Czech University of Life Sciences Prague

Faculty of Environmental Sciences

Vertical Gardens: Prototype Design for Reduction in Weight, Cost, and Complexity

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Declaration

I hereby declair that the work presented in this thesis is, to the best of my knowlede, origanal work, except as cited in the text. I have listed all literature and publications from which I have accquired information.The reserch was completed with the assistance of Peter Kumble.

Prague 22rd of April, 2015 Michael A T Clark

CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Department of Land Use and Improvement

Faculty of Environmental Sciences

DIPLOMA THESIS ASSIGNMENT

Michael Adam Thomas Clark

Landscape Planning

Thesis title

Vertical Gardens: Prototype Designs for Reduction in Weight, Cost, and Complexity

Objectives of thesis

This Research aims to develop a series of prototype living walls that can be pre seeded and improve upon the weight and cost of similar forms of living walls on the market. The research should result in several prototypes and data collected on the walls ability for successful germination as well as comparative weights and costs of the design.

Methodology

Based on existing living wall designs, a new design will be conceptualized and constructed to improve upon existing problems with vertical gardens. The new wall designs will be tested in a greenhouse using a hydroponics system to monitor the germination phase of growth. The costs of construction will be recorded and compared to market prices and the weight of the walls will be measured at various steps in the process and compared with other living walls on the consumer market.

The proposed extent of the thesis

60 pages of text, supporting images and tables.

Keywords

Vertical Garden, Seed Germination, Living Wall, Mentha spicata

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Recommended information sources

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Dean

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Abstract:

Vertical gardens have the ability to provide ecosystem services which benefit both the environment and society. These services can increase and become more effective with a more widespread use of vertical greening systems. This research looks at why vertical gardens are not more widely used and then begins to develop methods to overcome the barriers which prevent the large scale dissemination of vertical gardens. In this research project, three specific problems are addressed; one: wall weight, two: wall cost, and three: wall complexity. A series of prototype walls were designed with these problems in mind and built to be lower weight and lower cost than current walls on the consumer market. The problem of wall complexity was approached by trying to build a system which includes all of the components for plant growth except water and nutrients, and which could be easily erected and grown. The walls were designed to be flexible and easily transported, and they came pre-seeded. Once the walls were constructed they were tested in a greenhouse setting to determine if they could complete the first phase of the growth cycle which is germination, in this case using Spearmint (*Mentha spicata*) seeds. They were weighed at various stages of the process and compared to existing wall designs, and the costs were recorded and also compared with existing market products. The results of the study showed that the walls are substantially lighter and cost less than other wall designs. The growing test showed that pre seeded walls can achieve germination in a greenhouse setting. Although the results show that the concept has the potential to address these problems, there are further challenges with weight, cost and especially complexity of vertical gardens which demand further research.

Keywords:

Vertical Gardens, Living Wall Systems, seed germination, Ecosystem Services

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1. Introduction

Vertical gardens are an increasingly popular design feature in urban development. Although vertical vegetation has been used in architecture throughout history (Köhler 2008), the current form of vertical gardens known as living wall systems dates back to only about the mid 1980's (Séguin 2014). The engineering of these walls is very exciting because they have the potential to offer numerous benefits or "ecosystem services" to both society and the environment(Watson et al. 2005). They are much more than just a fancy architectural design feature if they can be developed as tools for the good of the planet and the human species. Currently there is a great deal of research into these potential benefits and how best to design vertical gardens in order to maximize these traits. The benefits can include food production (Green Living Technologies 2008), increased biodiversity (Chiquet et al. 2013), urban air filtration (Pugh et al. 2012), thermal regulation for both, individual structures and the "Urban Heat Island Effect" (UHIE) (Mazzali et al. 2012), sound reduction (Veisten et al. 2012), water filtration (Maksimović et al. 2015), environmental reparation (Despommier 2011), and economic benefits due to façade protection and reduced energy spending (Gao & Asami 2007). They are also an aesthetic improvement and benefit to the mental health of individuals (Clay 2001).

To varying degrees, all of these added benefits to our systems are under research. Much of the research is still young, but as information surfaces, it becomes clear that some of these glories come with their downfalls. Some of the biggest issues that arise from the new green wall technologies are the high costs of construction and maintenance (Perini & Rosasco 2013), the complicated hydroponic growing systems which require knowledge and experience to operate and maintain (Irwin 2013), and the demanding weight of the walls which require additional structure and an adequate building strength to support the system (Gartner 2008).

All of these complications confine and limit living wall systems. In practicality, living walls are available only to those who have the economic ability to pay for the system through its lifespan and because they have the wall, they are the ones who receive most of the benefits, or, because they are the *only* ones who have a wall, the benefits don't reach their potential. The high initial costs as well as the costs for continual maintenance and a professional with the knowledge to manage the wall makes them inaccessible to the masses (Perini et al. 2011; Irwin 2012). These costs are difficult to avoid because of the complexity and technicality of the wall systems. The construction of additional structures to manage the wall weight is yet a third cost, and unrealistic for small houses, especially in low economic areas where residents may not own their accommodations, or the integrity of the structure is questionable.

Many of the gains provided by vertical gardens require their widespread dissemination or only become greatly beneficial with their widespread use. UHIE, food production, environmental reclamation, and biodiversity all improve as benefits with increased numbers of vegetated walls, and really, all of the benefits increase the more green walls there are (Akbari et al. 2001; Despommier 2011; RSBP 2013). Living wall companies currently cater to large businesses and high paying customers. They are grand and impressive, and certainly important, but energy needs to be directed into creating volume. Future living wall development needs to look at how walls can spread rapidly, cover more area, and more kinds of structures, and how the essential benefits such as food and UHIE can get to the people and places that will most benefit from them.

Unfortunately there is no current research into developing walls that could be spread affordably to all levels of socioeconomic status, or used on varying types of structures, or managed by users with varied degrees of gardening knowledge and technical experience. The market is cluttered with numerous home products but none of them aimed at enabling the development of the ecosystem services which are the true gift of vertical gardens. In order to create a vertical garden that can be widely disseminated, research needs to examine how to reduce costs, reduce weight, and how to build a more user friendly system that can be managed simply and efficiently by all.

2. Aims of the Thesis

2.1 Thesis Goals, Intentions, and Approach

The aims of this thesis are to determine if it is possible to build a living wall system that is cheaper and lighter than current market products, and that can germinate seeds which are pre-planted in the walls.

The intention of the research is to explore alternative forms of living wall systems and in doing so improve the potential for vertical vegetation to provide services to the environment and to society. The experiment should provide a new prototype that improves upon existing living wall designs.

The approach will be to design a series of living wall prototypes that combat existing problems with vertical gardens such as weight, cost and functionality. Once the wall has been designed and built, it will be tested in greenhouse conditions with a hydroponics system in order to test the germination potential (the first phase of growth). The walls will also be weighed at various phases and compared to market products. The cost of the wall fabrication will also be recorded and compared to current market products.

2.2 Hypothesis

The hypothesis is that it is possible to build a pre-seeded geotextile living wall system that can complete the germination phase of plant development and both weighs less by unit and is cheaper than any product currently on the market.

3. Literature Review

3.1. Discussion on Living Walls

3.1.1. Definitions

Green walls come in many forms and represent an expanding category of gardening. This general identity of vegetation grown on a vertical surface can be variously termed, however there are some differences. Articles and websites often use these terms interchangeably, but the general definitions found in academic articles are as follows. “Vertical Greens”, “Vertical Greening Systems”, and “Vertical Gardens” are the umbrella names which include all kinds of walls with vegetation on them. They can then be classified by the way they grow (Perini et al. 2011; Mir et al. 2011). These groups include “Living Walls”, “Green Walls”, “Green Facades”, “Biowalls” and “Wall Vegetation”.

“Wall Vegetation” is spontaneous plant growth on walls with no human influence, or on occasion intentional plantings in degenerated walls (usually for aesthetics). Basically they are volunteer or intentional plants that find pockets of soil and nutrients in crevices (Mir et al. 2011).

“Green Facades”, are vegetated walls that derive their nutrients from soil at the base of the wall, either in the ground or in a planter box and are generally climbing plants such as ivy (Perini et al. 2011; Green Over Grey 2009).

“Living Walls”, “Green Walls”, and occasionally “Bio Walls” are all terms for the family of vegetated vertical surfaces that derive nutrients from the wall itself, or are self contained systems which means that all the necessary elements for growing the plants are incorporated into the walls. According to the vertical garden company “Green over grey”, “Living Walls” can be defined as “self sufficient vertical gardens that are attached to the exterior or interior of a building. They differ from green façades (e.g. ivy walls) in that the plants root in a structural support which is fastened to the wall itself. The plants receive water and nutrients from within the vertical support instead of from the ground.” According to Patrick Blank and George Irwin (both living wall patent holders) green walls use specific plant species to mimic their natural environment (Blanc 2001; Irwin 2010). More specifically looking at the entire living wall system (LWS), they can be defined as “pre vegetated, prefabricated modular panels or in situ applied panels… that always require a watering and nutrient distribution system… The panels are replaceable” (Mir et al. 2011).

This research is focused on the integrated nutrient systems and excludes green facades and wall vegetation. This text may use the various terms interchangeably when discussing vegetated walls with integrated water and nutrients.

3.1.2. History

The true origins of living walls are from nature itself; plants growing on cliff faces may be some of the original inspiration for vertical vegetation, and certainly are with current designs (Irwin 2010). Vegetation on walls has been used widely in architecture throughout history. The Mediterranean cultures used vines to cover buildings, and there is evidence that they took advantage of the temperature regulating qualities of vegetated walls in courtyards, using them as a form of air conditioning. Woody climbers were used in Central Europe on structures in the middle ages (Köhler 2008). Credit for the first concept of an integrated living wall is given to Stanley Hart White who patented a design for "botanical bricks" in 1938 (Hindle 2012). However, the modern living wall is attributed to Patrick Blanc, the French botanist who patented his design using textiles and hydroponic systems in 1988 (Séguin 2014; Blanc 2015). Over the last two decades, living walls have shown a rapid increase in popularity and design and are an increasing field of research and design in architecture and landscape architecture. They provide ecosystem services (see section 3.1.4), and possibilities for creating green space in areas where horizontal surfaces are limited (Wong et al. 2010). Historically, for centuries, greenery on buildings has been very common, but only in the last two decades has interest developed in their social and environmental benefits, and only in recent years has the focus shifted to contrived and regulated green wall systems (Wong et al. 2010).

Figure 3.1: Natural vegetation on cliff face (Source: Irwin 2010, Wikipedia.org 2015)

3.1.3 Types of Green Walls

This section is important to the research because it indicates the aspects of construction and maintenance of vertical gardens that require knowledge and skills beyond that of a lay person. It explains how they work and the different designs in order to create better understanding of their strengths and the elements that are successful as well as some of the issues that need to be solved and some of the complexities of vertical gardens which at this point in time make them prohibitive to use on a broad scale. This section addresses the technicality of the hydroponic systems and the need for additional support structures, which are both limiting traits of living walls.

As indicated in the Definitions section (3.1.1) this study focuses on integrated living wall systems, however for the sake of understanding, I will briefly describe the other vegetated wall varieties.

Wall vegetation:

Wall vegetation is usually spontaneous vegetation growing naturally on a wall. It takes advantage of structural degradation to find cracks, crevices or pockets of soil. It usually has an irregular growth pattern (Figure 3.2). Most often this is a natural occurrence, but there are some designs for walls where concrete walls with wide spacing are filled with soil and planted (Mir et al. 2011).

Figure 3.2: (a) and (b) Spontaneous wall vegetation (Source: Mir et al. 2011).

Green Facades:

Green Facades are climbing plants that attach themselves directly to walls, trellises, or cables. The key definer is that the nutrients are derived from the ground, either directly, or from a planter box with soil (Green Over Grey 2009; Perini et al. 2011) (Figure 3.3 and 3.4). This type of wall vegetation can take many years to fully cover a surface and can only be loosely guided by the supports provided (Mir et al. 2011).

The benefits are mostly similar to Living Wall Systems, however they are not as effective as thermal layers because they do not trap as much air as the structural green walls, and there is less potential for aesthetic variation. They also have the potential to cause damage to the building surface over time (Perini et al. 2011).

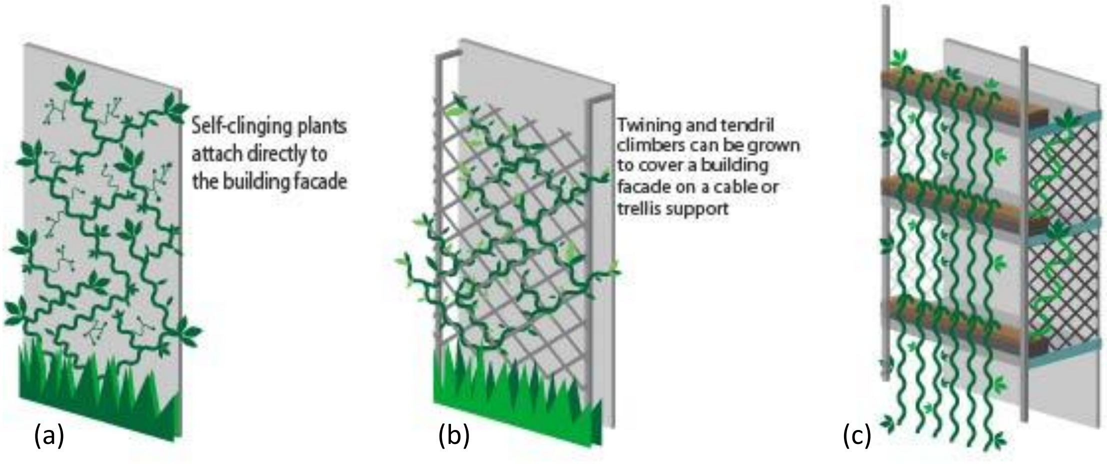


Figure 3.3: Green Façade's: (a) plants that attach directly to the wall. (b) Plants using a trellis support. (c) Plants grown in a planter box (Source: Growing Green Guide 2014).

Figure 3.4: Plants growing on a trellis support (Source: Growing Green Guide 2014).

Living Wall Systems:

Living Wall Systems are Vertical Greens where the plants are grown directly from a substrate attached to a wall. The strength of this vertical vegetation option is that they can be adapted to many conditions and cater to specific needs. They can be of almost any shape and dimension, live in any climate where shrubby vegetation and smaller vegetation grows naturally, and be either outdoors or indoors (Yeh n.d.). They also allow for a huge variety of plant species and can be engineered to grow a species which fulfills a specific purpose, especially in the urban environment (Francis & Lorimer 2011). Living Wall Systems generally use hydroponic irrigation and are separated from the actual building by a waterproof membrane (Mir et al. 2011). Living Wall Systems are an ever increasing category of designs and products (Irwin 2012) but at this point they can be divided by their system of functionality.

There are basically two systems. Pre made vegetated panels also known as (modular), and those built on site and planted later.

Premade/ modular panel system:

This category includes many variations in material and composition, but they are the same in that they are pre vegetated and then attached to a framework or a wall. The supporting framework is designed specifically for the vertical garden and is bolted to the wall. They have the ability to cover a wall in vegetation very quickly as they are pre planted (Designing Buildings Wiki 2014). They are made from plastic such as the ELT Living Walls (ELT Easy Green 2010) or stainless steel or aluminum, like Green Living Technologies system (Green Living Technologies 2015b). The growing medium can be foam, natural mediums such as coco fibers, peat or jute, and geotextiles, and in some cases soil. They usually include an irrigation system (Perini et al. 2011; Irwin 2012). The modular systems use a diverse range of plants and a wall can have many varieties from groundcover plants to ferns, edibles, small shrubs and perennial flowers (Mir et al. 2011). There are also succulent panels (Figure 3.5b) that are designed this way, though they tend to be small and expressly for aesthetic purposes, and most of these are "do it yourself" designs.

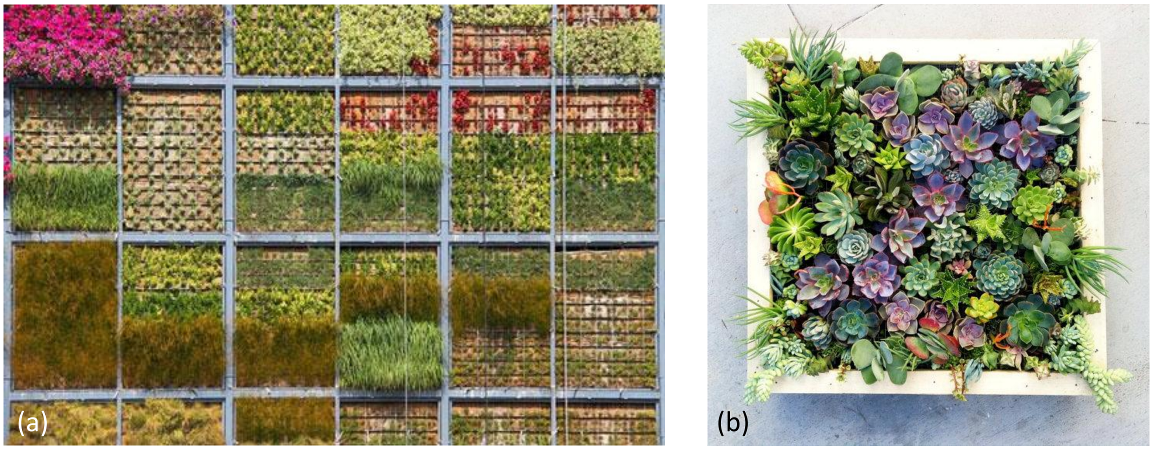


Figure 3.5: (a) Modular living wall system (Source: Fondalashay.com 2015). (b) Succulent living wall (Source: Livingwallart.com 2015).

These systems need built in watering and nutrient systems which means that the devices providing nutrients and water to the walls are incorporated in the walls themselves (Figure 3.7). Even though soil may be used, they are generally supplemented, and many of the mediums provide no nutrients at all. They use gravity to move water from the top of the system down, and a mechanical pump to push water to the top. The individual panels have inlets and outlets for water at the top and bottom which connect all of the panels allowing them to work together for water and nutrient transport. This is the basic process that makes the walls work (Mir et al. 2011). The reality of the hydroponic system is that they are often more complicated do to uneven drying and distribution of nutrients and moisture. Designers will organize the plant layout to maximize natural water movement, but they will also set up variously timed water and nutrient regimes (Irwin 2013). Water needs to be filtered to remove fallen debris and contaminates from the reservoir. Rain water can be used, but due to storage and maintenance, it is not considered a sustainable system (Mir et al. 2011). As with all systems, the orientation, size and species diversity of the wall dictate how complex the system needs to be in order to function (Perini, et al. 2011). The installation depends on the size of the wall. Some small units come as kits such as some of the Gsky panels,(Gsky Plant Systems 2010) but usually the framework is installed by the living wall company and the panels are installed already vegetated.

