



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

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Manuscripts

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

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5  
6 **Abstract**

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

23 **Keywords**

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

26  
27 **1. Introduction**

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

30 2050 (UNDESA, 2013). With this world wide population growth, the demand for both  
31 more food and more land to grow food is ever increasing (Birkby, 2016). The World  
32 Bank states that '*the world needs to produce at least 50% more food to feed 9 billion*  
33 *people by 2050*' and that '*climate change could cut crop yields by more than 25%*'  
34 (World Bank - web). There are a number of methods for increasing food production,  
35 such as using marginal lands or through genetic modifications but these are not always  
36 considered sustainable nor acceptable. Aquaponics can be seen as a promising and  
37 sustainable solution to overcome the looming food crisis. Growing more food in urban  
38 areas is seen as part of the solution and Konig *et. al.* (2016) note that as food security  
39 and infrastructure become a central issue in these urban areas, aquaponics offers one  
40 solution. Now that aquaponics is becoming more mainstream, the question that needs to  
41 be asked is, can aquaponics be made even more productive and thus more sustainable  
42 and how can this be done? This paper focuses on one aspect of aquaponics and the  
43 potential for aquaponics to be more sustainable by combining aquaponics with living  
44 wall and/or vertical farming systems to provide more sustainable food.

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

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<sup>1</sup> 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.

56 This paper provides the initial results and the issues related to vertical aquaponics as  
57 assessed through investigations and trials undertaken as part of PhD studies, during  
58 2016 at the University of Greenwich Green Roofs and Living Walls Centre.

### 59 **Aquaponics – Brief Description**

60 Aquaponics is the integration of recirculating aquaculture systems (RAS) and  
61 hydroponics in one production system (Somerville *et. al.*, 2014). It is in fact a bio-  
62 integrated food production system (Diver, 2006), where water from the fish tanks pass  
63 through filters and grow beds and back to the fish tanks. Filters remove the solid waste  
64 and the filters and the surfaces of the system itself act as a means for bacteria to convert  
65 dissolved wastes into beneficial nutrients (Somerville *et. al.*, 2014). Nitrifying bacteria  
66 convert ammonia (NH<sub>3</sub>) from fish waste water, first to nitrite (NO<sub>2</sub>) which is toxic to  
67 fish and plants and then to nitrate (NO<sub>3</sub>), which is easily and readily acceptable by  
68 plants and not as toxic to fish at appropriate levels. Thus, fish, bacteria and plants  
69 perform together in one growing community in a symbiotic process, (Somerville, *et. al.*,  
70 2014). Like high production hydroponic vegetable production, in aquaponics most  
71 production takes place in green houses where the microclimate can be controlled. The  
72 most common fruits, vegetables and herbs that are grown in the aquaponics include  
73 lettuce and leafy salads, herbs such as basil, pakchoi, kale, Swiss chard, arugula  
74 (rocket), mint, watercress, chives, tomato, spinach, peppers, squash, cauliflower and  
75 cabbage (Nelson and Pade, 2008). The production of quick growing vegetables and  
76 herbs such as lettuce with short life maturity cycles, (30-40 days for some soft leafed  
77 lettuce species such as Bibb [Butterhead] and basil) are more productive and the  
78 economic rate of return is higher based on repeat growing around the year. Additionally,  
79 ‘cut-again’ plants such as basil that can be cut and that can regrow after cutting offer the  
80 aquaponist a constant supply of the herb. Despommier (2013), reports in controlled  
81 environment conditions, eight times more produce can be achieved with indoor growing  
82 compared to outdoor growing with some leafy vegetables such as lettuce, spinach, basil  
83 and kale. The fish that grow successfully in aquaponics include tilapia, catfish, white  
84 bass, grass carp, arctic char, goldfish, koi fish and trout (Nelson & Pade –  
85 Recommended Plants and Fish for Aquaponics).

86

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

### 97 **Living Walls and Vertical Farming Systems – Brief Descriptions**

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

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

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<sup>2</sup> An acre is approximately 0.4 hectares.

