Research Article

Food Producing Facades Key to a Sustainable Future

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Abstract

The built environment uses substantial and increasing amounts of energy, contributing to Urban Heat Island effect, while population growth and urban development have outpaced food production globally. There is a growing trend to introduce green infrastructure into the built environment via green roofs, green façades, and urban agriculture. Research is limited, however, into the use of food producing plants being grown on a living façade to improve total building performance. The purpose of this research study was to test the assertion that food producing plants can be grown successfully in a vertical greenery system or green wall integrated into an existing commercial building façade. Specifically, this dissertation investigates the role of integrating food producing plants into a living facade to positively impact four outcomes: food production, thermal performance, air quality and rainwater management in a temperate climate.

This was a six-year long longitudinal research study. The findings from this study conclusively demonstrate that a maximum average production of 2.64 kilograms of produce per square meter of façade panel can be generated annually (0.54 lbs./ft2). The façade temperatures were reduced between 5.56oC-20.53oC (10oF-36.95oF) with approximately 20% reduction in cooling energy, reducing urban heat island. Airborne small particulates (PM2.5)were reduced a maximum of 5.6% for the living facade compared to the control. An average of 14.26 litres of rooftop rainwater per square meter of facade per day (0.35 gal/ft2/day) was used for irrigation. In addition, observational studies revealed enhanced access to nature for building occupants, wildlife habitat and biodiversity.

Keywords: Building Performance, Green Infrastructure, Living Façade, Urban Agriculture, Urban Heat Island.

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Araştırma Makalesi

Sürdürülebilir Bir Geleceğin Anahtarı Gıda Üreten Dış Cepheler

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Özet

Nüfus artışı ve kentsel gelişim küresel olarak gıda üretimini geride bırakırken, Yapılı Çevre Kentsel Isı Adası etkisine katkıda bulunarak, önemli ve artan miktarda enerji kullanmaktadır. Yeşil çatılar, yeşil cepheler ve kentsel tarım yoluyla yeşil altyapıyı yapılı çevreye dahil etme yönünde artan bir eğilim vardır. Bununla birlikte, gıda üreten bitkilerin, yaşayan bir cepheye entegre edilerek toplam bina performansını artırmada kullanımı konusundaki araştırmalar sınırlıdır. Bu araştırmanın amacı gıda üreten bitkilerin ticari bir bina cephesine entegre edilmiş dikey yeşillik sistemi veya yeşil duvarlar içerisinde başarılı bir şekilde yetiştirilebileceğini test etmektir. Spesifik olarak, bu tez, yaşayan cephedeki gıda üreten bitkilerin rolünün iliman iklim koşullarında, gıda üretimi, termal performans, hava kalitesi ve yağmur suyu yönetimi olmak üzere dört sonuca pozitif etkisi olup olmadığını inceler.

Bu çalışma 6yıl süren uzun soluklu bir araştırmadır. Bu çalışmadan elde edilen bulgular, yıllık olarak ortalama 2.64 kilogram (0.54 lbs./ft2) ürünün cephe paneli basına üretilebileceğini kesin olarak göstermektedir. Cephe sıcaklıkları 5.56öC-20.53öC (10oF-36.95oF) arasında düşürülerek, soğutma enerjisinde yaklaşık %20 azalma ile, kentsel işi adası etkisi azaltıldı. Hava kirliliğine neden olan küçük partiküller (PM2.5), yaşayan cephe için kontrol grubuna kıyasla maksimum %5.6 oranında azalmıştır. Bir metrekare cephe paneli basına ortalama olarak günde 14.26 litre (0.35 gal/ft2/gün) yağmur suyu sulama için kullanılmıştır. Ayrıca, gözlemsel çalışmalar, bina sakinlerinin doğaya erişiminin arttığını, doğal yaşam alanının ve biyo-çeşitliliğin arttığını ortaya koymuştur.

Anahtar Kelimeler: Bina Performansı, Kentsel Isı Adası, Kentsel Tarım, Yaşayan Cephe, Yeşil Altyapı.

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INTRODUCTION

Key Challenges Addressed by Food Producing Living Façades and Hypotheses

There are many challenges that can be met by increasing vegetation in cities through urban gardens, green roofs and living façades. This thesis identified a set of four challenges to set the hypothesis and metrics for food producing living façades to address food shortages, heat increases, air quality challenges and flooding in cities around the world.

Alongside rapid urbanization around the world, there is a growing gap between growth in human population and food production. Over 1.7 million global deaths each year (2.8%), attributed to low fruit and vegetable consumption (World Health Organization, 2004). The percentage in the U.S. is also striking, with over 11.1% of all US Households identified as "Food Insecure" (USDA, 2018), 9-12% of Pennsylvania households (Coleman-Jensen, Rabbit, Gregory & Singh, 2018) and 13.7% of Allegheny County households (Sundaram, 2018). The vertical surfaces of buildings provide an underutilized opportunity for urban food production, while also reducing surface temperatures, improving air quality and rainwater management – the subject of this research.