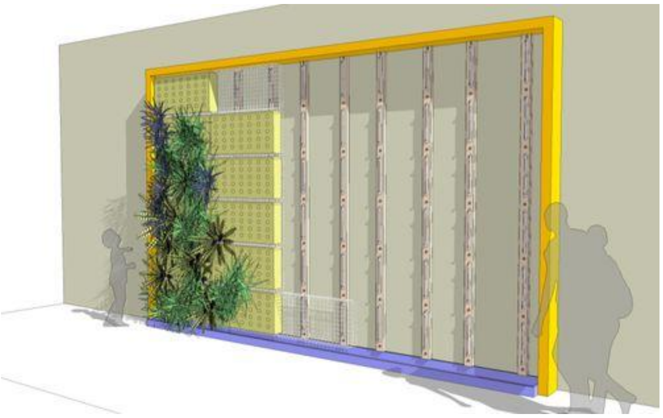


Figure 3.6: Diagram of panels in a modular system (Source: Fytowall.com 2015).

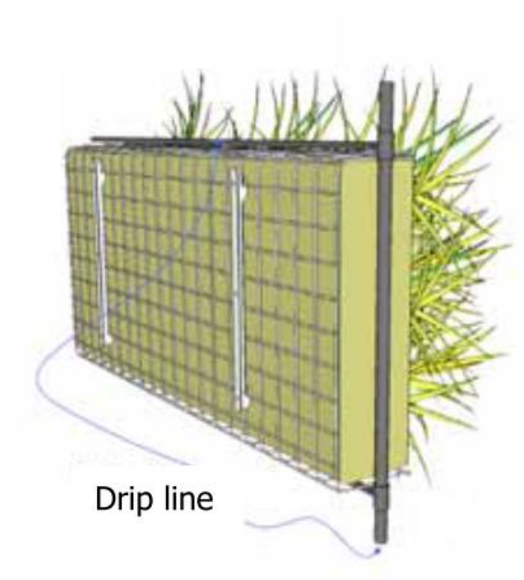


Figure 3.7: Model of individual module showing back with support structure and drip line (Source: Fytowall.com 2015).

Maintenance on these walls is the same as other living wall systems requiring weeding and trimming dead matter, but they have the added benefit of having individual units which can be removed and replaced without disrupting the wall (Gsky Plant Systems 2010). The Green living Technologies design allows for a system to be continually used. The edible walls grown in Los Angeles are used through multiple seasons, and when the season ends, the plants are cut at the roots and the roots are left to supplement the growing medium (Green Living Technologies 2008).

Walls built in Place/ Textile walls:

Textile walls are the second category of living wall systems. This design comes from Patrick Blanc and is now used by many companies. The walls create an external framework separate from the wall or building just like the modular system. They use a rigid PVC layer which is impervious and acts as a water proofing layer to protect the building. It also creates the rigidity and integrity for the whole wall (Blanc 2001). On top of the PVC there are two or more layers of textile, usually polyamide felt or other similar felt materials (Figure 3.8), but there are also examples of mineral wool, jute or coco fiber textiles (Green Home Gnome 2013; Jørgensen et al. 2014). Varieties of felts are now on the market, and are being engineered to improve water retention capacity and to be used specifically for vertical gardening. They are also called moisture retention mats, or capillary matting (Green Roof Solutions 2014). According to Patrick Blanc (2001), the polyamide felt is rot proof and has high capillarity which allows water to spread easily and evenly. His design simply uses two layers of felt, however some walls include other textile layers (Mir et al. 2011). Once the wall has been constructed, plants are inserted into pockets on the felt so that their roots are between the layers of felt and can grow between them clinging to the felt itself. The watering is provided from the top by an irrigation mechanism just as the panel system (Blanc 2001). The felt walls usually put the drip irrigation tubing between the felt sheets so that it is pressed between the two layers allowing the matting to soak up the water and spread moisture (see figure 4.1). This hydroponic system requires all nutrients for the plants be provided, and the watering system must work regularly. Just like the modular walls, the top dries more quickly and a calculated water schedule is necessary (Blanc 2001). Modern walls are using moisture sensors. The plants grown in this system are limited by the size of the pockets. Some roots may spread and interconnect, but the proximity of neighboring plants and limited root space limits the size and lifespan of plants (Mir et al. 2011). The system is designed to recycle the water by collecting runoff in a catchment basin and pumping it back to the top. It can also incorporate rain catchment (Blanc 2001).

Installation is considered quite simple and there is evidence of many “Do it yourself” projects on the internet. The actual construction of the wall requires building a framework, screwing the PVC to the frame, stapling the felt to the PVC, cutting holes in the felt for plants and inserting the plants (Irwin 2012). The major challenge is to design the water and nutrient cycles in accordance with the locations of plant species, the orientation, size and climate. This is the aspect that makes these walls challenging and requires experience (Irwin 2012). Maintenance is also quite demanding. Like the modular systems, many of the plants are hard to access depending on the size of the wall and weeding and trimming is required. Felt walls also have issues with root rot from a lack of oxygen. This happens from the layers of felt suffocating the roots. The walls are living so they are constantly changing and the nutrients and water may need to be adjusted regularly by an expert (Irwin 2012). Plants will also die and need to be replaced periodically.

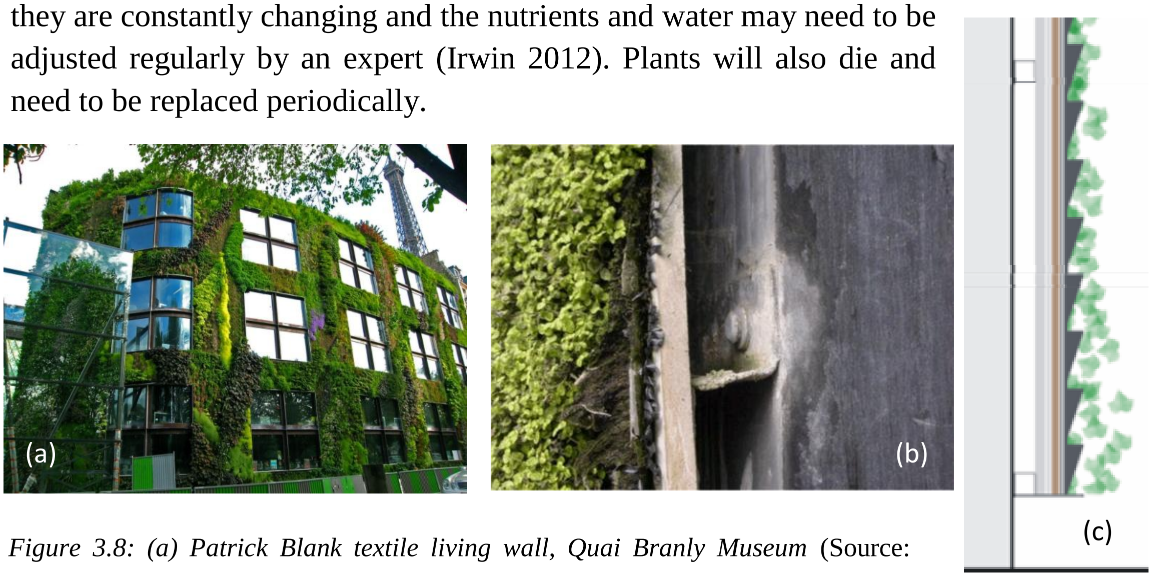


Figure 3.8: (a) Patrick Blank textile living wall, Quai Branly Museum (Source: Blanc 2015). *(b) Structure and layers of a Blanc wall* (Source: Irwin 2010). *(c) Textile wall structure diagram* (Source: Perini et al. 2011).

3.1.4 Benefits of Vertical Gardens

Note:

The benefits of vertical gardens are extremely important to this research because they justify the need to further develop living wall gardens in a way that allows them to be used on a wider scale. To understand the benefits and how they relate to ecosystem services, stands as the underlying influence behind this research (Watson et al. 2005). This section also discusses the difficulties and flaws in some of the research that necessitate further studies into the roles that vertical gardens can play in a societal and environmental context.

Discussion:

There are numerous potential benefits from vertical gardens and greening. Many of these benefits however are debated as indicated by the literature. Current research findings are either unclear about the extent of the benefits, or the negative traits of vertical greening might outweigh the benefit. Research is ongoing and often in preliminary stages, so definitive verdicts are not possible at this point. As studies and research continue to develop, it will become more clear which "benefits" have real social and environmental value.

It is important to differentiate these "values" based on their function and who they most benefit. The potential benefits of vertical gardens are widely varied and some of their traits better serve society and others better serve environmental functions.

According to the Millennium Ecosystem Assessment (2005) the functions of vertical gardens could be classed as ecosystem services. These are the services that are provided to society by the environment (Watson et al. 2005). These Categories are used to recognize the value of environmental properties that may not have a direct economic value for society. The categories include provisioning, regulating, supporting, and cultural (Watson et al. 2005). Vertical greening has the potential to fit into all of these categories.

Provisioning (material services):

Food source:

Vertical gardens are already being designed and used as food sources. Especially in cities they take advantage of unused surfaces in a setting where horizontal space is very limited (Green Living Technologies 2008; Green Living Technologies 2015a). Mobile Edible Wall Unit's (MEWU) are now on the market from Green Living Technologies (GLT), a vertical garden design, innovation and education company. These are prefabricated vertical gardens designed for urban agriculture. GLT is already offering educational courses on vertical gardening for students and has developed a project in a neighborhood in Los Angeles where they have built four public edible walls totaling 750 sq ft (~70 sq m) (Figure 3.9). They have grown such crops as tomatoes, cucumbers, strawberries, peppers, tomatillos, spinach, parsley, leeks, lavender, eggplant, zucchini, watermelon, and a variety of herbs. The walls function year around (Green Living Technologies 2008). Universities such as University of Washington are now researching the viability of vertical gardens as a food source growing green facades with hops and kiwi (Kelly 2012).

Figure 3.9: Los Angeles food bank wall sponsored by Green Living Technologies (Source: Green Living Technologies 2008).

The question is whether this production can influence food production on a large scale. Proponents of vertical gardening and urban agriculture such as Dr. Dickson Despommier, Author of “The Vertical Essay” (2011) discuss how vertical farming could become a crucial food source as the global population increases and urban areas expand. He cites benefits such as indoor vertical farming which prevents food loss due to weather and environmental disasters, the immediacy of the food (the food source would be at the site of consumption eliminating the shipping and reducing the ecological footprint), and little food would be wasted as a result of the proximity to consumers as well (Despommier 2011). According to Despommier (2011) one human requires approximately a 300 sq ft (~ 28 sq m) area of intensively farmed land to sustain them. He estimates that a 30 story building occupying one city block, approximately 3 million sq. ft. if designed as a vertical farm inside, could feed ten thousand people (Despommier 2011) .

Regulating (effects on environmental systems):

Air Quality:

Plants have the capacity to purify air and remove contaminates. Green walls are capable of absorbing toxic gas from vehicle emissions which improves the air quality, and it has been shown that vegetation in an environment reduces small particulates of less than 10 mm that are in the air. These particulates are detrimental to human health over time and particulate matter concentrations on the street level in urban areas are often above public health standards (Ottelé et al. 2010). Plants reduce a variety of airborne contaminates such as nitrogen oxide, dust and other volatile organic compounds, and also ammonia benzene and formaldehyde (Lohr & Pearson 1996; Wolverton, B.C., Wolverton 2003). One way to control this pollution is to affect the deposition rates. The pollutants adhere to different types of surfaces at different rates. Deposition is much higher on vegetated surfaces than on smooth, hard constructed surfaces (Pugh et al. 2012). According to this study in the UK, the air circulating in urban areas known as “street canyons”, where the buildings are taller than the width of the street, stays for a longer period of time and circulates locally. This circulation pattern increases deposition and the study shows that vegetated street canyons can reduce NO_2 by 40% and particulate matter by 60% (Pugh et al. 2012). So vertical gardens have the ability to work as an air filter both indoors and out. This study noted that the effects on one street canyon would be significant, so the potential of vegetated walls on a large scale in urban areas could have a dramatic impact on air quality.

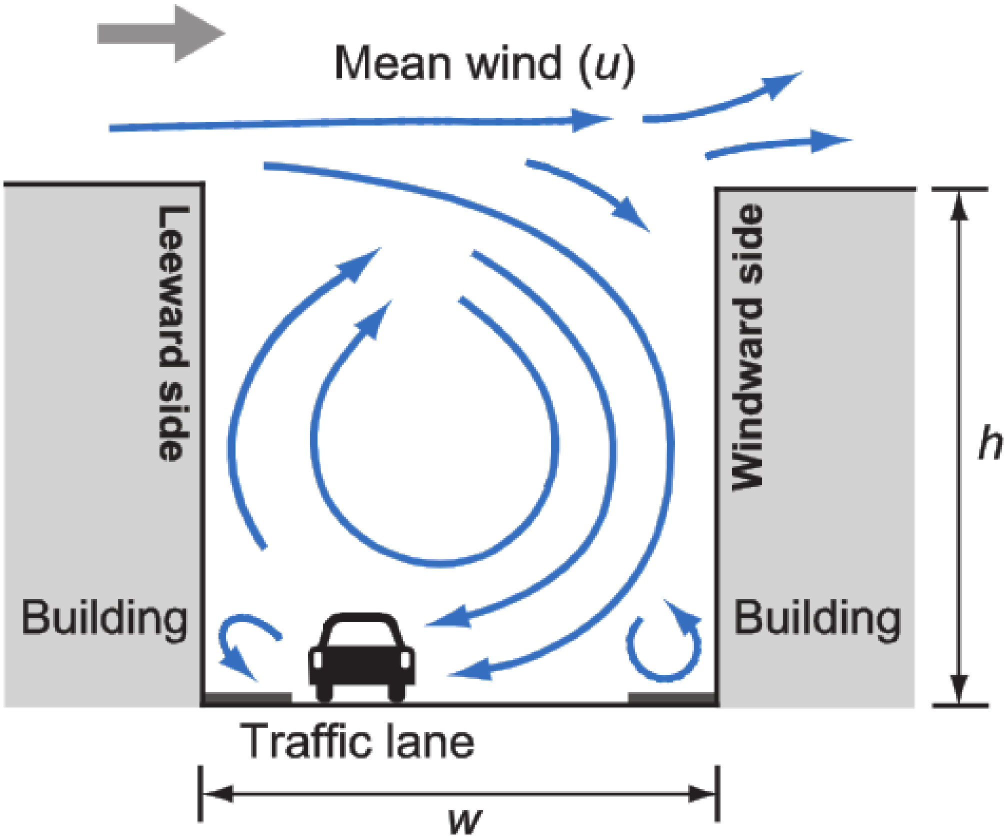


Figure 3.10: Air circulation pattern in an urban street canyon (Source: Pugh et al. 2012).

Thermal:

Vegetated walls affect the thermal qualities of individual buildings as well as the comprehensive temperature increase in urban areas known as the UHIE. In regards to individual buildings, green walls regulate temperature by both insulating and cooling the structure. The air between the vegetation and the building façade is trapped and warms creating an insulating effect (Perini et al. 2011). In warm conditions vegetation on walls allows buildings to cool by reducing the solar energy directly striking the wall. A fully vegetated wall only allows 5 to 30 % of the suns energy to pass through the leaves (Ottelé et al. 2011). A study comparing concrete walls to vegetated walls performed by the National University of Singapore noted a 6 to 10 degree Celsius reduction in temperature on the vegetated walls (Wong et al. 2010). This was in a tropical environment, and the major factors in this were the transpiration and the shading effect. One study showed that in the right conditions, in this case in northern Italy, with a large south facing wall that was not insulated, there was a 66 % reduction in cooling energy (Mazzali et al. 2012). The type of wall made a huge difference, and other types of insulated walls were only between two and six percent, but the study showed that the vegetation clearly has an impact and under certain conditions a tremendous impact.

The UHIE can cause cities to be 2-5ºc higher than surrounding areas (Figure 3.11). This happens because of artificial surfaces and their albedo, as well as from the lack of vegetation (Onishi et al. 2010). Concerning the ability of living walls to impact the UHIE, there are no comprehensive studies due to the lack of vertical gardens on a wide scale; however models have been created to predict the possible effects of vegetation on both walls and roofs of buildings. One model on green space in urban areas including green roofs and facades indicates that only 10% coverage of vegetation is enough to decrease maximum temperatures (Sussams et al. 2015; Gill et al. 2007). Another model indicates that the extensive use of vegetation on buildings could significantly reduce temperatures in urban canyons (Alexandri & Jones 2008). Yet another model performed found that 20% of the US national cooling demands could be eliminated by the widespread usage of vegetation to combat UHIE (Akbari et al. 2001).

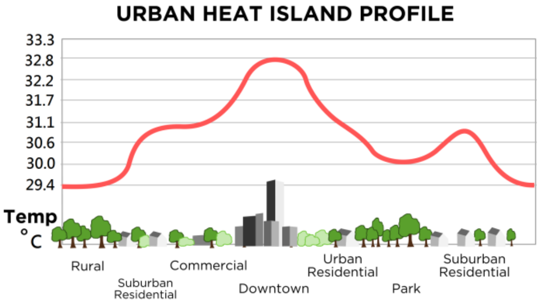


Figure 3.11: Diagram of the Urban Heat Island Effect and the areas of impact (Source: Arthro-pod.blogspot.cz 2015).

Acoustic:

Sound is a regulating service in the environment, but its impacts can be difficult to determine and sound is a difficult factor to control. By their nature, sounds travel distance, and are difficult to block out. Sounds in urban areas are far beyond anything natural and are a constant factor in the daily lives of urban citizens. According to Veisten (2012), "green walls provide an environment that both reduces noise and provides opportunities for amplifying natural and artificial sounds and creating supportive, exciting, higher quality urban micro and macro spaces. Beautification is therefore not only a visual matter, but a multisensory." This is beneficial for the health of the community, creating better conditions for restful sleep and peaceful surroundings.