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

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

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

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

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

143

## 144 **2. Materials and Methods**

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

147 1. The spatial arrangements of vertical versus horizontal aquaponics;

148 This raises issues of:

149 • Access for maintenance, management and ergonomics;

150 • Lighting;

151 • Pumping; and

152 2. Growing media suitability

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

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

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

164 Space

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

169 • Floating Raft (this is used in the University of Greenwich system);

170 • Gravel or other granular material; and

171 • NFT (nutrient film technique).

172 Water flows by gravity through the filtration tanks on through the grow beds and back  
173 towards the fish tanks where the water is then pumped back up to the fish tanks, usually

174 via an electrical pump or by 'air-lift' pump<sup>3</sup> from a sump. An air blower provides air  
175 and thus oxygen to both the fish and plants. The ratio between the different components  
176 of the aquaponics unit using the UVI system at the University of Greenwich (Figure 1)  
177 as an example is as follows:

- 178 • Fish tanks – 3.0m wide x 2.4m long (7.2m<sup>2</sup>);
- 179 • Filtration tanks – 3.0m wide x 1.2m long (3.6m<sup>2</sup>); and
- 180 • Plant tanks – 3.0m wide x 6.0m long (18m<sup>2</sup>).<sup>4</sup>

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

182 The above arrangement shows that the horizontal vegetable grow beds thus occupy  
183 more than 50% of the fish production volume of aquaponics unit and this is essentially  
184 the case for the raft, gravel and NFT systems. It must be noted that space in  
185 greenhouses which are climate controlled is an expense which needs to be calculated  
186 and using the same space to grow more vegetables must be more economical and thus  
187 essentially more sustainable. This is particularly relevant in urban areas where land  
188 values are expensive and raising productivity levels in urban areas may make  
189 aquaponics that much more economically viable. VF and LW systems, on the other  
190 hand, have an advantage over horizontal systems as the systems can be placed back to  
191 back and thus two sides of the living wall / VF system can be used to produce food  
192 which in principle decreases the space requirement. The Terapia Urbana LW system has  
193 49 plant pockets per square metre and thus utilising both sides the system can produce  
194 98 plants per square metre whereas the horizontal grow bed only can produce  
195 approximately 42 plants per square meter (Al-Hafedh *et. al.*, 2008; UVI). The UVI  
196 system plant ratio compared to the back to back Terapia Urbana system is 1: 2.42 which  
197 is a substantial increase. However, the number of plants one can produce per square  
198 metre also needs to include the access pathways that are required for management,  
199 between the horizontal grow tanks and between the VF / LW systems. Only then can a  
200 proper comparison be made. In the University of Greenwich Aquaponics Lab, the plant  
201 area of 6 metres x 3 metres which is 18 square metres accommodates 324 plants. This

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<sup>3</sup> 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.

<sup>4</sup> Note these areas include access paths and spaces between tanks which are at a minimum.



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

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

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

### 213 Lighting

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

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

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

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

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

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

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<sup>5</sup> 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.

<sup>6</sup> <http://www.cutilene.com>

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

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

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<sup>7</sup> <http://www.biotecture.uk.com/living-walls> (UK based)

<sup>8</sup> <http://mobilane.co.uk/products/livepanel> (Netherlands based but with UK operations)

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

<sup>10</sup> <http://www.cascadegarden.nemec.eu> (Czech based)

<sup>11</sup> <http://greenverticalgarden.com>

<sup>12</sup> <http://www.treebox.co.uk/products/easiwall-green-wall.html>

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

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

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

#### 295 Experiment 1:

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

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<sup>13</sup> The selection of the plants was based on the availability of seedlings in the greenhouse.

<sup>14</sup> 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.

