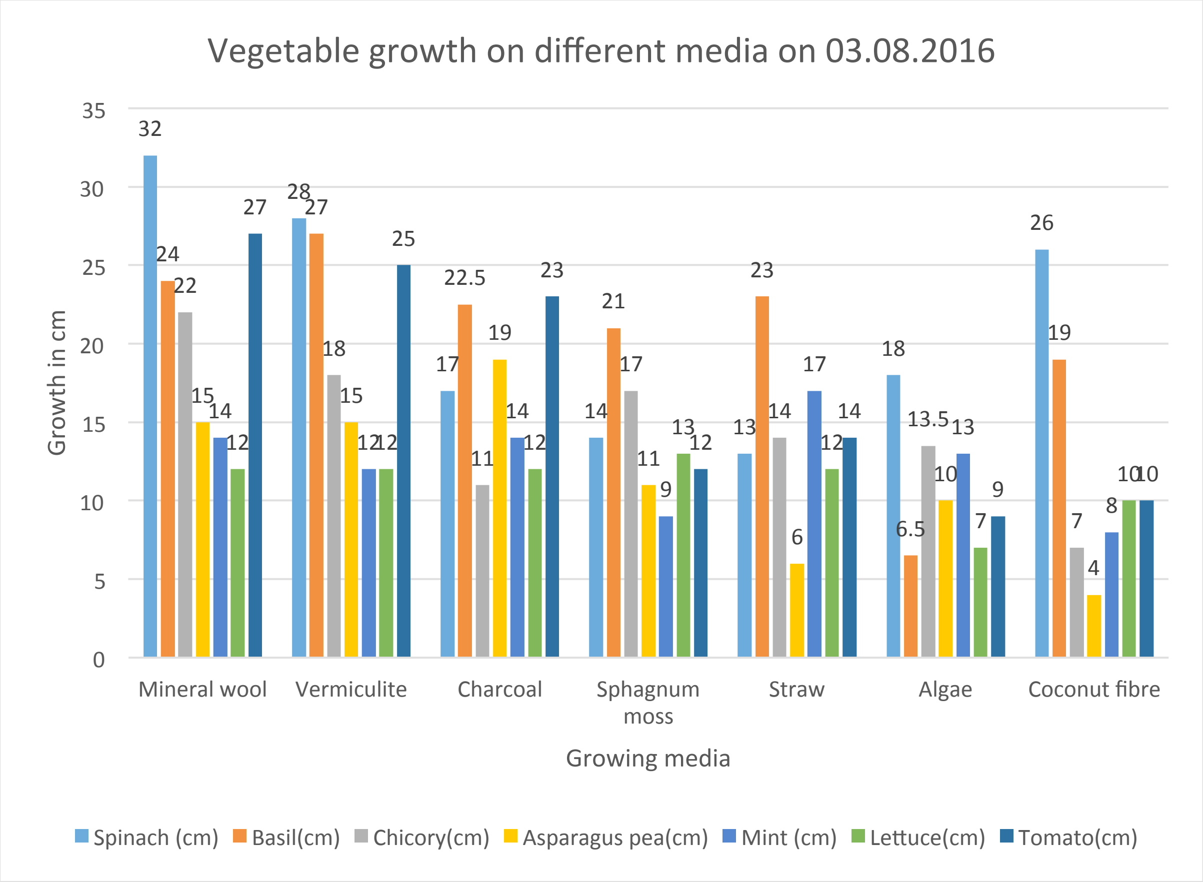

Figure 7. Vegetable growth (cm) in different media in Experiment 1

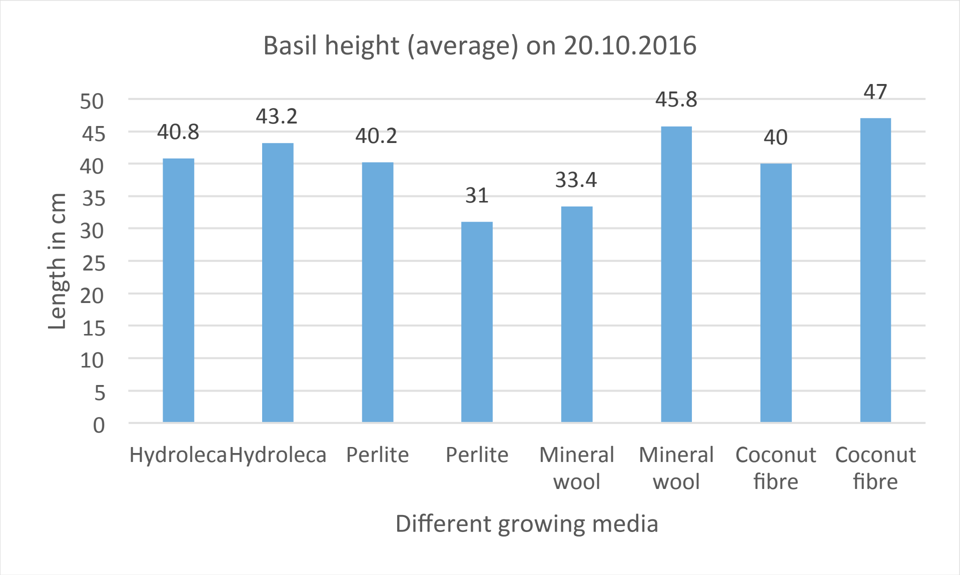

Figure 8. Basil growth on 20.10. 