Vegetation can change the dynamics of sound in three ways: 1. Absorption, where the plants trap the sound waves, 2. Diffusion, where the waves are reflected out in different directions and 3. Reduction, where the sound passing through is warped and diminished (Veisten et al. 2012). Green walls have a high attenuation especially for low and middle frequencies. Vegetation has a high absorption coefficient which increases as frequencies increase. The coefficient also increases with increased vegetation (Wong et al. 2010). In Veisten's (2012) study, they found that strategically located vertical greenery on an apartment complex in urban areas along heavily trafficked streets could not only reduce the noise level on the wall covered by the vegetation, but also for the other apartments further back in the complex. The sound was reduced 4.1-4.5 decibels. It was found that vertical gardens on quieter walls and not only walls directly on the street had a strong ability to absorb rebound noise and protect other areas (especially courtyards) from sound.

Water Recycling:

Green wall architects and “Do it yourself” green wall experiments are combining grey water recycling systems to their walls. Grey water and runoff can be collected and used to irrigate green walls (Green Roofs for Healthy Cities 2014). Many of these concepts still exist as theoretical possibilities supported by the success of green roofs and other green infrastructure such as bio swales. Often these designs are carried out as personal experiments or added benefits to a green wall design. They might also simply be tied in with other water filtration systems to maximize effectiveness (Maksimović et al. 2015). There are still many gaps in the research for the effectiveness and the efficiency of using green walls as filters. But based on the potential of plants to act as natural filters, the possibilities for vertical gardens to be used in this manner exist.

Supporting (enabling environmental processes):

Biodiversity:

The human population is growing rapidly and urban areas continue to spread. According to United Nations (UN) predictions, by 2050 the world population will be between 8.5 and 10 billion people (UNFPA, N.D.). This increases the demand for places to live and lands that support human existence such as agriculture. More than half of the world’s population currently lives in urban areas, and according to the UN the world is currently experiencing the fastest growth of urban areas in history; it is likely that by 2030, five billion people will live in urban areas (UNFPA, N.D.). With this growth, the planet will require another 100 million hectares to feed the global population with current technology, on top of the 800 million hectares already used. All of that converted land has a huge impact on habitat of animals and ecosystems. This is an area almost the size of Brazil (Despommier 2011). This situation demands that the urban areas increase their ability to support biodiversity. The State of Nature report in the UK explained that urban areas are in fact an important habitat area especially for small mammals, insects and birds (RSBP 2013). The growing cities, however, make it more difficult for these species to travel to and from natural and urban areas and the populations of many urban species are declining. In the UK, data has been collected on 658 urban species. Of that, 59% have declined and 35% are in rapid decline (RSBP 2013). It is becoming essential to develop habitat within urban areas, and green walls are one of the methods that can improve urban biodiversity. The Ans group, a vertical garden design firm who add bird and bat boxes to their walls state: “Rich in a wide variety of plant life they can provide a natural food source to support a sizeable range of invertebrates which, in turn, act as a source of food for larger animals such as birds and bats, both of which are currently under threat” (ANS Global 2014).

Another aspect of biodiversity aide provided by green walls is the walls attractiveness to pollinators. Bees and other pollinators have been largely impacted by human development. Forty-two % of invertebrates living in urban areas of the UK are showing strong declines in population (RSBP 2013). Globally about a third of all bees and wasps are threatened, and a couple species have gone extinct in the last 15 years while 70% of butterfly species are in decline (Buglife 2013). Some landscape architecture companies like Scotscape are designing vertical gardens to grow the flowering plants which attract bees, butterflies and other pollinators. Scotscape (2013) and non-profit groups like Buglife (2013) are sponsoring vegetated architecture projects that focus on pollination and partnering with companies to implement vertical greenery on their business buildings. Newcastle Science Central, an initiative to promote science, built the tallest green wall in the UK with the intention of attracting wildlife. It includes nesting boxes and bee hotels or sections designed for bees to rest (Newcastle Science City, 2014). One study in the UK looked at the use of green walls by birds. It was observed that birds actively used the vertical vegetation for food shelter and nesting, and comparatively were not observed near bare walls. They used roofs in the surrounding area as well, but were more abundant in areas with green walls (Chiquet et al. 2013). According to a study by Francis (2010) walls that are not intended as ecosystems are in fact diverse ecosystems even with sparse spontaneous vegetation. Engineered walls will better extend these ecosystems by mimicking the spontaneous growth, and even allowing for new spontaneous growth. This allows for the already present wall ecosystems to thrive (Francis 2010).

Figure 3.12: Bird on a living wall in Spain (Source: Technology4change.com 2014).

Environmental Reparation:

There is speculation on other benefits not directly provided by green walls, but secondary benefits which might arise with an increase in the development of urban greening in general. Vertical Gardens are seen by many as one element of a greater movement towards making urban areas more sustainable, and if these developments happened as they are theorized to work, there could be the added success. For example, if vertical farming was to become a viable food source, and urban areas were sites for production, external farmland could be reclaimed as natural ecosystems and habitats allowing for the development of other supporting and regulating services like carbon sequestration (Despommier 2011).

Cultural (social benefits):

Aesthetic/Health:

Although interpretations of aesthetics are subjective, vegetated walls are almost universally touted as aesthetic improvements to structures. One need only glance at online images of green walls to understand that they are almost always designed, or organized to be visually appealing, despite any other ecological benefits they may provide. They are an alternative medium for artists and most designs, beginning with the early walls of Patrick Blanc, use flowering plants, different tones, patterns, and textures to create a visually enticing image.

Figure 3.13: Artistic vertical garden (Source: Extendcreative.com 2014).

The visual appeal of vertical vegetation are not the only benefit of their aesthetic traits however, they also contribute to social health. In an interview with Stephen Kaplan, a professor of psychology at the University of Michigan, he discussed two distinct types of focus in humans, “directed attention” and “fascination”. Directed attention is a more asserted concentration which is commonly found in our active world in urban areas. It is the type of attention that comes with excessive sensory stimulation. There is a mental fatigue that accompanies too much of this type of focus. Nature stimulates the less directed form of concentration called fascination. Fascination is an automatic attention and allows the mind to rest. Kaplan’s studies on the use of nature for mental restoration began in the 1970’s and now it is widely accepted that nature has a positive impact on mental health (Clay 2001). The same report interviewed Doctor Terry Hartig, who did a study on focus and emotion after exposure to nature. In his study he asked test subjects to complete a test that was attention demanding. Afterwards he allowed some to spend time in a natural setting and others were kept away from nature. In a follow up test, the attention of those who had access to green space performed better than those who hadn’t and questioned about their emotional response to the challenging test reported less anger than those who had not had access to nature (Clay 2001). A study in 2007 looked at the impact of plant and bird diversity on the wellbeing of humans (Fuller et al. 2007). They found that the more visual natural diversity people perceived, the greater sense of well being they experienced.

It is very apparent from the extensive array of studies that the presence of vegetation in urban areas can improve both mental and social health simply by its presence and visibility. There are studies on many aspects of these benefits ranging from the impact of vegetation on healing rates for hospital patients to improving attention in children (Kuo & Taylor 2004; Park & Mattson 2009). Green walls by their nature can contribute extensively to these positive aesthetic and social benefits.

Other Benefits Not Connected with Ecosystem Services:

Economic:

The Ecosystem Services provided by vegetated walls have a great deal of value for the environment and society, but there is also the question of economic gains that can come from the use of vertical gardens. Some of these are directly tied to the Ecosystem Services and are plainly obvious for example the possibility of food production. As indicated earlier by the community vertical gardens in Los Angeles which is producing 750 sq ft (~ 70 sq m) of food (Green Living Technologies 2008). There are already designs and working models of small vertical farms. There are also the MEWU units designed for personal food production (Green Living Technologies 2008; Green Living Technologies 2015a). The transition to a production based vertical farm is simply waiting for the right person. There are already “Vertical Farms” that are using high rise buildings to grow large quantities of produce. Green Sense Farms in Indiana for example are farming on a large scale using this method growing up to four million pounds of food a year on a 30,000 sq ft plot (Bhanoo 2014). This is a different growing method than vegetated walls, but the only trait which differentiates them is the orientation of the surfaces.

The thermal balancing of buildings that was discussed also has economic value. It may save individuals money for energy costs when it comes to air conditioning or heating. Studies such as Mazzali's which show the ability to reduce cooling energy by 66% (Mazzali et al. 2012) easily lead to the conclusion that those numbers translate to energy bills. The study by Akbari (2001) that predicted a 20% drop nationwide in cooling energy using large scale vegetation in urban areas says that this could save 4 billion dollars in savings in the United States.

Market value retail prices of buildings with green walls have also been studied for their potential increase in value. The desirability of green walls may be subjective to a degree, but with potential to save costs on energy, the aesthetic and psychological benefits, noise amelioration as well as the other benefits, green walls are generally considered desirable in real estate. At least one study in Japan found that the value of housing with green walls and other vegetation mixed increased by up to 2.7% (Gao & Asami 2007). It was also noted during thermal studies by Wong, (2010) that by reducing the temperature fluctuation on the building façade it could reduce deterioration and extend the lifespan of the building.

3.1.5 Issues and Potential Problems with Green Walls

Note:

The principle questions of this thesis address issues of weight and structural demand, economic barriers and the first steps in the technicalities of the growing process in a geotextile living wall system. In this section I have included other problems with green walls in order to demonstrate the scope of the issues, and show the similarities between them and that the distinct forms of vertical vegetation have similar problems. This literature review also attempts to explore other problems that need to be addressed in order to make vertical greening systems successful on a broad scale such as environmental sustainability.

Discussion:

With all of the incredible services provided to society, the economy, the environment and to individuals, one might expect vertical gardens to be used in greater numbers. The hype and promotion found on websites advocating green walls, suggests that they have no flaws, however modern green walls and vertical gardens are still developing as technical systems, as designs as tools and as services, and in many respects their attributes are still unknown. Patrick Blanc’s wall in his home supposedly uses the original felt after 30 years (Blanc 2001) and his older public walls from 1998 and 2000 are still in existence (Blanc 2015) but with 15 years (and maybe 30 for his indoor wall) and just a few closely maintained examples, it is difficult to know what the nuances of the green walls will be, and just how successful they will be at providing the services that are expected of them.

Some of the promoted aspects of vertical gardens however, are in question, and there are some studies which are examining the viability of vegetated walls. One of the biggest questions is whether the walls are in fact sustainable. Are the walls actually economically sustainable? Are they environmentally sustainable? Are the steps required to build and maintain a wall through its entire life outweighed by its positive benefits or not?

Economic Sustainability:

A study by Perini (2013) performed a cost benefit analysis on several types of vertical vegetation systems. They looked at the installation, maintenance and disposal costs of the different green wall systems and compared them to the benefits such as real estate value, energy savings through thermal control, and air quality improvement. This study also attempted to determine whether vertical greening systems are economically sustainable based on present value, internal rate of return, and payback period. Their results found that only green facades grown from planter boxes had a benefit value greater than the costs (Perini & Rosasco 2013). This study shows that the major issues with green walls are the expenses because the costs of having the wall are not paid back through energy savings or increased property value when compared to the actual life cycle cost of the walls. This is a prohibitive factor in their widespread use. However, there are many issues with their study that are the same issues with many green wall studies; there is not yet enough information to find conclusive answers, and the variables are so many, that numerous assumptions must be made. For one, this study was set in one location, Genoa, Italy, and used a virtual building for the research. The setting of a green wall alone creates numerous variables, such as climate, costs for various services, types of plants etc… Secondly, the study was forced to make numerous assumptions. They used predictions from green wall companies of 50 year life spans, which have never been tested. They had to value various services which have no standard value such as carbon sequestration and air quality, and they had to choose not to include others such as urban heat island and food production. They note that many of the benefits are not currently valued which impacts the study. Although the study is based off current data, it falls into the realm of many studies of the kind which are lacking in adequate information to make a clear defense of their findings. The takeaway message however, is that with our current paradigm and valuations of benefits, green walls are prohibitively expensive.

Initial costs of building green walls are also high, and often prohibitive. Commercial firms charge high prices and often mandate a one year maintenance contract. There are numerous products on the market that you can buy and then construct yourself, but these too are expensive. A set of 4 felt pockets measuring 12 by 24 inches (31 cm x 61 cm), designed to place soil and plants in, costs 65 Euro just for the pockets (Plants On Walls 2015). The felt pockets are a consumer targeted product, and presumably expensive because they are marketed as "one of a kind" but it goes to show that living technologies are not cheap. The market prices in Europe in 2011 for installation and materials only, could range from 30 euros to 800 euros/m2 just for direct greening systems such as trellis and planter box green facades. Living wall systems including modules or panels with soil or other substrates, foam substrates and felt layers ranged from 350 to 1200 euros/m2. The most expensive of these was the foam substrate, and the cheaper was the felt system from 350 to 750 euro/m2 (Perini et al. 2011). The costs rise significantly with the living wall systems due to more materials, irrigation systems and more complex installation, and more plant varieties. The green facades are much simpler and require less input. None of these costs account for maintenance (Perini et al. 2011).

These costs are not realistic for consumers of a lower socioeconomic status who might benefit most from vertical gardens. Unless there is outside support or government subsidies, the costs will not allow living walls to be used by all economic strata of society.

Environmental Sustainability:

It is easy to focus on the things that green walls are giving to the environment and society, but what were the costs to create and maintain these systems? With the steps from production, the materials, the energy the maintenance and the disposal, are the positive returns greater than the costs needed to make vertical vegetation a reality?

Once again the answers to these questions are not simply discovered. The constant issue of the complexity and range of the possibilities makes it difficult to test these questions. It is especially difficult because of the numerous services provided by vertical vegetation that have no easily quantifiable value such as carbon sequestration, aesthetics, habitat, and others. When do the values of the pollination provided or the psychological health benefits equal the energy required to fabricate the wall structure? One can ask similar questions at almost every level. In a study by Feng and Hewage (2014) they performed a life cycle analyses on three varieties of green walls to determine if the energy consumption and the chemical emissions of the walls was exceeded by the energy savings and air purification of the functioning wall. They looked at the costs of walls at the phases of "1) raw material depletion, 2) manufacturing, 3) transportation, 4) installation, 5) maintenance, and 6) disposal“ and then measured it against the performance of one square meter of living wall over the walls life span indicated by expected life of materials. The simpler wall systems such as the green facades were found to be sustainable, as the material needs were minimal and simple and lasted up to 50 years. The felt textile wall, however, was found to be unsustainable, largely because of the heavy environmental impact from PVC production and its emissions, and the short lifespan of the felt which cannot offset the emissions (Feng & Hewage 2014).

The study admits a number of constraints that fit with all green wall studies. They acknowledge the numerous green wall benefits, but note they are only able to study the "two major quantitative benefits" (air purification and energy savings). They also admit that the results will be largely influenced by the materials used, as were their major findings, and the results could be different using alternative materials. They did accommodate for some variation in climate, but they noted that plant type, building type, and climate differences are all major untested factors. And lastly, the study agrees that the lifespan of green walls is yet unknown and that the lifespan of their test walls were assumed (Feng & Hewage 2014). So while this study provides valuable evidence that some green wall systems may not be environmentally sustainable, it has many limitations in its ability to measure the benefits, and to accommodate the ever increasing range of green wall systems and materials.

Another study using a very similar felt wall performed an "eMergy" evaluation of the energy consumption to the energy savings, over the lifecycle of the wall, with similar phases to the Feng (2014) study. This eMergy evaluation assigns values to the renewable and non renewable resources used in units of energy. This study was more focused, limited to south facing walls in the Mediterranean climate. It also used computer simulation based on the information from real walls to expand the study to a larger scale and compute the energy functions of the walls. This study was focused solely on the energy savings, but accounted for more factors in the energy consumption and savings such as human labor and water (Pulselli et al. 2014).

The results found that the walls were indeed sustainable over a 25 year period. They noted that plants were harvested locally which eliminated the transportation footprint, and that rainwater catchment systems were incorporated (Pulselli et al. 2014). This all indicates that the life of the wall and the way that it is designed and used is incredibly important to determining its sustainability.

Technical Challenge (System Complexity):

Another aspect of living wall systems, specifically those kinds that are not planted in the ground or that do not use soil is the limitation of the hydroponic system. According to George Irwin, the founder of Green Living Technologies, and expert on living wall systems, Hydroponic systems are complex and complicated systems that have a high rate of failure without proper experience (Irwin 2013). What this means in a practical sense is that hydroponics systems which are required for most of the current green wall systems on the market, limit the viability of green walls for the masses. Irwin notes that "Medias / root support structures, clean water, temperatures, pH levels, lighting, nutrient solutions, and oxygen exchange (oxygen to nutrient ratios), are part of the synchronization of successful hydroponic walls". He follows this up by saying "You have to be an expert in design, irrigation, indoor and outdoor plants, growth media, lighting, pest and disease management and fertilizers". While these statements might be the extreme end of green wall experience, it makes a strong point that there are numerous technical factors at work in green walls, all of which can lead to problems or failure. This aspect of the vegetated wall makes it difficult for laymen or inexperienced growers to build successful walls, and therefore limits the rapid and large scale spread of green walls (Figure 3.14 a).

Amongst the factors listed by Irwin, there are also considerations that each element of the wall has an impact on the entire system (Irwin 2013). For example, different materials as growing media will demand different irrigation configurations. And on top of that, understanding the mechanics of the pump, drip line, calculating the amount of water required, and often needing multiple water systems to compensate for gravity and different drying rates, all require knowledge which is beyond that of a lay person (Irwin 2013). Essentially, living wall systems, as they currently are, are not designed to be used by a lay person.

This may be one of the hardest barriers to address, however it is also important to note that plants want to grow. The basic needs are known and if they can be provided in some manner, there is potential for success. Amongst commercial vertical greening companies, the lush thriving image of the wall is very important, but plants naturally follow a cycle of growth and decay. A wall built for a service outside of the marketing paradigm does not have the same pressure to look perfect or be in a state of 100 percent health. Home managed walls watered by hand with added nutrients might not have the same thriving image, but they could be successful in providing services to the environment, society and individuals.