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

### 315 Experiment 2:

316 This 2<sup>nd</sup> experiment was set up adjacent to Experiment 1, (externally facing east), on the  
317 1<sup>st</sup> of August 2016 using the Green Vertical Garden Company (GVGC) pot system. The  
318 individual plant pots were attached to a stainless steel reinforcing mesh panel supported  
319 by the scaffolding support system used for experiment 1 over 1m<sup>2</sup> using 40 pots with 5  
320 horizontal rows and 8 vertical columns of pots (Figure 3). In this experiment, only one  
321 herb bush basil (*Ocimum minimum*) was used across the whole living wall with different  
322 growing media used in the vertical columns (Figure 4). Two columns of each of the  
323 following media were used: Hydroleca, vermiculite, mineral wool and coconut fibre<sup>16</sup>.  
324 This strategy aimed to identify the best inert growing media. The system was irrigated  
325 using an irrigation pipe to supply nutrient rich water into the top row of pots and then  
326 the water flowed through each pot to the next via a small irrigation tube from a hole  
327 located at the bottom of each pot.

### 328 Experiment 3:

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

332 For all three experiments the following activities were carried out:

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

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<sup>15</sup> This tank contained 60 litres of water with added hydroponic solution manufactured by Canna

<sup>16</sup> Horticultural grade vermiculite, mineral wool and coconut fibre were used.

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

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

346

## 347 **Results**

### 348 Experiment 1:

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

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

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

### 365 Experiment 2:

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

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

### 382 Experiment 3:

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

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

- 395 • There was considerable growth difference in terms of diameter of the chicory on  
396 different media. The diameter of chicory on coconut fibre was 22.6cm compared  
397 to hydroleca at 16.6 cm (Figure 10).
- 398 • The average chicory diameter on perlite medium was 17.8 cm (Figure 10) and  
399 average height was 9.2 cm placing it in 3<sup>rd</sup> position in terms of both height and  
400 diameter.
- 401 • The average chicory diameter was 20.5cm on the mineral wool medium (Figure  
402 10) and thus the 2<sup>nd</sup> best in terms of diameter performance.

### 403 **Discussion**

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

405 Analysis of the data from Experiment 1 showed that spinach in mineral wool had the  
406 highest growth (32cm after 34 days from planting). The spinach in vermiculite achieved  
407 the 2<sup>nd</sup> highest growth (28cm) whereas the lowest growth was in straw (13cm). The 2<sup>nd</sup>  
408 lowest growth for spinach is recorded in the sphagnum moss (14cm). The conclusion is  
409 that the mineral wool medium performed best with spinach and vermiculite performing  
410 the 2<sup>nd</sup> best. On the whole both perpetual spinach and tomatoes have grown very well in  
411 this experiment. On the other hand, the asparagus peas had grown very poorly. At the  
412 end of the experiment, all the asparagus peas were poor, whereas lettuce, basil, chicory  
413 and mint grew well in the top layer and the peripheral areas of the living wall. Tomato  
414 and spinach grew best on the top row of the living wall. It is expected that this is due  
415 mainly to the additional natural light received especially in comparison to the other  
416 rows where light levels were less and caused by overshadowing of the above plants.  
417 Thus the experiment showed that the top and peripheral vegetables grew very well and  
418 that light intensity, in this instance has determined the higher growth of the plants  
419 compared to the plants growing more centrally within the living wall. The variation in  
420 growth could also be to greater nutrient availability in the top layer, but if this is the  
421 case then all the plants on the periphery and those located at the bottom would not grow  
422 very well. This was not the case. Post-harvest root and growing media analysis showed  
423 that roots within the mineral wool, vermiculite and sphagnum moss spread widely into  
424 the growing media and the back wall regardless of the plant type. This indicated the  
425 superiority of these media compared to the charcoal, algae and coconut fibre and straw



426 substrates. As noted previously horticultural grade coconut fibre was not used in the 1st  
427 experiment and the lack of root penetration is likely due to the poor quality of the  
428 medium. Good root penetration into the medium indicates a healthy plant which is well  
429 nourished. The main issue with this type of LW is that plant roots readily invade the  
430 structure of the LW and it is difficult to remove the plants at harvest (Table 1). If cut  
431 again species were used over a long period of time where replanting was not going to  
432 occur then this would be less of an issue.