2016 using different growing media in Experiment 2

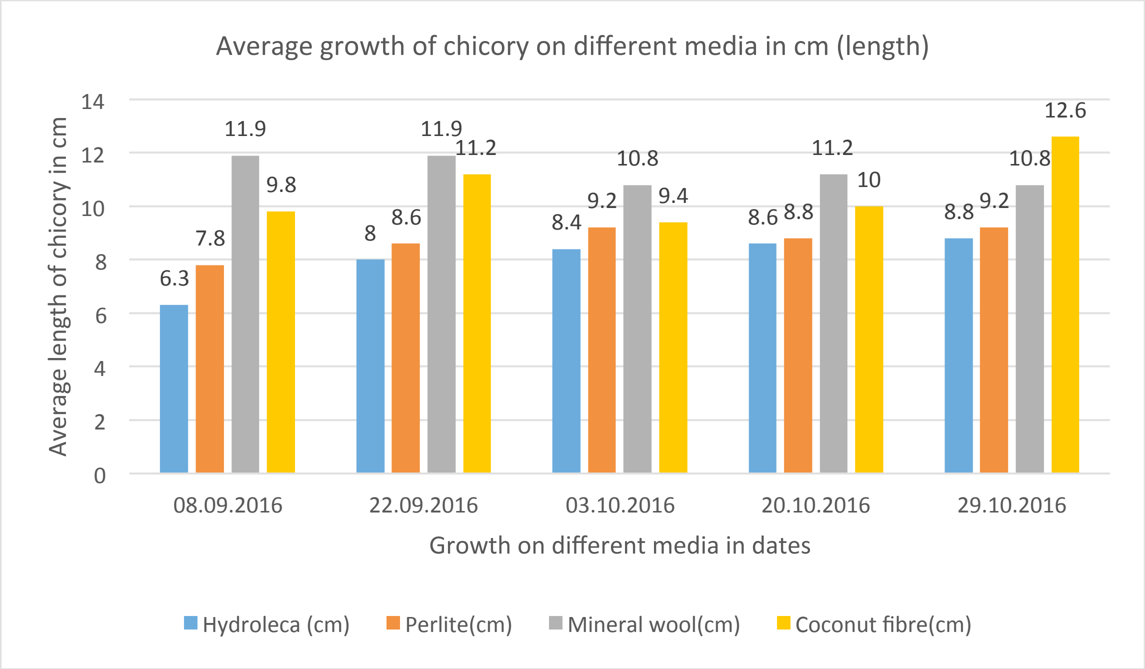

Figure 9. Average growth (length) of chicory on different media in living wall Experiment 3