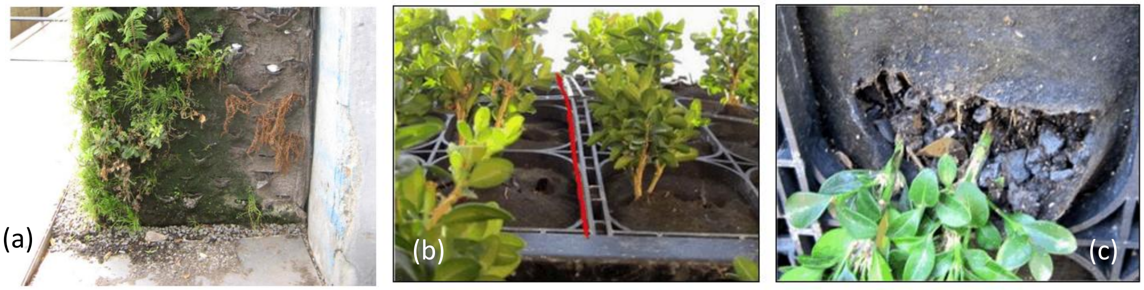


Figure 3.14: (a) Wall failing due to poor design and inadequate maintenance (Source: Perini et al. 2011). *(b) and (c) Structure damaged by weight of the wall, red line shows wall bend* (Source: Irwin 2012).

Actual Wall Problems (Plants):

The plants themselves are a wholly different area of knowledge that can lead to complications. Choosing appropriate plants to achieve benefits, choosing plants that work together, the debate about local or imported plants, plants dying from various causes, orientation of the wall, season, climate, elevation and exposure are all factors that can influence the success of the wall. These make every wall unique and require that it be managed individually (Blanc 2001; Irwin 2012). This lack of uniformity also creates a challenge for creating walls that could be distributed widely and used on a large scale.

Aside from determining which plants to use to provide the most benefits, or the greatest success of a benefit, it is important to understand which plants work together. Two plants might provide similar services, but not grow in the same conditions. This leads to difficulty in keeping the plants alive because of differences in water, light and nutrient needs. The factor of growing on a vertical orientation makes it difficult to predict the distribution of water due to gravity. It is common to find the tops of walls too dry and the bottoms too wet, also causing plants to die or grow poorly (Irwin 2013).

Imported plants, or plants with greater needs in the environment might have a greater environmental impact (Pulselli et al. 2014). Plants have unique needs and when they are not growing in their natural habitat, they are more susceptible to pests, disease, and other ailments. One of the big problems with green walls in this situation is their vulnerability to root rot due to suffocation. This is especially common with felt walls which don’t allow enough oxygen between the layers and suffocate the roots. Also contaminates to the water source can lead to infections and die offs (Irwin 2013).

In the end, living wall systems require a large amount of maintenance, which may counter their benefits. They require both time energy and knowledge which are not available to all people.

As said above, vertical gardens should be understood in degrees. A professional wall has a higher standard than a private wall in a suburban area in that the professional wall has an expected level of success and was designed and built by someone with special knowledge, but gardens of all kinds are successfully grown by uneducated gardeners all over the world. What is important is to disseminate a form of garden that can begin to be used by gardeners and grown simply with the necessary information being little more than traditional gardening, and an interest in the survival of the plants.

Structural Needs/Weight:

The weight of the living wall can play a big role in which locations can accommodate them. Unless the wall is free standing, or self supporting, the building structure must be able to manage the added weight (Figure 3.24b, c). There is an endless range of building types and strengths. For many engineered buildings in cities, this weight is not a problem, but if green walls were to become more common in residential neighborhoods, or as a viable development plan in developing countries, the weight could play a role. Most walls also require some extra structure or frame work from which the wall will hang. This drives up weight, cost, and technicality.

Patrick Blanc's felt and PVC walls are around 30 kg per square meter with the metal frame (Blanc 2001). His wall is advertised as a light weight wall that can be placed on any wall without height or size limitations. It may not be a problem for modern, large or engineered structures, but this weight is enough that the strength of the wall must be considered. Although there is no right or wrong judgment on the weight of walls, the lighter they are, the more places they can go.

ELT Living Wall Company uses modular panels with a growing medium. Their weight is about 75 kg per square meter when saturated (ELT Easy Green 2010).

This shows that the difference between the modular systems with a growing medium and the textile systems using felt, other geotextiles and PVC is dramatically different.

A company called Green over Grey produces a living textile wall that is 20kg per square meter. They claim that this is the lightest wall on the market (Green Over Grey 2009).

Green wall guides suggest that an engineer is consulted when building a green wall. The risks of applying too much weight to a building are potential damage to the wall, or in the worst case, potential collapse causing property damage and possibly injury (Gartner 2008). There are a number of weight factors to consider when adding a green wall to an existing building or vertical surface. The first thing to consider is the final constructed weight of the entire wall, but there are additional weights that could be added such as maintenance equipment like scaffolding, and the people who could be using them. Another factor is the "transient load" which is a moving short term force including wind and seismic activity (Growing Green Guide 2014). It is also important to plan for the mature weight of the plants which might not be evident when the wall is built and depending, on the plant variety and wall size, could change the weight substantially. The weight of the wall when fully saturated will also be much heavier. The older the wall and the larger the area of vegetation, the more important it is to know the weight (Growing Green Guide 2014). Engineers recommend that the firm who designed the wall always be consulted for load issues (Gartner 2008). This is valid if a green wall company was used, but consultation may not be available for "Do it yourself" green wall construction.

Figure 3.15: Aluminum structural framework for a geotextile living wall. It is in the second phase of construction and partially covered by white rigid PVC sheets (Source: Irwin 2012).

3.2 Supporting information

3.2.1 Hydroponics

Hydroponics systems have the ability to control all factors involved in the growing process of plants. This makes them both capable of eliminating all problems, and very complex to use. Hydroponics is a growing method that removes soil from the growing equation. It eliminates issues such as disease or contaminates that result from soil; however soil also acts as a buffer and a nutrient stabilizer allowing the plants to acquire the nutrients they need and to leave what they don’t. With hydroponics that buffer has been removed, so the water and nutrients must be very specifically calculated to ensure that the plants neither get too much nor too little (Şahđn et al. 2014). Even so there are problems such as root rot (*Pythium*) caused by a non sterile system (Colorado State University 2014), and any number of failings caused by problems with water temperature and pH, nutrient balance, water oxygen, and growth medium temperature. If used correctly however, the system can be more efficient with water and nutrients than traditional growing methods (Şahđn et al. 2014).

The main thing that changes with hydroponics for vertical gardens is the orientation and therefore the added difficulty of the uneven distribution of water and nutrients. The hydroponics system in connection to the plant varieties is the most complicated part of the vertical garden (Irwin 2013). This is the factor that makes a wall of diversity and of size much greater than a few square meters difficult to manage without professional assistance. All of the hydroponic systems researched and found on the market utilize a built in irrigation system.

3.2.2 Geotextiles

Jute:

Jute is rarely used for vertical gardens and is mostly heard of in “do it yourself” projects (Green Home Gnome 2013). However, it has a number of attributes which make it a great candidate for vertical gardens. It has both high water retention and good drainage, able to hold up to 400 % of its volume. It is cheap and abundant and ecologically it is low impact, making it more sustainable than synthetic versions like felt (Choudhury, N.D.). The problem is that it will rot more rapidly than the other textiles (Worldjute.com 2002) (Figure 4.3).

Coconut Fiber:

Coconut Fiber is used in vertical gardens and other hydroponic setups as a rooting medium (Jørgensen et al. 2014). Coco coir can only hold 150% of its volume and drains quickly. So retention abilities are poor compared to the other textiles however it is not as dense and allows some air to pass through allowing oxygen to get to the roots; it is also cheap (Choudhury, N.D.) (Figure 4.3).

Polyamide Felt:

Polyamide Felt is the synthetic fabric designed to retain a large quantity of water. It spreads water in a homogenous distribution (Blanc 2001). It is widely used for vertical gardens and many varieties are designed for this purpose. Some can hold as much as eight liters per square meter (Green Roof Solutions 2014). Their major flaw is that they do not allow oxygen to the root area of plants and create the conditions for root rot (Irwin 2012) (Figure 4.3).

3.2.3 Spearmint (*Mentha Spicata):*

Mentha spicata known commonly as spearmint is an herbaceous perennial plant that uses rhizomes to spread. It is indigenous to Europe as well as other parts of the world (Huxely 1992). Spearmint is a common edible grown in vertical gardens, especially “do it yourself” gardens, but also in Projects like the Urban Farming Food Chain program (Green Living Technologies 2008). It is popular due to its hardy nature. Spearmint has shallow roots and can be maintained at a reasonable size (McCormick 2013). Mint can also grow in both confined places or with room to spread, and its runners will start new shoots in vacant areas. This feature of the plant allows it to create a solid ground cover (Bonnie Plants 2015). Mint species are hardy in growing zones 4 to 11 (Park Seed 2015). These zones are determined by climatic conditions, especially low temperatures that plants can endure. Mint can survive as low as -35^{o}c (USDA 2012). By nearly all sources, mint is considered an easy plant to grow. Despite their hardiness, the germination phase has a number of variables that increase the likelihood of success. According to Baskin and Baskin (2014) light, moisture, oxygen, temperature and sometimes ph values are key factors to successful germination of all seeds. In the case of *Mentha spicata* the seeds should be sewn no deeper than 5 mm in the substrate as they require some light to germinate. They are quite accepting of variation with ph and tolerate a range from 5.5 to 7.5, but 6.5 is ideal, and their germination temperature range can also vary a great deal but between 20 and 30°c is ideal. If it is cooler, the germination might happen at a slower rate (Park Seed 2015). Mint prefers moist well drained soil, but during germination it is better to keep the seeds consistently damp (Herbgardening.com 2014). Once the cotyledons and the first two true leaves have formed, nutrients can be administered (Vancleave 2015).

Figure 3.16: Spearmint (Mentha spicata) (Source: Wikipedia.org 2015).

3.2.4 Dissemination of Vertical Gardens

Currently vertical greening systems and living wall systems are not widely used. They are still a developing technology where the systems are often complex, the weight to great, and the cost too much, especially for many situations such as low socioeconomic areas where green space is lacking, and the inhabitants could greatly benefit from the food source and other benefits. Dickson Despommier, (2011) in his essay on vertical farming, talks about the continued growth of urban areas and the need to feed those populations. He claims that growing crops up rather than out is the solution to feed those populations without so much waste (Despommier 2011). In a study by Cilliers et al. (2012) on the differences in private garden plant growth in urban areas along socioeconomic divisions, it was found that lower socioeconomic groups are more likely to grow provisioning or useful plants such as food and medicine and fewer ornamental plants than the higher socioeconomic groups. These studies were from various African cities, mostly in South Africa, but with some data in Australia and Latin America. This study shows the reliance on ecosystem services amongst lower socioeconomic groups. The poorer communities also had smaller areas of green space and less access to public green space (Cilliers et al.

2012). In another study by Shackleton (2014) they discussed the migration to cities where the majority of new residents are low income. The study was also in South Africa and compared government housing projects to the informal low income housing areas. They found that the planting of trees and green space in the government projects was not considered in the development plan and the density of trees was much lower than the informal areas. It also indicated that the livelihoods coming from tree products in the government developed project areas were lower (Shackleton et al. 2014). While these two studies are dominantly in South Africa, they stand to represent that urban green planning in low socioeconomic areas is lacking, and that those demographics benefit from the provisioning services provided by green space, and that green space is often limited. Though it is hard to find discussions on developing vertical gardens for mass use and dissemination to the populace, there are murmurs within the countless articles and reviews of vertical gardening that are asking in what direction the field will go.

4. Methodology

4.1. Methodology: Steps and Procedures

The methodology used in this experiment included the design and construction of a living wall prototype, or rather three prototypes which used the same design but different growing mediums. The constructed walls were then used in a test to see if it was possible to germinate seeds which were pre planted in the walls, and to see if there were differences between the various types of media used. The experiment was conducted in controlled greenhouse conditions. The additional steps in the methodology were to weigh the walls and to record all costs for their construction. This methodology was designed to examine the first steps in the development of an alternative living wall system with the goal to determine possible weight reduction, cost reduction, and simplification of the living wall growing process.

4.2. Methodological Concepts

Concepts for the methodology of the experiment came from the consideration of existing challenges with vertical gardens, and with partial consideration of a design that could be used by amateur gardeners. Some parameters had to be controlled in order to limit variables. In the case of the experiment, the use of a regulated greenhouse and a hydroponics irrigation system were employed for this purpose. However the design of the walls was geared towards further experiments where the walls could be located in less controlled locations such as outdoor conditions, and also watered by hand with only the addition of nutrients necessary.

Some of the considerations when designing the walls:

- Light weight. The walls needed to be a weight that could be managed by an individual or at most a few inexperienced individuals lacking machinery and tools needed for installing a large structural wall, basically it should be easily set up by a lay person. The tools needed to mount the wall should be basic household hardware tools. Although it is impossible to say that these tools will be available at all venues, the simplest tools considered necessary were a hammer and nails. And though not all structures can be considered for their weight bearing capacity, the weight of each unit should not require equipment to carry or hang. At a size of one square meter for each growing units, the intention was to build a wall that did not exceed 10kgs when fully saturated.
- The wall should come equipped with its own protection for the structure it will hang from. The structure should need no barrier or water proofing, so the back of the wall

that faces the structure needs to be impervious. In an ideal situation it would be extended away from the wall to allow air to pass behind.

- Aside from the weight it should be easily transported. Rigid materials become increasingly cumbersome and difficult to manage as their size increases. This gave rise to the idea of a flexible textile wall that can be rolled and easily transported when dry. Many sizes of such walls could be built, but they could also easily be constructed as section and hung next to one another fulfilling the same role as a single piece vertical garden.
- The walls needed to be affordable. This is also a very vague notion as affordability varies greatly by society and individual and is never uniform. As a starting point, the goal for this wall was to build it with materials that cost less than the least expensive market competitor offering similar textile based green walls. According to Perini et al. (2011), the low price end of the market for textile walls is approximately 350 Euros per square meter. This cost could include installation, management and service contracts on top of the wall itself. The intention for these walls would be that the wall itself and nutrients to support the plants would be the only costs.
- Because the design would largely be based off of existing wall designs using similar materials, it would be assumed that the life cycle would be similar to existing textile wall designs. The design could also include the possibility of replanting in the case of plant failure or mortality.
- The type of plants that can be grown is a massive area of research and is beyond the scope of this study. In the case of a hand watered wall, it is likely that either one plant variety or types of plants with very similar requirements be planted together. The simplicity of the walls might limit the plant diversity; however multiple wall sections with distinct species could be placed in close proximity (see figure 4.9c for example of possible wall proximity). The success of these walls would ultimately be measured by their ability to provide the services that benefit the environment, society and individuals. Once the wall design exists, it could be customized and tailored towards specific functions, climates purposes or conditions.
    - The design concept that was proposed for this experiment when considering the plants was that their room for rooting not be hindered, so the interior of the walls where the roots would take and spread should allow those roots free range to grow as much as possible allowing maximum plant growth.
- The walls should be as close to “all inclusive” as possible, meaning that the simpler the wall is the more people are able to use it and the more widespread its application can be. This gave rise to the concept of a pre-seeded wall where it need only be hung and watered until the seeds germinate, and then watered with supplemental nutrients. An inclusive wall eliminates transplanting, and the need for space that comes with that. The sacrifice could be the look of a lush verdant wall where all plants are

successful, but a wall that is designed to provide services can still provide them even if 100 percent of the plants have not germinated and grown.

4.2.1 Wall Construction

The first step in the methodology was to design and construct the walls. The basic organization of the walls was based on the designs of Patrick Blanc which include two layers of textile material and a third layer at the back made of an impervious material. The Patrick Blanc design uses two layers of polyamide felt which will hold the root wad of the plant between them, and they are stapled to a sheet of rigid PVC (Figure 4.1). It is a very simple construction design that has been proven to be successful, especially with the success of Blanc's walls.

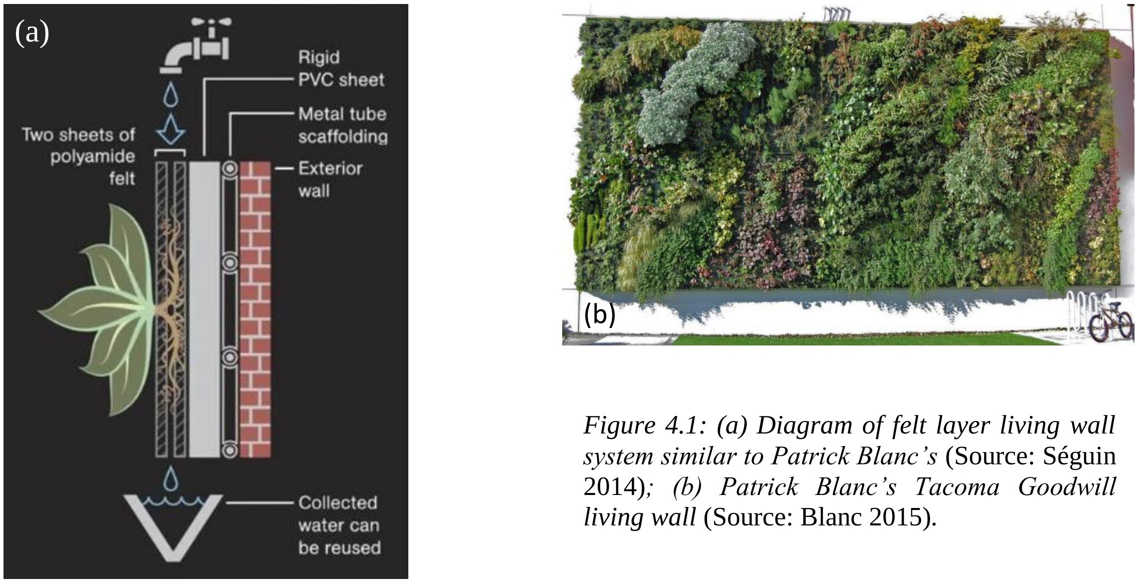


Figure 4.1: (a) Diagram of felt layer living wall system similar to Patrick Blanc's (Source: Séguin 2014)*; (b) Patrick Blanc's Tacoma Goodwill living wall* (Source: Blanc 2015).

These walls took the basic concept of three layers, but made one key change by replacing the rigid PVC backing with a thin flexible layer of black plastic pond liner. It is an impervious barrier like the rigid PVC, however it is much lighter (Table 5.6 and 5.7) and it allows the wall to be rolled or folded making their transport much easier by reducing their dimensions.