433

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

435 In Experiment 2 the basil grew best on the coconut fibre compared to hydroleca and  
436 mineral wool and vermiculite media with an average height of 43.5cm for the coconut  
437 fibre, 42cm for the hydroleca and 39.6cm for the mineral wool. The vermiculite  
438 performed least well and grew to an average height of 35.6cm. The plants did appear to  
439 perform better towards the top of the living wall and towards the edges which indicated  
440 that there may have been some overshadowing effect on the inner most plants which did  
441 not perform as well. Some irrigation problems occurred where the small sized irrigation  
442 pipe leading from one pot to the lower point became blocked by the media. This  
443 occurred a number of times with the coconut fibre and vermiculite substrates. These can  
444 be readily unblocked through sucking out the clogged material but this could not be  
445 done at a large scale. In the 2<sup>nd</sup> experiment root penetration on the coconut fibre was  
446 excellent all over the medium (Figure 11). This even distribution is evidence that the  
447 water and nutrients were mixed well in the media and supported the plant well. The  
448 advantages of the mineral wool and coconut fibre substrates over the other media in this  
449 experiment was that they were very easily harvestable, being easily removed from the  
450 plant pots. The hydroleca and vermiculite materials were more difficult to work with as  
451 the material was easily displaced at planting and at harvest. Mineral wool is considered  
452 the best substrate when it came to harvesting as the whole block with roots was readily  
453 removed, but then there is an issue with recycling, whereas coconut fibre and the roots  
454 within could be readily composted. The 2<sup>nd</sup> best root penetration was observed within  
455 the vermiculite medium, but the roots did not occupy the vermiculite and pushed it aside  
456 (Figure 12). The roots within the hydroleca was superficial staying within the upper

457 regions or middle regions on the media but penetrating through and within the clay balls  
458 (Figure 13). Although the basil grew reasonably well within the hydroleca substrate,  
459 there were issues with seedling stability at the time of planting as the plants would not  
460 readily be supported by the coarse grained oval material. The root penetration through  
461 the mineral wool was very good but the roots mainly passed through the substrate and  
462 collected at the bottom of the pot (Figure 14).

### 463 Experiment 3.

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

478

### 479 Conclusions

480 The results of the above three experiments indicate that vertical farming and the use of  
481 living wall technologies is a promising area to be integrated into the aquaponics.  
482 Whereas horizontal aquaponics, apart from gravel systems, uses direct water flows, LW  
483 and VF technologies need to use media to hold the plant roots in place. Thus it is  
484 essential to ascertain the most suitable substrates and in these three experiments coconut  
485 fibre was found to be the best growing medium and mineral wool was found to be  
486 second best. There are advantages and disadvantages of both these substrates. Coconut

487 fibre and the roots within can be readily composted but when coconut fibre is used with  
488 smaller irrigation pipes, blockages can occur. Horticultural grade mineral wool performs  
489 well, but cannot be readily recycled and thus is likely to be considered to be less  
490 sustainable. The research also found that with some plants the stability of seedling  
491 plants was an issue for example with coarse grained media such as hydroleca. Issues  
492 that arose through the management of the research indicate that not all LW are the same  
493 and that plant root penetration through the substrate is a key factor. If the roots can  
494 penetrate the material of the LW this will cause problems in harvesting. Irrigation is  
495 also an issue that is key to the success of vertical aquaponics. Whereas horizontal  
496 aquaponics is characterised by free flows of water, vertical aquaponics requires  
497 pumping as well as additional piping which can become blocked because of residues or  
498 from substrates. Additional filtration may be required and suitable pipe sizing to stop  
499 clogging will be necessary with some LW systems. The experiments undertaken on the  
500 roofs of University of Greenwich Green Roofs and Living Walls Centre has illustrated  
501 that vertical aquaponics is possible. But what still needs to be shown is that difficulties  
502 can be overcome and that more plants can be grown in less space thus making vertical  
503 aquaponics more economical and more sustainable than conventional aquaponics. The  
504 spatial and energy components of this research are ongoing and the results will be  
505 published at a later date, but what we can show here is that there are solutions to solving  
506 those problems that arise specifically as part of vertical aquaponics. These are as  
507 follows:

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

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

520     ▪ An appropriate inert media such as coconut fibre and mineral wool is necessary  
521 to integrate the living wall systems with aquaponics. Plant roots need to  
522 establish readily within the media. These need to be assessed with regard to their  
523 carbon footprints and their sustainability.