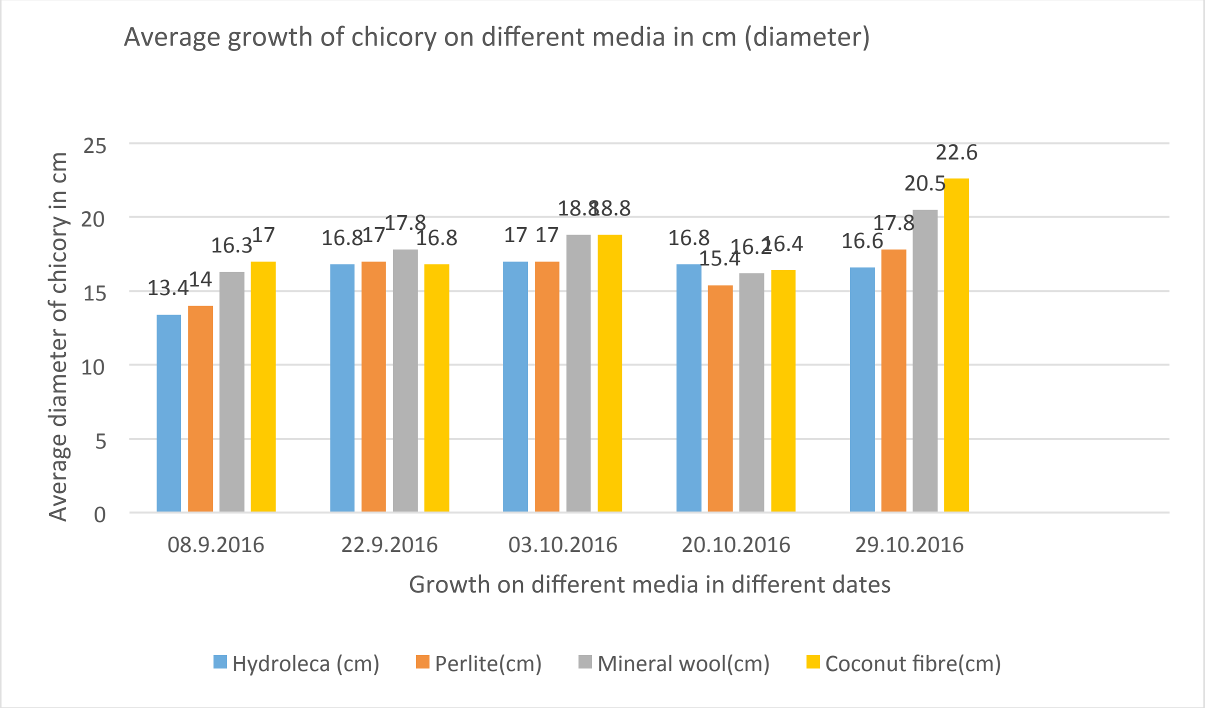

Figure 10. Average growth (diameter) of chicory on different media in living wall Experiment 3

Table 1. Ranking of plant growth based on measurement and visual characteristics (5-Excellent growth, 4-Good growth, 3-Moderate growth, 2-Poor growth, 1-Very poor growth) on the 30.07.2016 in Experiment 1

	Spinach	Basil	Chicory	Asparagus pea	Mint	Lettuce	Tomato
Mineral wool	5	5	5	2	5	5	5
Vermiculite	5	5	4	2	3	3	5
Charcoal	5	5	3	2	5	3	5
Sphagnum moss	3	4	4	2	3	2	2
Straw	2	3	2	2	2	3	2
Algae	3	3	2	2	5	2	3
Coconut fibre	5	2	3	2	4	3	3

Figure 11. Basil root penetration through coconut fibre (Living Wall Experiment 2)

Figure 12. Basil root penetration through vermiculite (Living Wall Experiment 2)

Figure 13. Basil root formation pattern through hydroleca (Living Wall Experiment 2)

Figure 14. Basil root penetration through mineral wool (Living Wall Experiment 2).

Figure 15. Chicory root penetration through vermiculite (Living Wall Experiment 3)

Figure 16. Chicory root penetration through hydroleca (Living Wall experiment 3).

Figure 17. Chicory root penetration through coconut fibre (Living Wall experiment 3).

Figure 18. Chicory root penetration through mineral wool (Living Wall Experiment 3).