Three prototypes were built, all of them with black plastic backing, a top layer of polyamide felt and a thin layer of black ground cloth that served only to block light from passing through the top felt layer which was white (Black felt would be ideal because it would not be translucent like the white is. This is important because the roots need to be in complete darkness (Jørgensen et al. 2014), but in this case color options were limited by the availability of the resources). The only component that varied in the three walls that were constructed was the middle layer of textile; one wall had a second layer of polyamide felt, the second wall used a jute geotextile, and the third used a coconut coir geotextile. These materials were selected for their distinct water retention properties, their different costs and their different weights.

The water retention for the textiles was tested by soaking each wall with seven liters of water; the amount of seven liters was simply used because it was the necessary quantity to submerge the walls. The walls were submerged in the seven liters of water until they were fully saturated and then placed under 150 watt grow lights with a room temperature at a steady 25 degrees Celsius. The temperature was the recommended average for growing mint (Bonnie Plants 2012; Herbgardening.com 2014; Park Seed 2014). The double felt wall was able to absorb approximately 3.5 of the seven liters of water. The jute and felt wall held approximately three liters, and the coconut fiber and felt wall absorbed 2.5 liters. After evenly soaking, the walls were oriented in vertical position and their drying time recorded. The wall was considered dry when it was dry to the touch both on the surface and between the layers.

Table 4.1 drying time for geotextiles used in walls).

	Felt/Felt	Jute/Felt	Coco Fiber/Felt
Surface	solid	1cm grid	2cm grid
Drying time: top 1/3	~ 1.75 hours	~ 1.25 hours	~ 1 hour
Drying time: bottom 1/3	~ 3 hours	~ 2.5 hours	~ 2 hours

One factor based on the availability of materials was the nature of the material surface or design. The felt is a solid layer which improves the water absorption, but restricts the oxygen (Irwin 2012) The jute and the coco fiber textiles are both mesh designs with woven fiber strands. This allows a great deal more open area which both reduces their moisture carrying capacity, and increases the available space for oxygen within the wall. These surfaces could also have an impact on root development within the walls; however that is beyond the scope of this study.

Figure 4.2: (a) Felt textile. (b) Jute textile. (c) Coconut coir textile (Photo: Author).

The walls were one square meter each and have a profile of approximately one cm when all the layers are connected. The dimensions of the walls were based on the limitations of the greenhouse space primarily, but also to use basic dimensions that could easily be extrapolated.

Step by step instructions for the construction of the textile green walls were as follows:

1. All layers of material were cut into one square meter section.
2. The layers of each wall were organized as described previously: (plastic backing, geotextile layer 1, geotextile layer 2, light barrier) and then sewn together by hand using thread (it would be more efficient to use a sewing machine if available). The stitching first followed the perimeter of the squares and then subsequent stitches were added to the edges of plant pocket locations. These stitches were small and only at single points so as to not hinder root growth of plants. Therefore the roots could spread across the wall as far as they needed to without barrier (Figure 4.4b).

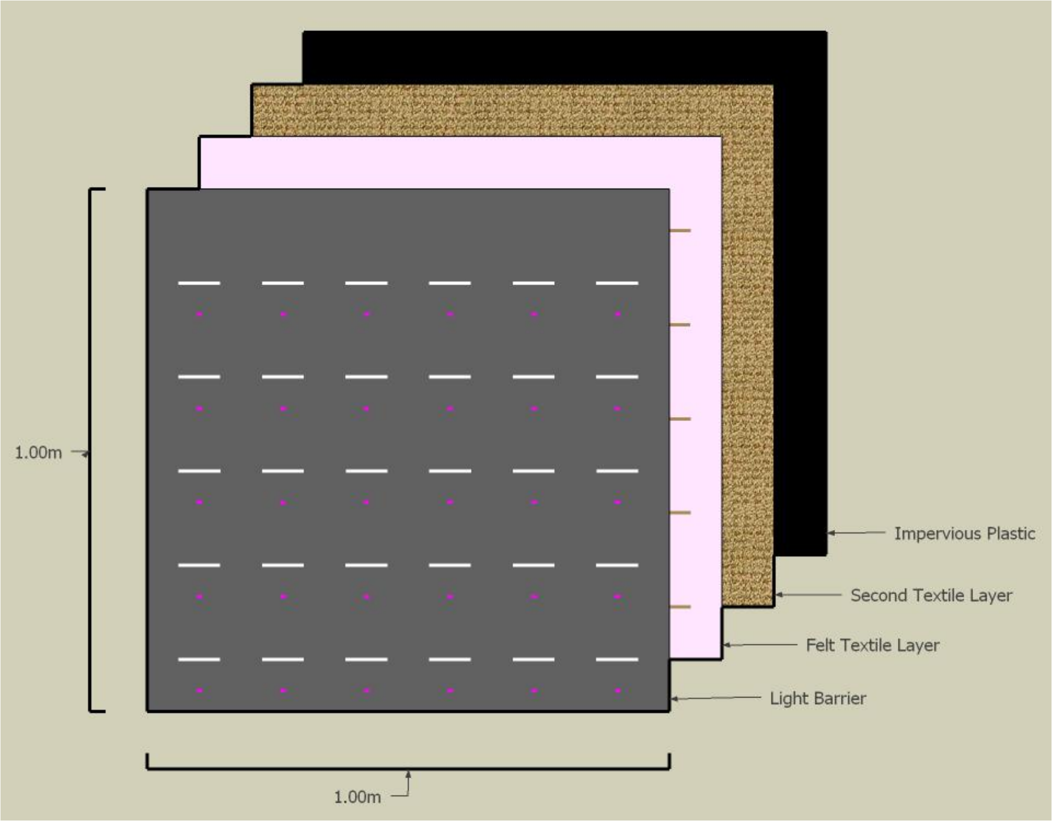


Figure 4.3: Organization of wall layers

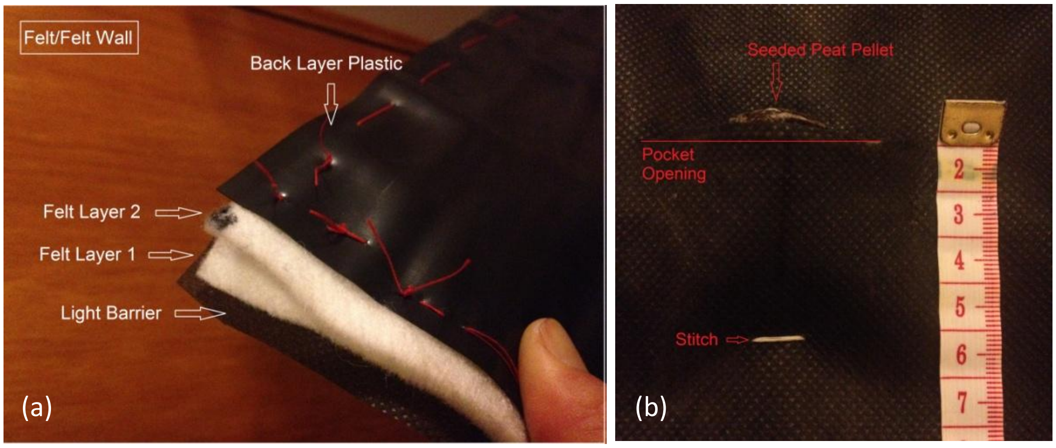


Figure 4.4: (a) Felt wall stitched together. (b) Stitch placement on the wall face (Photo: Author).

3. The plant pockets were then laid out with each wall containing thirty pockets; six columns by five rows. The pocked width was 8 cm, and pockets were spaced 8 cm apart, with 6.5 cm on the edges. There were 18 cm between the rows, and 10 cm beneath the bottom row. They were arranged so that each plant had the same growing space. The pockets were cut in the top layer of the felt textile horizontally in a straight line with scissors. A stitch was added 4cm bellow the opening of the pocket on center. This was to prevent the seed plug from falling through when inserted (Figure 4.5).

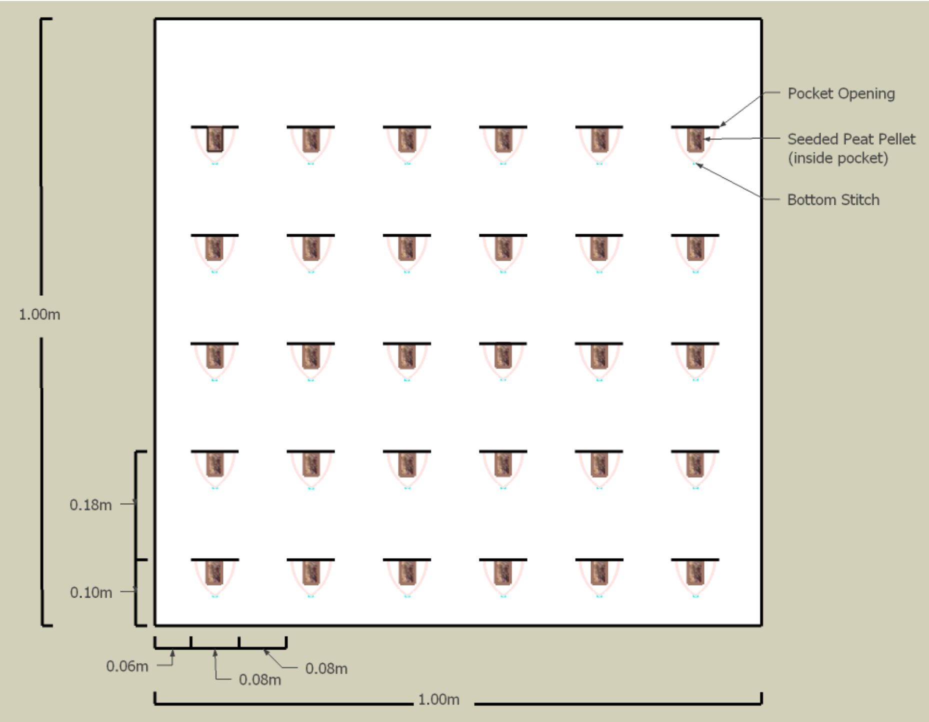


Figure 4.5: Organization of pockets on wall.

4. After the wall layers had been secured, the next phase was seeding. This phase added an additional element to the walls. Seed starting pellets made from compressed sphagnum peat were seeded and then inserted into every pocket of the walls. The compressed seed starting pellets used were Roseto, Jiffy brand, 24 mm in diameter, and approximately 3.5 cm in length when saturated. The pellets are compressed when dry, and when saturated they expand. These seed starting plugs were selected largely because of their cost and because of their availability. They were the only seed starting medium available in retail stores in Prague. There is some consideration of other seed starting mediums addressed in the discussion section, however, for the purpose of seed germination, Jiffy pellets are designed for the task and are a contained medium which produces little loose material. They are also light weight, cost effective and available. They are widely considered an effective method for starting seeds (Jiffypot.com 2015)

Table 4.2: Jiffy Peat Pellet Specifics.

	Jiffy: Sphagnum Peat Pellet
Dimensions	24 mm diameter x 35 mm length (when saturated)
Water absorption capacity	15-20ml
Drying time in 25 degree conditions	~ 10 hours

Figure 4.6: (a) Diameter of dry peat pellet. (b) Length of dry peat pellet. (c) Length of wet peat pellet (Photo: Author).

5. A tiny hole was drilled in each dry pellet no more than three millimeters in depth and then two spearmint (*Mentha spicata*) seeds were inserted using tweezers, as per planting requirements (Evans & Blazich 1999; Park Seed 2014) (Figure 4.7). The pellets were then put in the pockets of the textile walls still dry with the seed holes facing upwards. In this way the seeded Jiffy pellets were part of the walls as a complete unit. This was the final step in the fabrication of the pre seeded walls.

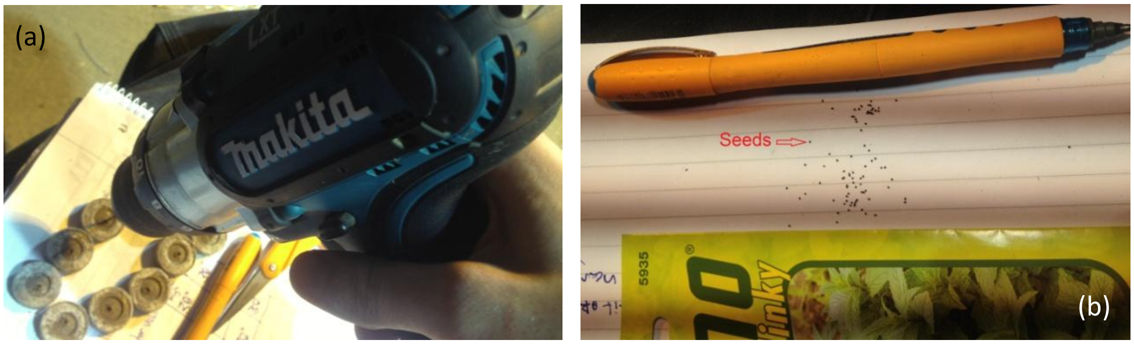


Figure 4.7: (a) Drilling seed holes. (b) Spearmint (Mentha spicata) seeds (Photo: Author).

4.2.2 Lab Conditions and Controls

The experiment was conducted under greenhouse conditions in order to better control the growing conditions for the plants and to have some ability to regulate and monitor the external factors that could influence the walls. This decision was made based largely on a study by Jorgensen et al. (2014) where various growing mediums for vertical gardens were tested in greenhouse conditions.

The greenhouse was 2m by 3.5m and the roof sloped from 3.8m down to 2.5m. It was made of clear glass on all sides so natural light could reach the plants at all times. The temperature could not be directly controlled. The room was heated by gas pipes and fluctuated from day to night, was influenced by outside temperatures and could only be adjusted by a fan that blew air out of the room and by opening a window. Natural lighting was supplemented with artificial grow lights. The fixtures were old Czechoslovakian street lights. Full spectrum, 150 watt, metal halide grow lights each producing 9500 lumens were used. Three of these lamps were used and each of the three walls was oriented as close to center on the lights as was possible. However the lights were fixed and the room was only slightly wider than the green walls when placed side by side (appendix I).

The steps involved in hanging the walls had two phases. The first was the construction of a frame and the second was the attachment of the hydroponics irrigation system.

1. The framework was built from conventional lumber. A cross beam with a thickness of 5cm x 4cm was cut to a length of 3.2m and then placed horizontally at two meters height on triangular wooden braces so that the beam sat just below the level of the grow lights (Figure 4.8). Then angle braces were attached for stabilization. The structure was assembled using a drill and screws. Then wooden lathing was cut into one meter sections and the top strip of the walls (about 3 cm) was sandwiched between two strips of lathing and screwed together. This horizontal wooden strip at the top of each wall was used to evenly distribute the weight of the walls while

hanging. Two holes were drilled through the lathing of each wall, each set about 10cm in from the end. Plastic zip ties were then threaded through the holes and looped around the horizontal beam so that the green walls were all hanging next to one another in a row with their tops suspended at the same level. (see Figure 4.9c) This was the extent of the structural support for the walls. No other additional support was used. The beam that was 4cm x 5cm and was able to hold all three walls when fully saturated (approximately 16kgs with hanging hardware).

Figure 4.8: Wooden framework and hanging mechanism with complete wall panel attached (Photo: Author).

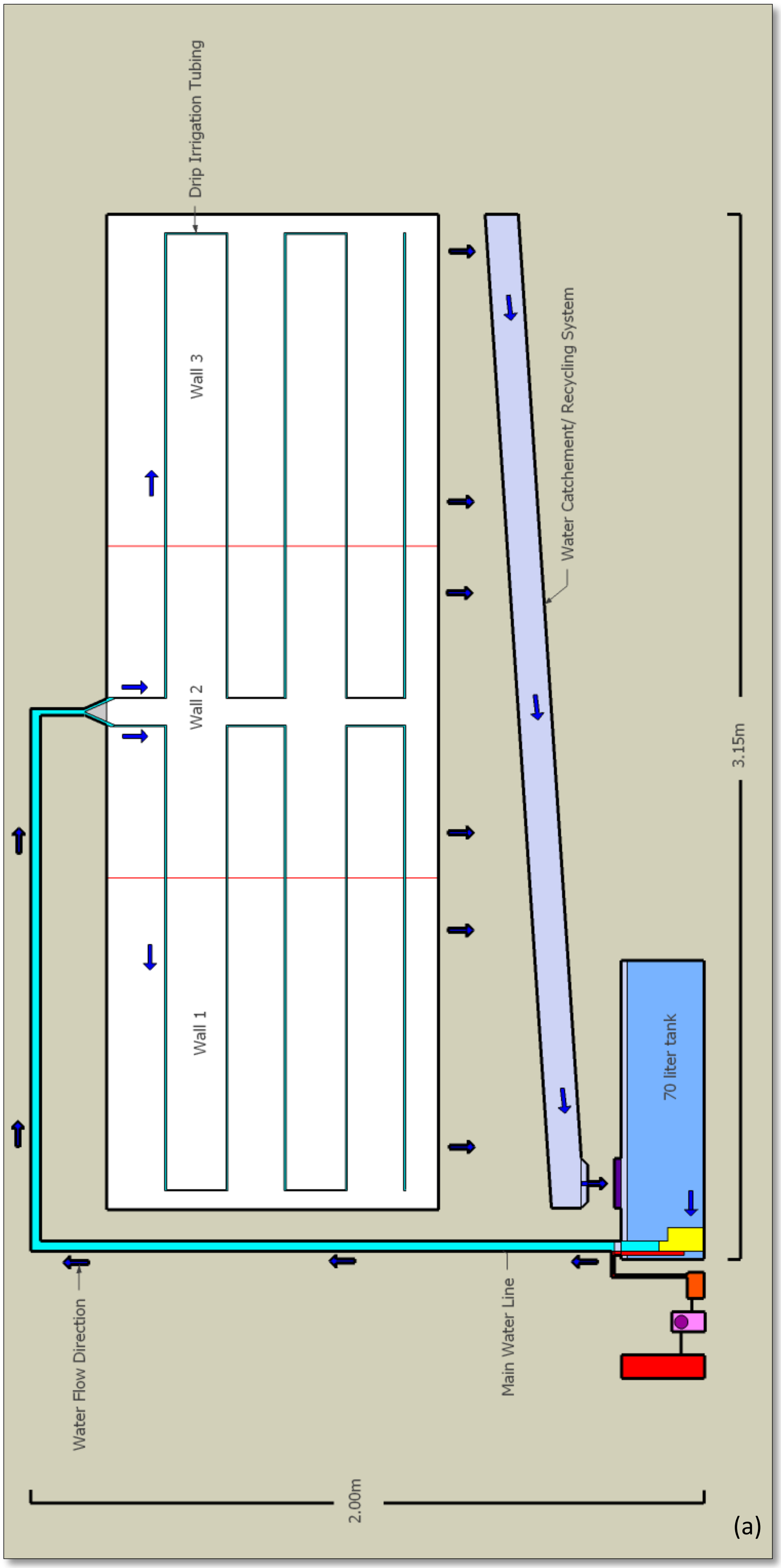
2. The hydroponics system was the second phase of the wall construction. This was a much more technical phase. The concept came from methods used by both textile greenwall fabricators and modular greenwall fabricators. This is the basic system used by Patrick Blanc and George Irwin of Green Living Technologies. It was also the system used in the lab study by Jorgensen et al. (2014).