524     ▪ The container (pot or pocket) in which the plants will grow needs to be  
525 impervious to roots to allow for easy extraction of the plant and easy disposal of  
526 the roots and substrate which could be composted.

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

531

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Figures

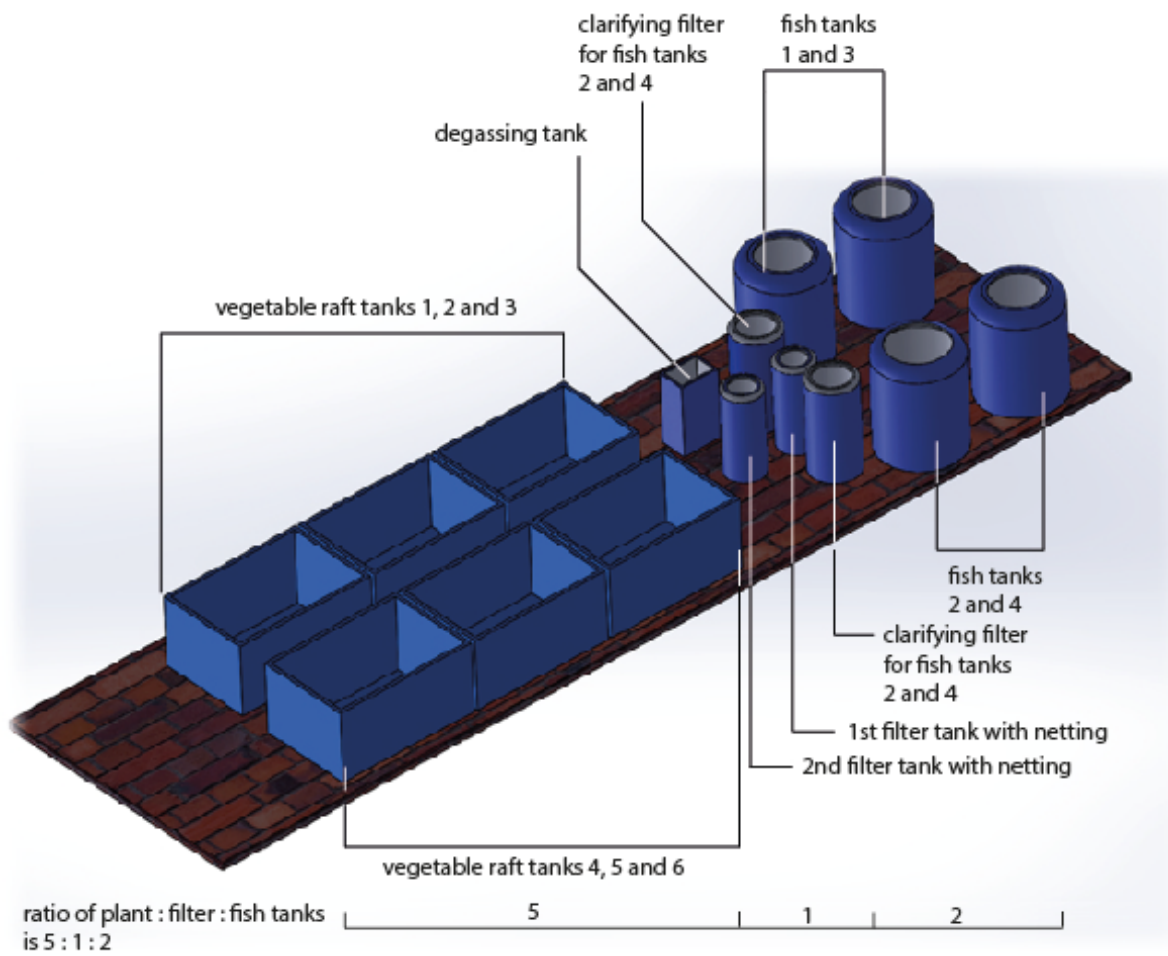


Figure 1. Spatial arrangement of the UVI system as set up at the University of Greenwich Aquaponics Lab



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

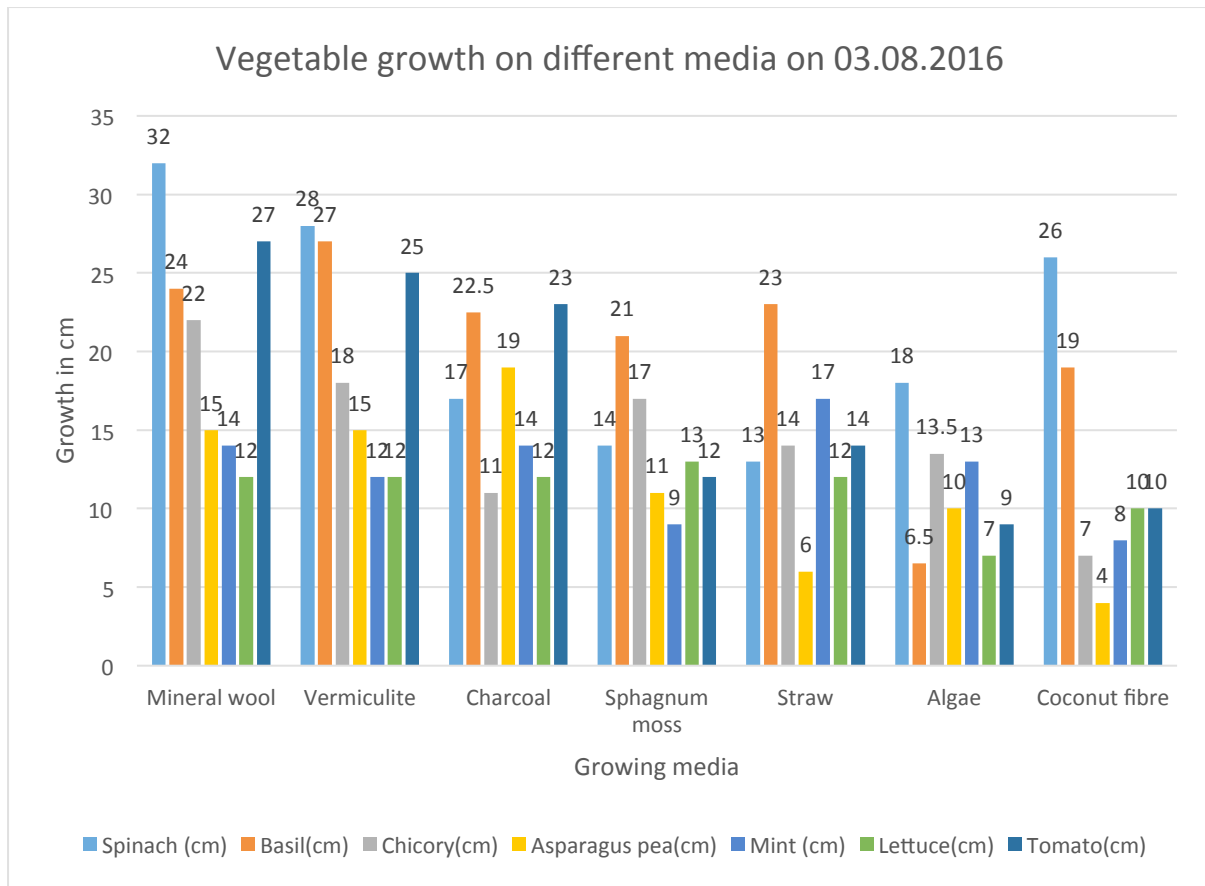


Figure 7. Vegetable growth (cm) in different media in Experiment 1

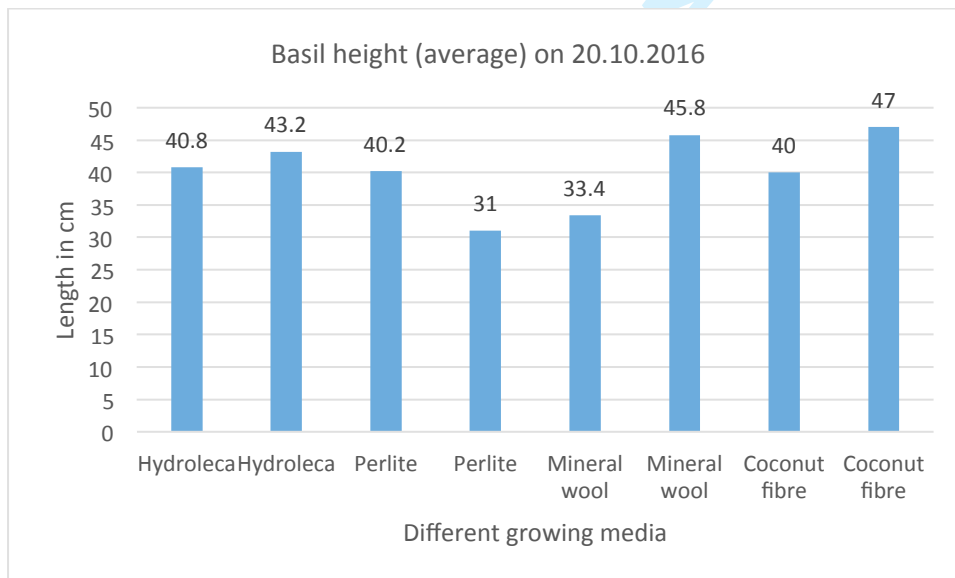