   The concept of the system is simple. Water is mechanically pumped to the top of the wall and then spread across the wall by drip system tubing and allowed to run down the wall from gravity. The water that exits the wall at the bottom is then collected and recycled.

   For this experiment a 70 liter tank was placed on the ground beneath the wall. A catchment device made of rain gutter was constructed at a slope directly underneath the walls so that all water dripping from the walls would fall into the gutter. The gutter then directed the water through a filter as was suggested by Mir et al. N.D., and into the tank (Figure 4.9a).

A water pump of 12 volts at .85 bar (Figure 6, Appendix I) was placed at the low point in the water tank which pumped water through a hose to the top of the wall. This hose connected to drip lines which were oriented on the surface of the wall with one water emitter placed above each seeded pocket. The hose fed two drip lines which started at the middle of the central wall and split, each snaking across one and a half walls. This split in the middle was to ensure even water pressure (figure 4.9). Most professional vertical gardens place the irrigation system between the layers of textile (Blanc, 2001, Mir et al. N.D.). In this case however, the design of the wall was intended for simplified use where the wall could be watered manually. The drip line was to ensure that each plant received equal quantities of water and that the watering could take place at consistent intervals. In essence, the drip line simulated hand watering by feeding the plants externally through directed water. The nature of the polyamide felt would still allow for the water to spread through the wall (Blanc 2001). The drip line was attached to the wall by stitching the line to the external layer of the wall itself using the emitters as the connecting points. The emitters were designed to discharge 25 ml of water per minute, however upon measuring the volume of water discharged in real time; they only produced 20 ml per minute. At this point, the pre-seeded walls were hung and connected to the irrigation system, and ready for the germination trial.

Figure 4.9: (a) Water catchment, filtration, and reservoir. (b) Water hose splitter. (c) Drip irrigation system attached to surface of living wall system. (Photo: Author).


Drip Irrigation Tubing
Wall 3
Wall 2
Wall 1
Water Catchement/ Recycling System
70 liter tank
3.15m
Water Flow Direction
Main Water Line
2.00m
(a)

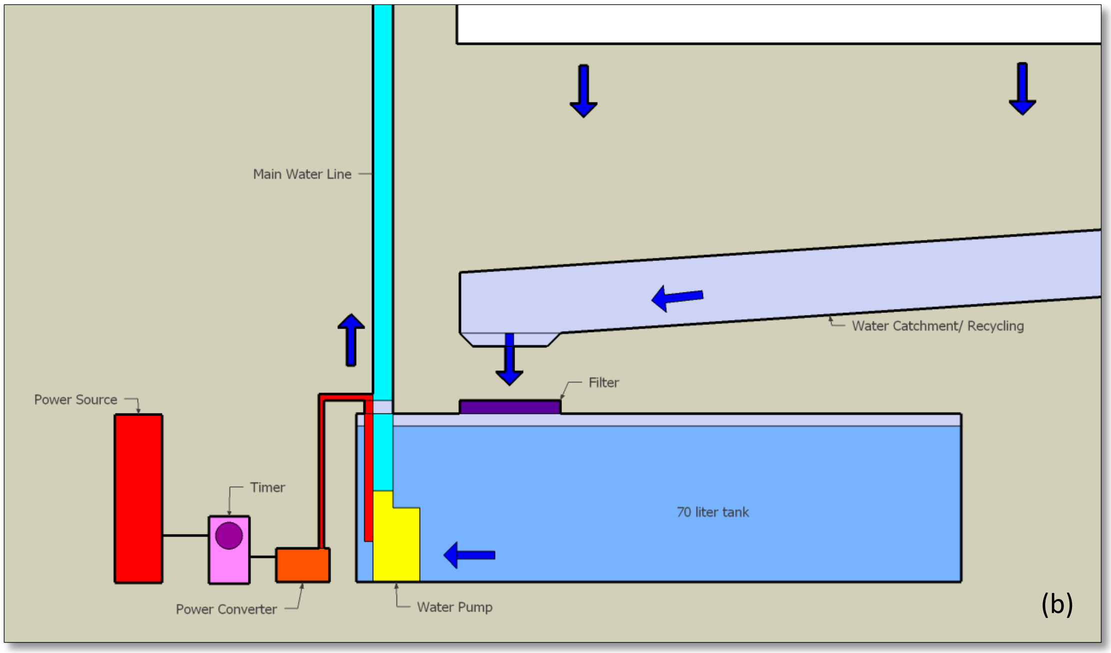


Figure 4.10: (a) Diagram of hydroponic system and cycle used for the experiment. (b) Zoom of technical function.

4.3 Costs

During the construction phase of the experiment, the costs of all wall materials used were recorded for future analysis by comparing them to current market prices of existing vertical garden models.

4.4 Wall Weight

The weight of each wall was recorded at four different points in the experiment.

1. Dry weight of seeded wall
2. Fully saturated weight of seeded wall
3. Dry weight of wall with mature vegetation
4. Fully saturated weight of wall with mature vegetation

The weight of each wall was measured in various conditions in order to understand their variation from dry to wet and from their unused form to full vegetation. Full saturation and full vegetation are considered their maximum weight. The walls could then be compared to one another.

The measurements taken with mature vegetation are taken as a potential weight because the plants germinated in the walls did not complete their cycle to maturity. The plants used were transplanted into the walls for the purpose of weight measurement.

4.5 Green Wall Growing Tests

The growing phase was carried out as a greenhouse experiment where the constructed walls were tested under controlled greenhouse conditions. This phase of the study was to determine of the seeded walls could germinate indicating the viability of the walls and determining whether the product itself could indeed function as it was intended.

The walls were seeded with spearmint (*Mentha spicata*). This plant was chosen for various reasons that made it an appropriate candidate for the research. The germination traits were considered, but also the growing phase and the maturity phase. The germination conditions were simple and consistent. The light, moisture and temperature could remain constant, or they could handle some fluctuation of conditions. This means that they were not too specific with their needs and had a high likelihood of germination success if they were provided with basic requirements (Mills 2014; Herbgardening.com 2014). The growing phase was similar for the following reasons: first of all, it is a hardy plant which is adaptable and accustomed to a wide range of conditions (Herbgardening.com 2014; Mills 2014; Park Seed 2014), which means that it can grow successfully without the risk of failure due to some variation and inconsistency. The second reason was the nature of the plants growing method. Spearmint is a ground cover plant which spreads by sending out runners (Mitchell 1998). This is beneficial because the plants remain small and the roots can mix with neighboring plants and even take advantage of open spaces or holes in the top layer of the wall (Mitchell 1998; Mills 2014). There is no part of the wall that is closed to any other part between the layers where the plants grow. The only barriers are the individual points where the layers are connected with a stitch. The mint plants could use the open and connected space to spread so their roots would have only the limits of the actual wall edge. Mints are herbaceous plants which are more advantageous in terms of weight in the low profile walls. Their maximal size is about 45 cm (Herbgardening.com 2014).

Figure 4.11: Spearmint (Mentha spicata) as a mature plant (Source: Commons.wikimedia.org).

4.5.1 Germination Phase

One of the most pertinent questions concerning the true success of the walls was whether the seeds would actually germinate in the conditions of the walls. In order to test this, the walls were placed under specific watering, temperature and light regimes which would induce germination.

Control Group:
A control group of thirty seeded Jiffy peat pellets (equivalent to one wall) were placed in growing trays and placed under a germination dome of hard clear plastic. The control group was in the same greenhouse with the same temperature, light cycle and watering cycle as the walls, but the seeded pellets were not in the wall and the orientation was in the traditional horizontal plane. If the control group was to germinate and the walls were not under the same conditions, it would indicate that there was a flaw in the design and functionality of the wall itself.

The conditions of the germination were based on the needs of Spearmint as indicated by common knowledge amongst master gardeners and their recommendations (Evans & Blazich 1999; Mills 2014; Park Seed 2014). These factors included light, moisture and drainage, temperature, and Ph.

Mint seeds germinate between 10 and 16 days (Herbgardening.com 2014; Park Seed 2014). A window of 30 days was allowed for the plants to germinate from the time the watering began, before non germinated pellets were considered a failure.

Light Cycle:
The experiment was conducted in late December and January, 2014-2015, when light was insufficient for mint germination. Mint seeds need some exposure to light in order to germinate, so they were sewn shallow and exposed to spring light conditions when mint would naturally germinate, which were based on the light hours in Prague, Czech republic (50.08° N) Mint will commonly begin germination after the last frost (Herbgardening.com 2014; Park Seed 2014) which in Prague is between April 1st and April 10th on average. The light hours at this time are 13 hours of daylight. By the end of the thirty day germination period, the light should increase to 14.5 hours.

The grow lights were managed by a timer. They were adjusted four times during the thirty day cycle, each time increasing the light hours (Figure 10, Appendix I). They were operated during the first week from 5:30 to 8:00 when the natural light was available. They turned on a second time at 16:00 and off again at 18:30 for a total of thirteen hours. The subsequent three adjustments followed the same pattern with increased periods of light until the final period when they received 14.5 hours of light.

The lights were as close to directly above the walls as possible. The orientation of the lights was directly down and could not be adjusted (Figure 8, Appendix I).

Temperature Management:

The ideal temperature range for mint seed germination is 20° to 30° C (Park Seed 2014), The greenhouse was heated by a central gas heating system and there was no control over the settings. The only method of regulating the heat was to turn on the fan that moved air out of the room, or to open the window. Taking the average high and low temperatures in the room for a week found that the average high temperature was 25° C and the average low temperature was 20° C. This showed that the range was suitable for the germination of mint seeds. The room was influenced by external temperatures and there was fluctuation over the course of the experiment from 17° to 31° C. It was also noted that the lights affected the temperature and the high temperature of the day was often reached when the lights were on. The average temperature of the room rose to approximately 27° C once the lights were in effect. Another factor was that the bottoms of the experimental walls, both further from the lights and nearer the floor, were colder than the tops of the walls.

On days when the external temperature increased and the room was over thirty degrees, the fan was run for approximately two hours. However, the room could not be constantly monitored, so the temperature was only controlled loosely by the central system, and effectively created closer conditions to the needs of spearmint than external temperatures by creating a temperature range where mint seeds could germinate.

The temperature was measured by two digital thermometers which recorded the high and low temperatures in a 24 hour period. One thermometer was placed on level with the top of the walls at the closest point from the walls to the light. The second was placed on level with the bottom of the walls.

Watering Cycle:

Although spearmint is commonly considered a very hardy plant that can do well in different soil types, it is recommended that spearmint be planted in well drained soil (Mills 2014; Herbgardening.com 2014; Park Seed 2014). This soil type allows it to stay damp but not saturated or the seeds could rot (Evans & Blazich 1999). Based on the drying time of the peat pellets and their water absorption potential, the watering cycle was set at 20 ml of water per plant three times per day with the shortest interval of seven hours in the afternoon when temperatures were most likely to reach their high, and the longest interval of nine hours at night when water loss from evaporation would likely be lowest. This schedule would allow the seeds to remain moist at all times and only temporarily soaked (Table 1, Appendix II).

Although the water retention capabilities of the textiles is important during the growth phase of the plants, the retention capacity of the peat pellets is considered of primary importance during the germination phase as it houses the seed and is responsible for the direct moisture contact with the seeds.

Spearmint can tolerate a wide Ph range. It can grow in conditions between 5.5 and 7.5 but a pH of 6 to 7 is ideal (Mitchell 1998; Mills 2014). The water used was Prague city water accessed from a faucet in the greenhouse. The water was alkaline. It had a pH of 8, so the water was adjusted using a pH balance formula (both pH Up and pH Down) to set the pH at an average of 6.5. The pH was checked daily, and adjusted as needed or adjusted every two days when the water tank was filled.

The water tank was topped every two days using a watering can. The water was at room temperature and the pH was measured using an electrical pH meter. Except for the pH balance formula, no nutrients were added during the germination phase as seeds do not require external nutrients to germinate.

The water pump was operated by an automated timer which turned on the pump three times daily for one minute allowing each seed its allotted water quantity. The water which drained from the wall was collected in the rain gutter and transported through a cloth filter back to the tank for subsequent use.

4.6 Analysis

Cost:

The total cost of the prototype walls from the experiment was compared to current (2011) market prices as studied by Perini et al. (2011) as well as other marketed products that fit into the categories of vertical greening systems, including modular walls, textile walls and green facades.

Weight:

The total weight of the walls was compared to current systems on the market which advertise their weight, especially those claiming to be low weight walls.

Function:

The walls were analyzed by the success of germination. The date of each pocket's germination was recorded in the thirty day period and charted. The walls were compared to the control group. Monitoring of the wall conditions occurred daily and the conditions were recorded. Observations of visual and physiological changes were noted and recorded when a change occurred.

5. Results

5.1 Costs

The seeded textile walls used for this experiment were built from materials immediately available in Prague, Czech Republic. The cost of the materials used is indicated in Table 5.1. This reflects the costs of all materials at retail price.

Table 5.1: Wall material cost by unit.

Material	Cost
Thread- 1 spool	20CZK
Seeds- pack of 500	47CZK
.5mm Plastic Pond Liner / meter	77.25CZK
Polyamide Felt/ meter	49.5CZK
Jute textile/ meter	27CZK
Coconut Coir Textile/ meter	34CZK
Ground Cloth/ meter	8.5CZK
Peat Pellets 24 mm- per pellet	2.4CZK

5.1.1 Prototype Walls

The cost of each individual wall without hanging materials and irrigation system are as follows:

Table 5.2: Polyamide Felt X 2.

Material	Cost
Thread	1CZK approx.
Seeds- 60 approximately	5.6CZK
.5mm Plastic Pond Liner- 1 meter sq	77.25CZK
Polyamide Felt- 2 meters sq	99CZK
Ground Cloth- 1 meter sq	8.5CZK
Peat Pellets- 30 units	72CZK
Total	**263.35CZK**

Table 5.3: Polyamide Felt/ Jute Textile.

Material	Cost
Thread	1CZK approx.
Seeds- 60 approximately	5.6CZK
.5mm Plastic Pond Liner- 1 Meter sq	77.25CZK
Polyamide Felt- 1 meter sq	49.5CZK
Jute Geotextile- 1 meter sq	27CZK
Ground Cloth- 1 meter sq	8.5CZK
Peat Pellets- 30 units	72CZK
Total	**240.85CZK**

Table 5.4: Polyamide Felt/ Coco Fiber Textile.

Material	**Cost**
Thread	1CZK approx.
Seeds- 60 approximately	5.6CZK
.5mm Plastic Pond Liner- 1 Meter sq	77.25CZK
Polyamide Felt- 1 meter sq	49.5ck
Coco Coir Geotextile- 1 meter sq	34CZK
Ground Cloth- 1 meter sq	8.5CZK
Peat Pellets- 30 units	72CZK
Total	**247.85CZK**

These costs are the total price of the functional wall without the hydroponics system or the structural framework. The additional materials needed for the experiment are not considered necessary to the success of the walls, but only necessary for the experiment.

5.1.2 Market Prices

To determine the meaning of these costs in terms of accessibility to potential users, the total cost of the walls was compared in cost per meter to current market prices as was documented in a study by Perini et al. (2011), as well as other vertical garden products marketed online such as Sage Vertical Garden’s walls and Plants on Walls’ design.

Table 5.5: Costs of various vertical gardening systems converted to Czech Koruna(CZK) on March 10, 2015 from the records according to Perini, Ottele, et al. (2011); Sageverticalgardens (2015) and Plants On Walls (2014).

Wall Type	Cost Range	Year
Direct greening on walls from climbing plants	800-1,200CZK/m2	2011
Indirect climbing plants with support system	1,100-2,000CZK/m2	2011
Indirect living wall system with planter boxes	2,700-21,800cCZK/m2	2011
Modular living wall systems	10,900-16,400CZK/m2	2011
Foam substrate living wall systems	20,400-32,700CZK/m2	2011
Geotextile living wall systems	9,500-20,400CZK/m2	2011
Empty felt pockets (plants on walls)	1,800ck-30x60cm	2015
Personal indoor vertical garden (Sage Systems)	1,300ck- 25x30cm	2015

5.2 Weight

Table 5.6: Weight of walls at various phases of the experiment.

Weighing Conditions	Felt/Coconut Textile	Felt/Jute Textile	Felt/Felt Textile
Dry wall- pre germination	1.47kg	1.43kg	1.35kg
Wet wall- pre germination	3.07kg	3.47kg	3.61kg
Dry wall –full vegetation	2.15kg	2.11kg	2.04kg
Wet wall full vegetation	3.95	4.36kg	4.5kg

5.2.1 Advertised Market Weights

Table 5.7: Weight of various walls on the market according to company claims (Blanc 2001; ELT Easy Green 2010; Green Over Grey 2009; Plants On Walls 2014).

Designer	Weight
Patrick Blanc	30kg/m2
ELT Living Walls	75kg/m2
Green Over Grey	20kg/m2 (lightest wall on the market)
Plants on Walls (planted and watered pockets)	25kg/m2

5.3 Wall Functionality and Germination

Each chart represents a wall and each cell one seeded pocket (30 per wall). The date indicates when the pocket germinated. The first day of the experiment was December 27.

5.3.1 Polyamide Felt X 2

Table 5.8: Seed germination dates.

	A	B	C	D	E	F
1	19-Jan	16-Jan		16-Jan	15-Jan	
2		8-Jan	6-Jan	7-Jan		
3		6-Jan	13-Jan	7-Jan	8-Jan	9-Jan
4	13-Jan	15-Jan	15-Jan	16-Jan		14-Jan
5		20-Jan		19-Jan		

19 of 30 seeds germinated

Table 5.9: Germination period observations.

Date	Observations
12-28	Top row dryer than lower rows at observation time just before mid day watering. Light more centered over left side of wall.
1-2	Several peat pellets on the edges are losing quantities of material. The water flow appears more forceful where the irrigation tube bends.
1-3	Some mold apparent on most peat pellets in 4th row, and more in 5th row.
1-4	Top row consistently dry before watering occurs. A2 pellet has water damage.
1-6	First seeds germinated (day 11) A5 pellet has water damage.
1-7	A lot of white fuzzy mold on rows 4 and 5, a little on row 3 as well. Germinated seed on b3 appears unaffected.
1-10	Bottom row always wet, 4th row also stays wet most of the time. Mold is still spreading, but slowly. E4 pellet has water damage.
1-11	End of expected germination period- only 7 seeds germinated- rows 2 and 3
1-12	Mold appears to be diminishing, possibly from increased light
1-13	D3 washed out. New plastic cover installed in greenhouse and temperature increased. First germination in three days.
1-16	Top row is still dry, but seeds are finally germinating
1-25	No germination for five days

5.3.2 Jute Textile/Felt Textile

Table 5.10: Seed germination dates.

	A	B	C	D	E	F
1	16-Jan	18-Jan				18-Jan
2	18-Jan		13-Jan	7-Jan		15-Jan
3	15-Jan	7-Jan			6-Jan	6-Jan
4	17-Jan	15-Jan	15-Jan	15-Jan	9-Jan	14-Jan
5			15-Jan			13-Jan

19 of 30 seeds germinated

Table 5.11: Germination period observations.

Date	Observations
12-28	Top row dryer than lower rows at observation time just before mid day watering. Light centered on wall
1-3	Some mold apparent on most peat pellets in 4th row, and more in 5th row.
1-4	Top row consistently dry before watering occurs. B4 pellet damaged
1-6	First seeds germinated (day 11)
1-7	A lot of white fuzzy mold on rows 4 and 5, D3 pellet damaged
1-10	Mold is still spreading, but slowly. Bottom two rows are wet,5th is very wet, middle damp, top row dry. Small clear worm in one of the un-germinated peat pellets on the fourth row.
1-11	End of expected germination period- only 4 seeds germinated
1-12	Mold appears to be diminishing, possibly from increased light
1-13	New plastic cover installed in greenhouse and temperature increased. First germination in three days. Windows opened to reduce temperature.
1-16	Top row is still dry, but seeds are finally germinating
1-18	A3 washed out.
1-25	No germination for seven days

5.3.3 Coconut Textile/ Felt Textile

Table 5.12: Seed germination dates.

	A	B	C	D	E	F
1				19-Jan	19-Jan	
2	19-Jan	15-Jan	19-Jan		19-Jan	
3		13-Jan		13-Jan		
4	19-Jan			8-Jan	15-Jan	16-Jan
5	15-Jan	17-Jan		10-Jan		

15 of 30 seeds germinated

Table 5.13: Germination period observations.

Date	Observations
12-28	Top row dryer than lower rows at observation time just before mid day watering. Light centered on right side of wall
1-2	Several peat pellets on the right edge are losing quantities of material. The water flow appears more forceful where the irrigation tube bends.
1-3	Some mold apparent on some peat pellets in 5th row
1-4	Top row very dry before watering occurs. F3 and F4 pellets damaged
1-7	Mold spread a little on 5th row and some mold apparent on 4th row.
1-8	First seeds germinated (day 13)
1-10	Mold appears to be about the same on 4th and 5th row. Top very dry, row 2 also quite dry. D2 pellet damaged.
1-11	End of expected germination period - only 2 seeds germinated
1-12	Mold almost completely gone. Only small white speckles on row 5.
1-13	New plastic cover installed in greenhouse and temperature increased.
1-15	Germination infrequent and sporadic
1-16	Top row is very dry and absorbs little water
1-19	Surprising number of germinated seeds
1-21	A4 washed out.
1-25	No germination for six days

5.3.4 Control Group

Table 5.14: Seed germination dates.

Control Group													
4 Jan	4 Jan	4 Jan	4 Jan	6 Jan	6 Jan	7 Jan	7 Jan	7 Jan	8 Jan	8 Jan	8 Jan	8 Jan	8 Jan
10 Jan	11 Jan	13 Jan	13 Jan	14 Jan	14 Jan	15 Jan	15 Jan	16 Jan					

23 of 30 seeds germinated

Table 5.15: Germination period observations.

Date	Observations
1-4	First seeds germinated two days before expected germination period.
1-5	Small amounts of mold on some pellets
1-11	Twelve seeds germinated during the expected germination period
1-25	No germination for nine days, 7 seeds never germinated

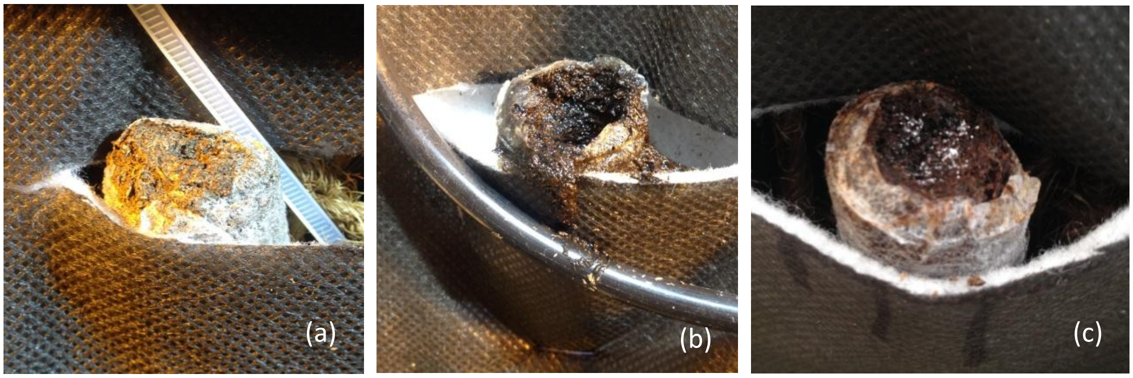


Figure 5.1: (a) Overly dry peat pellet. (b) Washed out peat pellet. (c) Mold on peat pellet (Photo: Author).

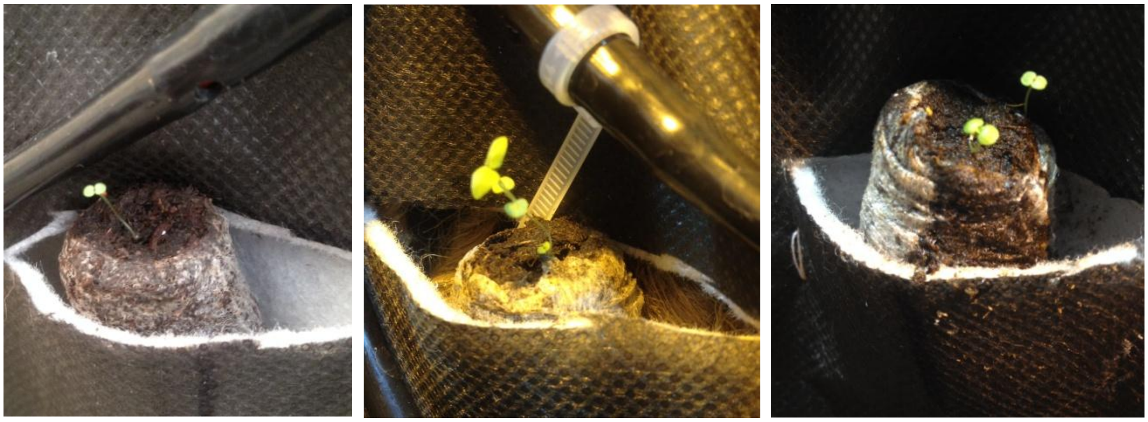


Figure 5.2: Germinated Spearmint seeds (Photo: Author).

6. Discussion

6.1 Discussion of the results

Note:
As the experiment transpired, it was clear that there were numerous questions at each step and possible flaws or at least unclear elements. The experiment was one with many variables and numerous factors which were difficult to confine. A great deal of the academic literature concerning living wall systems notes that it is a challenging area of study due to the dynamic nature of the walls, and also, there is still a lack of research in the field. The small body of research allows for many interesting questions, but also many assumptions and a situation which prompts the very old scientific approach of "guess and check".

Although the functionality of the prototype walls was the driving research question, it became clear through the steps in the process that the experiment would be multi-part, containing questions concerning weight and cost as well as function. These auxiliary questions furthered the research towards the intentions behind the research. Although the research could have been accomplished without these questions, they must be considered necessary to the ultimate goals of the project.

To a large degree, this experiment was dictated by the available conditions. The strength in the theory might have been undermined by the material options and the conditions available for the experiment. Factors such as materials, budget and venue conditions were factors throughout the trial. However, as an early experiment of a prototype, the experiment certainly showed the potential of the project, and the need for further research.

6.1.1 Costs

When looking at the cost comparison there is really no debate about which wall model is the least expensive. The average cost of the prototype walls constructed for the experiment was 250 CZK. The cheapest form of vertical greening method on the market as found by Perini et al. (2011) was 800 CZK (converted from Euros in March 2015) and the cheapest textile wall, of which the experimental prototype walls are similar, is 9500 CZK. The walls built for the experiment are a fraction of this cost. Why?

To understand this price difference it is important to note that custom living wall systems (which are those found on the market) involve a number of "factors" that the walls used in this experiment eliminate. It is, however, considered part of the intention of these walls to eliminate those "factors" and so the comparison of total cost is justified and it can also be understood why the prices have such a dramatic difference. The living wall systems on the market include the cost of the design which does not exist in the single species pre-seeded walls built for the experiment. The hydroponic system and the costs of the installation are also components of the market systems which represent no cost for the prototypes in the experiment as they are designed to be self installed and, in future experiments, hand watered. There is also, of course, the influence of the market in which the custom walls are sold for profit. There is no question that the actual fabrication of the market walls is less expensive than their retail price, but it is unknown what the price differentiation from the manufacturing cost is. This does create some inconsistency in the results because the recorded cost of the market walls is the retail price and the recorded cost of the experimental walls is only the material cost.

A further question might be to ask the price comparison of the raw materials used in similar market walls compared to the walls of the experiment, or, as the prototype walls are developed further, to enquire into the possible large scale fabrication costs of such walls.

By some evidence of materials purchased in bulk, and if the walls were to be manufactured on a large scale, there is a great deal of speculation that the experimental walls could be substantially cheaper to produce. For example, Polyamide felt purchased at a gardening store in Prague cost 49.5 CZK/m while online bulk distributors such as Alibaba.com can supply the material for .25 CZK/m when ordered in bulk (Alibaba.com 2015). The Jiffy seeding pellets could be purchased for 2.4 CZK per pellet but online stores such as EBay or Amazon sold the same pellets for 1.7 CZK per pellet.

There is no way to know the exact cost of bulk production, but based on cost differences with materials, an assumption can be made that the total cost of the walls manufactured in bulk would be lower than the cost of the prototype.

It is also interesting to note the costs of the supporting materials such as wooden framework to support the living walls and the hydroponics system. These costs represent a major difference between an automated system and a hand managed system, which serves to further demonstrate ways that the costs of green walls can be affected. The costs can vary significantly depending on conditions but as an example, this experiment spent approximately 8000 CZK for the supporting framework and the hydroponics system which is ten times more expensive than all three walls together. With these expenses, the walls are beginning to near the low end of the walls recorded in the Perini et al. (2011) which were 9500 CZK.

Another possible flaw in the comparison of market walls and the experimental walls could be the cost of the walls in relationship to their life span. It is unknown what the life expectancy of a vertical garden is, because they are still new technology, but expectations range from 10 to 50 years depending on the system. (Perini et al. 2011) It is impossible to determine at this point the life expectancy of the walls built for this experiment.

As a final summation of this experiment, it is clear that different wall types have massively different factors which can create dramatic differences in their price, but what the research shows is that the fabrication of a wall can be very affordable and so the potential for a much cheaper form of living wall system exists.

6.1.2 Weight

The wall with two layers was the heaviest when fully saturated as was expected based on the felt absorption capacity. With vegetation its weight was 4.5 kg. It should be noted that the plants used for weighing were not grown in the walls but rather inserted with their root wad as mature plants for the purpose of weight calculation (figure 6.1). This weight then can only be taken as an example of the likely weight, albeit a fairly accurate example.

Further questions might be the difference in wall weight with different plant varieties.

Figure 6.1: wall with transplanted vegetation at mature stage including root wad. Vegetation planted for weight measurement (Photo: Author).

When compared to the commercial walls, which advertize or divulge their weight (not all companies share the weight of their walls), the prototype walls are four times lighter than the walls of the company Green Over Grey, which advertise their walls as the lightest on the market (Green Over Grey 2009). This is likely due to the low profile lightweight plastic backing that was used in place of the rigid PVC commonly used in commercial products. The commercial brands could also include the mounting hardware and framework which are required for the support of the walls. This element in the experiment is not weighed because the hardware in the experiment was not intended to be part of the completed walls. The prototype walls could simply be hung from grommets and require virtually no supporting framework (more in section 6.2.3).

The weight of the experimental walls was based on a one square meter size. The commercial walls can be designed at much larger sizes. If the experimental walls were to be designed as larger walls, it is possible that they would need additional support which would affect the weight.

This experiment shows that all of the prototype walls, Jute, Coco and Felt, are substantially lighter, by square meter, than the commercial walls currently on the market.

6.1.3 Germination Results

The results of the germination phase are that the Spearmint seeds were capable of germinating in the walls. In that sense it can be determined that the walls are a success through the phase of germination.

The degree of success, however, is in question. Just about two thirds of the peat pellets had successful germination in the 2X Felt wall and the Felt/Jute wall. Exactly half of the pockets germinated in the Felt/Coco wall, and in the control group 23 of the 30 germinated making it the most successful group, but only by four seeds.

There are two main categories for the questions that surface the first category are the walls taken as a whole, and the second category for the comparison of the walls to one another.

Category One:

Question One:

The first question that arises is why so many seeds in all categories (control and walls) never germinated? And what could have caused the seeds to never germinate? Had the control group been closer to a 100 percent germination success, the prototype walls themselves could be scrutinized more closely, but the failings in the control group indicate that there may be some factor with the conditions that impacted the success of the germination. One challenge with this experiment in which seed germination was a focus, was that there are many factors that can have an impact on the success of the seeds. As was indicated in the methodology, these factors were controlled as much as possible; however there was still a margin of error and no secure way to determine which factors were the culprits responsible for failed seeds. The possibilities are as follows:

- The seeds themselves could have been faulty. Not all seeds will germinate, even in the ideal conditions (Baskin & Baskin 2014). The seeds used could have been dead before they were planted.
- The quantity of light might not have been sufficient. Some of the holes in the peat pellets could have been too deep and the seeds may have received minimal light, or possibly no light. The seed plugs were drilled while dry and the seeds inserted. Only after, once they were in the walls (and in the case of the controls in the grow trays) were they saturated. The peat pellets, as became apparent, had the nature of breaking down and particulates could have buried the seeds. The holes might also have elongated too much when first saturated, placing the seeds far from the light (more in section 6.2.1).
- The temperature variation could have been too extreme. Although the literature indicates that Spearmint is hardy (Park Seed 2014; Bonnie Plants 2012) it is possible that the night and day fluctuation was too much. This seems unlikely given the success of the other seeds, but with the inability to precisely control the temperature, this aspect cannot be ruled out as a possible reason for failure.
- Yet another consideration is the pH. Spearmint can also handle variation in pH, however, the pH was only tested in the reservoir and never after it had contact with the walls or the peat. It could be that some chemical reaction with these components led to intolerable pH ranges. If that were the reason, it would have to be an issue with the peat, because the control group had no contact with the walls.
- Mold was evident on all three walls and the control group. With all of the walls, the mold was apparent on the bottom two rows where the walls remained wet longer due to gravity forcing the water down. The control group may have stayed moist longer due to humidity because it was under a dome. However there was no correlation in any of the groups between the moldy seed pods and the germination success. Many pellets on the walls with mold germinated. And most of the pellets with mold in the control group germinated.

Question Two:

The second question is what part of the walls as a group and the supporting hydroponics system could have led to the failure of seeds; factors that were not present with the control group.

- There is some compelling argument that some of the seeds were washed out by the force of the water from the emitters. As shown in (Figure 5.1b) the peat pellets could come apart and the material was in some cases dislodged and washed away. The seeds, which were tiny, could have been washed away with the debris from the peat. There is no question that one germinated seed from each wall was dislodged by water. They were all found in the residue which came from the peat pellets. There was no correlation between the three walls though as to a place more likely to experience a wash out, and no clear indicator in the flow of the water showed those places to be vulnerable. It could be that the peat pellets that washed out were weaker than the others and more prone to damage. With the disrupted pellets however, there was some pattern. On the 2X Felt wall, three pellets were disrupted and none of them ever germinated (Table 5.9). Two of those were on the edge where the irrigation tubing curved- A2, and A5. The tube irrigation showed some inconsistencies in pressure where the tubes made dramatic curves. The walls could not be observed during each watering, but during some observations, the emitters by the curves demonstrated more abrupt water spurts, and faster movement of water. This was consistent with the two pellets in column A which were damaged. The Felt/Jute wall had two disrupted pellets. D3 was also on a curve and it never germinated. B4 happened to be on a straight stretch of tubing but it was also damaged, however it germinated. The Felt/Coco wall also had three damaged pellets. Two on the edge F3 and F4. F3 never germinated. D2 did not germinate either. The data is not completely consistent, but it is very possible that some of the disrupted pellets, especially those near the curved tubing lost the seeds due to a wash out. There was no chance for this problem with the control group because the bottoms of the pellets were submerged and allowed to absorb water. Some literature indicates that water force can cause seeds to be dislodged from germination pellets similar to Jiffy Peat Pellets (Roth 2009).

- It is possible that the quantity of water was too great or too little. There is strong evidence that the moisture had an impact on the seeds in the walls, but it does not explain the control group which was given the same water as the wall, and was exposed to the same conditions. The control, which was level, with drainage through the bottom of the tray should have created uniform conditions for all of the pellets. If there was a problem with the water quantity, it is more likely that most or all of the seeds would have failed. In regards to the walls however, the bottom row generally had a lower success rate and a slower rate of germination than the rest of the walls. It suggests that in the case of the walls, some of the seeds remained too wet and were incapable of germination
- In the opposite case, there is also evidence that the top rows could have been too dry. The top rows also performed worse than the rest of the walls. They either did not germinate or were slow to germinate. This is also a possible cause for the failure of some seeds.