Figure 8. Basil growth on 20.10. 2016 using different growing media in Experiment 2

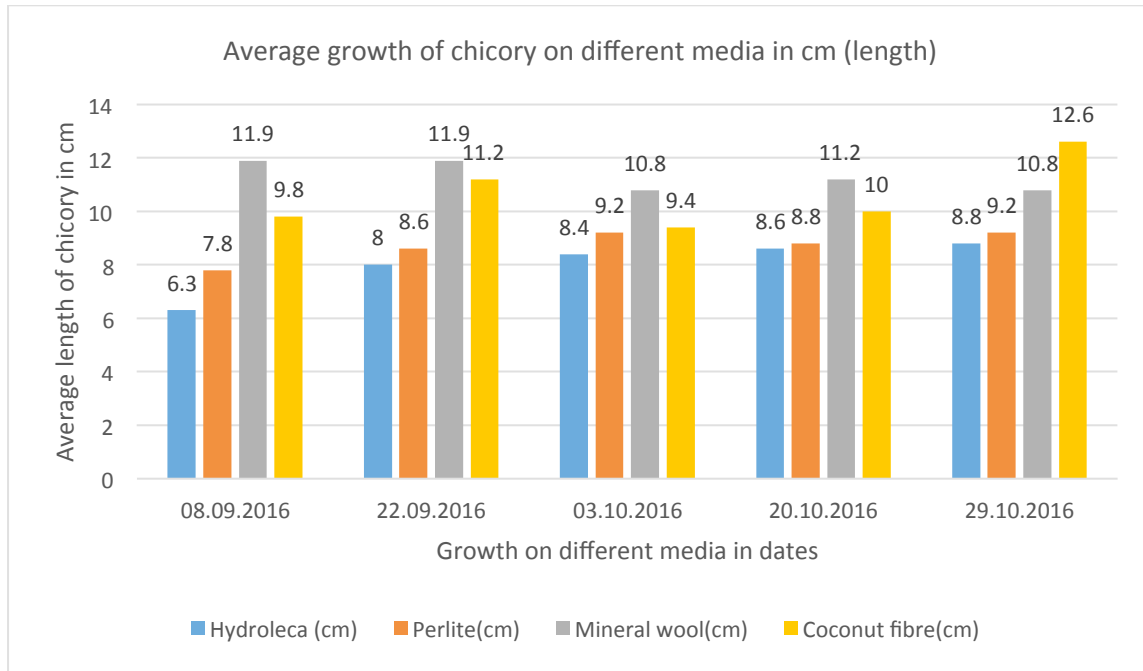


Figure 9. Average growth (length) of chicory on different media in living wall Experiment 3