These are all potential problems for seed germination, and though some are more likely than others, they should all be considered. There is also the chance that there was some combination of some or all of these factors. The venue was old, inconsistent and impossible to control in certain manners. There were further factors that were never measured due to missing equipment which could be questioned such as humidity levels in the room, and oxygen levels in the peat pellets.

Question Three:

The third question is concerning the rate of germination which was abnormal in all groups. This also indicates that there was some issue with the conditions which delayed many of the seeds. According to the literature (Park Seed 2014; Herbgardening.com 2014) the seeds were expected to germinate between 10 and 16 days. The control group had four seeds germinate on day 9 of the experiment and then 12 more seeds germinated in the expected period (Table 5.14). The day 9 germination is close and can be considered acceptable. Eight of the seeds germinated on days 12 and 13, right in the middle of the expected period. Seven seeds germinated after the expected window. There were seeds every day from the 13th through the 16th indicating that there was some consistency. There were no extreme outliers; they were simply late in coming. The 2X Felt group had only seven seeds germinate during the expected germination period and then 12 seeds after the period, which suggests that the conditions became more favorable after the expected germination period ended (Table 5.8). The Jute had only four (Table 5.10) and the coconut wall only two seeds (Table 5.12) germinate during the expected window, so all of the walls taken as a group experienced much better growth between generally the 13th and the 19th, or day 18 and day 24. This is consistent amongst the walls, but does not fit as well with the control group which did experience the majority of germination within the expected window, and ended germination before the others. Without comparing the walls to one another at this point, they generally show that the top row and the bottom two rows germinated after the expected window. Rows 2 and 3 were mixed, but overall they were more likely to germinate within the window. The general situation may have been that the conditions may not have been perfectly favorable, but they were clearly *favorable enough.* They were on the edge of acceptable which allowed the majority of the seeds to germinate but not all. Possible explanations are as follows:

- Moisture content could have played a large role in the delayed germination period. The control group was on a level plane and was given an equal water quantity. The walls had the element of gravity which changed the quantity of water that each row was in contact with. Despite the fact that each pellet was given equal quantities of water, the top rows dried earlier and the bottom rows remained wet longer. The control might have been closer to ideal conditions which allowed more of the seeds to germinate in the expected window. The imbalanced water in the walls might have pushed them further from the ideal conditions prolonging the germination time.

- The quantity of growing light could also have played a large role. If some seeds were too deep in the peat pellets, they might have had less light which caused them to take longer to germinate. The light increased during the experiment to mimic spring conditions. As was shown in (Table 1, Appendix II), the light increased from 13.5 to 14 hours on January 10th (day 15) It is possible that the extra period of light allowed some seeds which did not receive enough light before, to germinate.

- The temperature spiked on January 13th to 31 degrees Celsius when a layer of greenhouse plastic was installed in the lab (this was unexpected and not able to be controlled). After that development, the windows were used to regulate temperature to some degree but the average temperatures were consistently higher by one or two degrees than they had been previously. This correlates with the time when more of the seeds in the walls began to germinate, and also with the later germinations in the control group.

- The most likely scenario is that the light, the temperature, and the moisture conditions all combined to prolong the germination period.

Category Two:

Question One:

The next area to examine is the variation between the walls themselves and how they compare to one another. The walls were identical except for the second textile layer. The intention was to find some notable difference caused by the different materials, but with the variety of external factors, it is difficult to say that the success of each wall was related to the material. There is some evidence however, of the impact that each material had on the germination. To begin, it is important to remember the design of the watering system.

Although it was understood at the advent of the experiment that gravity would cause an uneven distribution of water, the experiment dispersed water in equal quantities to each plant. Professional wall companies design specific and complex water cycles in order to compensate for gravity, however in the case of a hand watered system, or with a much simplified gravity fed system, these controls are not possible. Feeding each plant an equal quantity of water is the extent of the control and would allow for the experiment to show differences between the three wall types.

As was expected, the peat pellets on different levels showed immediate response to the water movement. The top rows of all the walls were much drier, and the bottoms remained moist much longer. Mold was evident on the peat pellets on the bottom two rows of all walls. The mold began to disappear by appearances on all the walls on January 12th (Table 5.9, 5.11 & 5.13).

The key differences between the walls were the speed and extent of drying on the top, and the length of saturation on the bottom.

The 2X Felt wall took the longest to dry. It had the greatest quantity of mold on the bottom. None of the seeds in the bottom two rows germinated until after the expected germination window. The bottom row had only two seeds germinate and they were the last days to have germination of any of the walls. B5 was the final germination on January 20th, nine days after the germination window ended. Because this germination time was so different from the middle rows which germinated generally between January 6th and January 9th, it raises the question of the differences between those rows, the main difference being water quantity. This suggests that the bottom of the 2X Felt wall was too wet for normal germination.

The Jute wall was similar to the 2X Felt wall in that the bottom was also wet and experienced late germination. The bottom row only had two seeds germinate, just as the Felt wall. The germination window was almost the same as that of the 2X Felt wall; however one of the pellets on the fourth row did germinate in the expected window. The bottom row germinated much earlier than the bottom row of the felt wall with the last germination on the jute wall beating that of the 2X Felt wall by four days. The Jute wall was expected to drain faster than the felt wall which it appeared to do. The earlier germination on the bottom coupled with better drainage supports the theory that a higher water quantity slowed the germination or caused failure.

The Coconut wall did not have as many germinations total as the other two walls, but it had three seeds germinate on row five versus the two on row five that the others experienced. The time of germination was long, but one of the seeds on row five germinated during the expected time window. It is likely that due to the higher drainage capacity of the coconut wall, the bottom was less frequently saturated, and the conditions on the bottom rows may have been more suitable to normal germination.

The situation with the top of the walls is just about the opposite. All of the germination on row one occurred at the very end of the germination period. It is possible that the late germination in this case was caused by excessive dryness. The 2X Felt wall, which retained the most moisture did the best then the Jute wall, and then the Coconut wall, which was by far the most consistently dry on the top row, and had the lowest success.

The dryness on the top was certainly from the gravity, but it could have been aided by the proximity to the grow lights which increased the temperature notably at the top of the walls. There is no clear correlation however, between the location of the light above the wall and the germination success.

There is strong evidence pointing to the water retention of the various walls and the success of the germination, but there are enough other possible factors (as were discussed previously) that it cannot conclusively be determined what caused the germination patterns on the experimental vertical gardens.

6.2 Discussion of Methodology

6.2.1 Wall Design

The wall design was close, but not entirely in accordance with the original concept. The reason for this was almost entirely due to the availability of materials. There are in fact many materials from which the walls could be constructed. Following are thoughts on the materials and possible alternatives.

Textiles:
The three tested materials: Felt, Jute, and Coconut coir, were all of interest because of their prior use in vertical gardens and in the case of Jute and Coconut, because they are natural fibers. They were not ideal however for a few reasons. In testing three distinct materials, it would have been better controlled had they all had the same surface pattern. For example, they could have all been woven with a one centimeter grid. The felt was especially disappointing because it was white and somewhat translucent. Because the interior of the walls needed to be devoid of light, the additional material of the black ground cloth was necessary. Although it was insubstantial in weight, and effective in blocking light, there was some concern that it wicked water away from the walls and even prevented some absorption, so it is possible that the added outer layer changed the functionality of the walls. Unfortunately, black felt was not evidently accessible for the experiment.

Further studies could substitute these textiles with various other materials. Walls could be built with other woven mesh textiles from natural fibers such as hemp, silk, or even cotton. They could also use synthetic mediums. The surface could also be varied, woven forms of various size, or uniform surfaces.

Seed Pods:
The seed germination pods, in this case the Jiffy peat pellets were another element of the walls which were used because of availability. Although they are effective and designed for the task of germination, they have problems that would be better avoided with the walls. For one, the material was pressed and able to come apart, in essence, erode. This created the hazard of losing the seeds, and also created a mess, and likely would shorten the life of the walls. The pellets are also rigid, so the hole where the seed resides is open to the air and although it is oriented with the hole up the seeds are vulnerable to washing out. The hole for the seed is also quite difficult to make uniform as the peat expands when wet, making some of the holes deeper than others. In Future research, it would be

better to use some synthetic plug such as foam which can pinch the seed and which will not come apart or change shape. There are other forms of seed starting plugs on the market, but again, the peat pellets were the only available resource.

Plants:
The plant choice of *Mentha spicata* was good in many senses considering its mature form, but as a seed it had a couple of flaws. The seeds were tiny and light and so might easily have become dislodged and they also needed light exposure which required the hole to be open which led to the same problem of vulnerability.

Countless plants could have been used, and each would be unique and come with its own problems and strengths, but it might be advantageous to try seeds that can be completely contained in the growing pod.

6.2.2 Comparative Research

A great deal of the organization and implementation of the experiment was inspired by an experiment done by (Jørgensen et al. 2014). This research was focused on root growth of plants rather than germination and they were looking at three growing mediums as well as a variety of plant types. The chief interest was in their methodology. They too used a greenhouse and regulated the water using drip irrigation for fixed time and volume. They worked in the normal growing season and needed no artificial light, and they were able to regulate the room temperature so that there was only a fluctuation of a few degrees. They used plants which were already started. They experienced some debate over the results because of the two part experiment of different growing media and different plants, but their results had some similarities to mine. They too found that the movement of water and the various retention capacities of the growing media had a huge impact on the plants. Although the different plants had different needs and various plants performed better or worse depending on the growing medium, they found that the lower part of the wall, even with a small wall held much more water and the plants were not able to grow as large due to the high water content. They noted that the different growing mediums had a dramatic impact on the plant growth due to their distinct water retention properties.

6.2.3 Technical Components

Hanging hardware:
The hanging hardware was not a built in component of the prototype walls. This was partially due to the challenge of finding the correct parts and also the challenge of constructing the hanging mechanism. The original idea was to use a light weight stabilizer rod of possibly aluminum or plastic running along the top for the purpose of keeping the wall spread. The wood that was used worked, however it could not be considered part of the wall and could therefore not be factored into either weight or cost.

A stabilizer with grommets as part of the complete wall construction could change the total cost and total weight.

Light placement:
The location of the lights was fixed and could not be adjusted there is no evidence that the location of the light had an impact on the success of the seed germination, however, there was a light imbalance on the walls that might have influenced future growth of the plants.

Water pumps and general problems:
The construction of the hydroponics system was the most challenging part of the experiment set up. It became apparent that the quality of the mechanisms was vitally important. Three different water pumps broke during the experiment nearly causing disastrous results. Two timers also failed. One pump failed because of the timer and ran all of the water until the pump ran dry. A second failed because the water pressure was too great and it stopped the motor. The third failed because moisture got into the power converter and burnt up the motor. The timers simply ceased to function. All of this could be blamed on low budget materials leading to the conclusion that in a hydroponics system, the quality of the parts correlates with the success of the experiment. It also indicates that the hydroponics system truly is complicated and requires skill and knowledge. It has many parts that can fail, and there are many things that can go wrong, all of which can cause the wall to fail. It demands constant attention, and requires money because the parts cannot be handmade in most cases. It is not user friendly or accessible to a lay person. It was further encouragement to abandon the hydroponics system altogether in future experiments.

6.2.4 Future Research

It would be an interesting study to try other plants on the same walls, but the simplicity of the walls is their biggest limitation in this case. Plants grown together would have to have very similar needs because the walls as they are now are not technical and cannot deliver varied nutrients or water volumes. Experiments could be done with hand watering and multiple nutrients regimes to see if multiple plants could be achieved. Certainly other plant varieties should be tested with the walls in general.

It is necessary for the plants to transition from germination to rooting and maturation. The walls cannot truly be considered a functional success until the plants have achieved a complete life cycle. The other factors involved such as oxygen content and root spreading patterns need to be examined

A further experiment would be to try the walls in an outdoor setting during the natural growing season and without the hydroponics system. They need to be explored as a vertical garden system that could be managed as part of a private garden with only added nutrients as an extra aspect.

Increasing the size of the walls, or covering a building wall with one meter units and running a growth trial to research the capabilities and limitations of size is of interest.

Generally alternative designs with other materials and components to improve upon weight cost and functionality is necessary.

7. Conclusion

Living wall systems, vertical gardens, green walls, and other similar forms of vegetation on walls, most certainly have a place in the future development of manmade landscapes. They have the potential to provide numerous benefits to society and the environment, but there is a need for new designs and new systems, especially forms that can be used by many people and in many locations.

The ultimate goals of this research were to begin developing a living wall system that could be accessible to users without special knowledge or skills or equipment, and walls that could be affordably disseminated to cover large areas. Within these theoretical questions there were three measurable questions that if answered could contribute to the ultimate goal. The hope was to develop a wall which was lighter than the existing walls on the market, and light enough to be managed by an individual, walls that were cheaper than those existing currently on the market, and to determine if a wall could be built pre seeded and successfully complete the germination phase of growth.

On some level, all three goals were accomplished. The weight was significantly lower than market products, the cost was also substantially cheaper, and some seeds from the pre seeded walls were able to germinate showing that this phase of the growth cycle has potential in vertical gardens.

During the development of the living wall prototypes there were several other intentions in the design that were proposed in section 4.1. The wall needed to have a built in protection for the support wall. This was accomplished by using pond liner plastic. The walls should be easily transported and handled. This was accomplished by the use of flexible materials which allowed the walls to roll up and thereby shrink in dimension. It should be possible to replant the walls; although there was no specific feature for this, each plant pocket could be replanted or reseeded simply by removing the existing plant and inserting another. The design can also theoretically be used with multiple plant varieties, and the pockets all open to the interior of the walls which allows the root system the potential to grow unchecked. Although these were not the main aims of the thesis, they were considered important for future research and these sub goals were accomplished with the design of the wall.

The walls achieved what they were supposed to, but it also became clear that further research and new design concepts are greatly needed. The technical components were especially challenging and require skills, knowledge and time. It is still in question whether the walls could be successful without an automated hydroponics system, and be more simply hand watered. The factors which impacted the seed germination were numerous, and the germination was only partially successful. It is also unknown whether or not the germinated seeds could transition to the rooting phase and achieve maturity.

The greatest contribution of this research is the concept of an alternative form of living wall that can be used widely by many users for the good of society and the environment. This experiment has shown that cost, weight and functionality can all be improved upon in future living wall designs.

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Appendix I:

Experiment Supporting Photos

Figure 1: Greenhouse/ Experiment site. (Photo: Author).

Figure 2: Greenhouse/ Experiment site (Photo: Author).

Figure 3: Czechoslovakian street lamp fixture with cover (Photo: Author).

Figure 4: 150 watt, Metal Halide bulb in fixture (Photo: Author).

Figure 5: Grow light specs (Photo: Author).

Figure 6: Water Pump (Photo: Author).

Figure 7: Water cycle/ light cycle timer (Photo: Author).

Figure 8: Location of light fixture. Red line indicates location on wall directly below the light bulb (Photo: Author).

Figure 9: Complete constructed living wall system with framework and hydroponics irrigation system at the beginning of the germination phase (Photo: Author).

Appendix II

Experiment Data

Date	light hours	temp high top	temp low top	temp high bottom	temp low bottom	4:00 water	12:00 water	7:00 water	ph
27-Dec	5:30 - 18:30	27	20	25	20	20 ml	20 ml	20 ml	8
28-Dec	5:30 - 18:30	27	20	24.5	20	20 ml	20 ml	20 ml	7.2
29-Dec	5:30 - 18:30	26.5	18	23	17.5	20 ml	20 ml	20 ml	6.8
30-Dec	5:30 - 18:30	26	17	22	17	20 ml	20 ml	20 ml	7
31-Dec	5:30 - 18:30	26.5	17.5	23	17	20 ml	20 ml	20 ml	6.9
1-Jan	5:30 - 18:30	26.5	18	23.5	18	20 ml	20 ml	20 ml	6.5
2-Jan	5:30 - 18:30	27	19	24	19	20 ml	20 ml	20 ml	6.6
3-Jan	5:15-18:45	27	20	24	19.5	20 ml	20 ml	20 ml	6.5
4-Jan	5:15-18:45	26.5	19	24	18.5	20 ml	20 ml	20 ml	6.4
5-Jan	5:15-18:45	27	21	25	21	20 ml	20 ml	20 ml	6.7
6-Jan	5:15-18:45	27	21	25.5	20.5	20 ml	20 ml	20 ml	6.3
7-Jan	5:15-18:45	27	20	24.5	20	20 ml	20 ml	20 ml	6.6
8-Jan	5:15-18:45	27	21	24	20.5	20 ml	20 ml	20 ml	6.5
9-Jan	5:15-18:45	27.5	21	24	20	20 ml	20 ml	20 ml	6.4
10-Jan	5:00 - 19:00	27.5	22	25	21	20 ml	20 ml	20 ml	6.7
11-Jan	5:00 - 19:00	27.5	24	25.5	22	20 ml	20 ml	20 ml	6.4
12-Jan	5:00 - 19:00	27	23	25	22	20 ml	20 ml	20 ml	6.5
13-Jan	5:00 - 19:00	31.5	26.5	30	24.5	20 ml	20 ml	20 ml	6.5

14-Jan	5:00 - 19:00	29	24	26	23	20 ml	20 ml	20 ml	6.3
15-Jan	5:00 - 19:00	28	23	25.5	22.5	20 ml	20 ml	20 ml	6.3
16-Jan	5:00 - 19:00	28.5	23	26	23	20 ml	20 ml	20 ml	6.5
17-Jan	5:00 - 19:00	28.5	23.5	26.5	23	20 ml	20 ml	20 ml	6.8
18-Jan	5:00 - 19:30	29.5	24.5	28	23.5	20 ml	20 ml	20 ml	6.7
19-Jan	5:00 - 19:30	29	23.5	27.5	23	20 ml	20 ml	20 ml	6.3
20-Jan	5:00 - 19:30	28.5	22	27.5	21.5	20 ml	20 ml	20 ml	6.4
21-Jan	5:00 - 19:30	30	24.5	28	23.5	20 ml	20 ml	20 ml	6.4
22-Jan	5:00 - 19:30	29.5	24.5	27.5	23.5	20 ml	20 ml	20 ml	6.7
23-Jan	5:00 - 19:30	29.5	24	27	23.5	20 ml	20 ml	20 ml	6.5
24-Jan	5:00 - 19:30	27	21	25.5	20.5	20 ml	20 ml	20 ml	6.4
25-Jan	5:00 - 19:30	27	20	25	19	20 ml	20 ml	20 ml	6.7

Table 1: Conditions chart, showing data recorded in the greenhouse during the trial period.