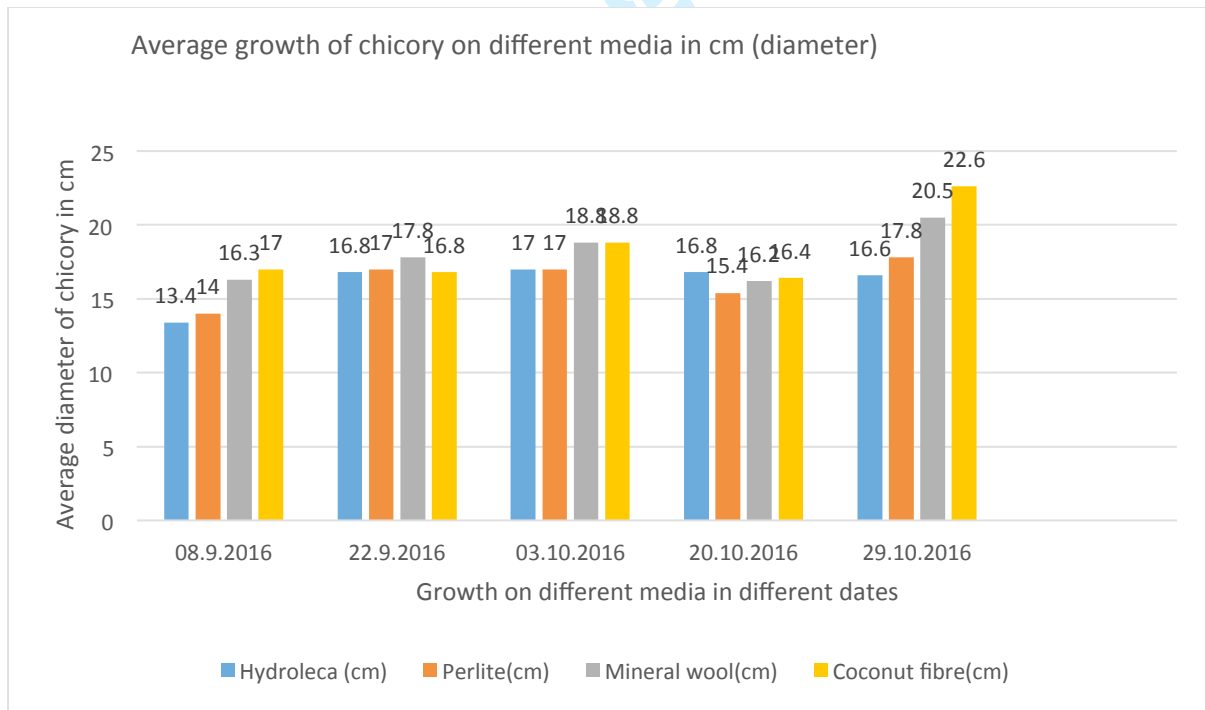


Figure 10. Average growth (diameter) of chicory on different media in living wall Experiment 3

**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**

	<b>Spinach</b>	<b>Basil</b>	<b>Chicory</b>	<b>Asparagus pea</b>	<b>Mint</b>	<b>Lettuce</b>	<b>Tomato</b>
<b>Mineral wool</b>	5	5	5	2	5	5	5
<b>Vermiculite</b>	5	5	4	2	3	3	5
<b>Charcoal</b>	5	5	3	2	5	3	5
<b>Sphagnum moss</b>	3	4	4	2	3	2	2
<b>Straw</b>	2	3	2	2	2	3	2
<b>Algae</b>	3	3	2	2	5	2	3
<b>Coconut fibre</b>	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).