Buildings in the U.S. use 76% of all electricity (Mazria & AIA, 2006); 10% for cooling in 2019 (EIA, 2020), with 9.6% of component loads due to heat gain on building surfaces (Huang & Franconi, 1999). Air Conditioning accounts 15% of total energy costs for commercial buildings (ASi Controls, 2014). Cooling loads contribute 117 million metric tons of CO_2 per year in the U.S., other greenhouse gasses and pollutants (US Department of Energy, 2021). Air conditioning contributes 20% or more to peak power demand, challenging grid reliability (Energy Storage Center, 2013). This leads to high façade surface temperatures and increased air conditioning exhaust which contributes to and exacerbates urban heat island effect. Annually in the US 600-700 people die due to heat waves. *"Heat wave mortality risk increased 2.5% for every 1°F increase in heat wave intensity and 0.38% for every 1-day increase in heat wave duration."* (Anderson, 2010).

Air pollution kills an estimated 7 million people worldwide annually (World Health Organization, 2021). Forty-five percent of the U.S. population live in counties with unhealthy levels of particulate or ozone pollution (Hahn, 2020). Pittsburgh consistently ranks among the top ten cities in the US for small particulates (Lynn, 2020). The lack of landscape in urban environments is correlated with a 4% increase in fine (PM_{10}) and ultra-fine ($PM_{2.5}$) dust particles (Kohler, 2008).

In natural ecosystems, evaporation accounts for 80% of water, with 1% going to runoff, while in the built environment evaporation is only 25%, with 70% going to runoff (Dreiseitl, 2005). In cities with combined storm sewers, the immediate runoff quantities result in Combined Sewer Overflows (CSO's). In Pittsburgh as little as $1/10^{th}$ of an inch of rain (2.54 mm) can cause CSO's (Knauer, 2003). Present rainwater management allows immediate building and site runoff into urban storm sewer systems resulting in increased flooding. Storm water management with grey infrastructures also increases the frequency and severity of drought compromising the hydrological cycle due to the lack of natural groundwater recharge (Lyle, 1994; Schmidt, 2009; Dreiseitl, 2005).

Hypothesis and Research Questions

Bringing nature into the city is a tradition as old as the hanging gardens of Babylon, but it is only in the late twentieth and early twenty-first centuries that this concept has matured into a strategy for incorporating plants and living systems into a performance-based approach to the design and functioning of the built environment. This includes the introduction of urban agriculture not only on land within the city, but also on top of and integrated with the green roofs and green façades of local commercial and residential buildings. This new approach of bringing productive landscape and agriculture right into the city, integrated within the building envelope itself, provides a new opportunity to increase food production on previously unproductive urban surfaces. The challenges are to quantify how much food can be produced in a temperate climate and what other benefits might be gained alongside food production. This research answers one overriding hypothesis:

The use of food producing plants grown on a living façade will generate a substantial, measurable, and useful amount of fruits and vegetables and also improve total building performance in three key metrics: decrease urban façade surface temperature, improve urban air quality, and decrease stormwater runoff.

Specifically, four research questions were asked:

1: Living Facades will increase urban food production, producing measurable amounts of fresh vegetables, fruit and herbs.

2: Living Facades will decrease façade surface temperatures during the heat of the day in summer.

3: Living Facades will improve air quality by reducing $PM_{2.5}$ particulates at the building façade.

4: Living Facades will decrease Stormwater runoff through the collection and redeployment of rainwater for irrigation.

THEORETICAL FRAMEWORK OF THE METHOD

A Taxonomy of Choices for Configuring Living Façades

To quantify the potential of living façades to increase urban food production and offer other environmental benefits, it is important to distinguish the types of living wall configurations and background research on their relative performance impacts. A review of more than ninety research articles helped to define types of vertical greenery systems (VGS), design variables, performance metrics and outcomes shown in Table 1. Areas highlighted in green are studied in this experimental research effort.

Physical Metrics						
Green Wall Type	**Growing Media**	**Plant Types**	**Irrigation / Filtration**	**Openings / View**	**Access / Maintenance**	**Innovative / Technologies**
Carrier System (Panels)	Soil Mix	Deciduous	Stormwater	Transparency	Low rise	Photovoltaics
Support Systems (container & Trellis)	Depth	Evergreen	Greywater	Seasonality	High rise	Hydroponics
	Soil less / Felt	Agricultural	Blackwater			Wastewater Treatment
		Ornamental				

Table 1. Physical metrics

In the book *Vertical Greenery for the Tropics,* (Wong, 2009) Vertical Greenery Systems (VSG's) were defined in two general categories – support systems or trellises that are coupled with the ground or containers and carrier systems with panels of growing medium to support a broader range of plant types, as shown in Figure 1:

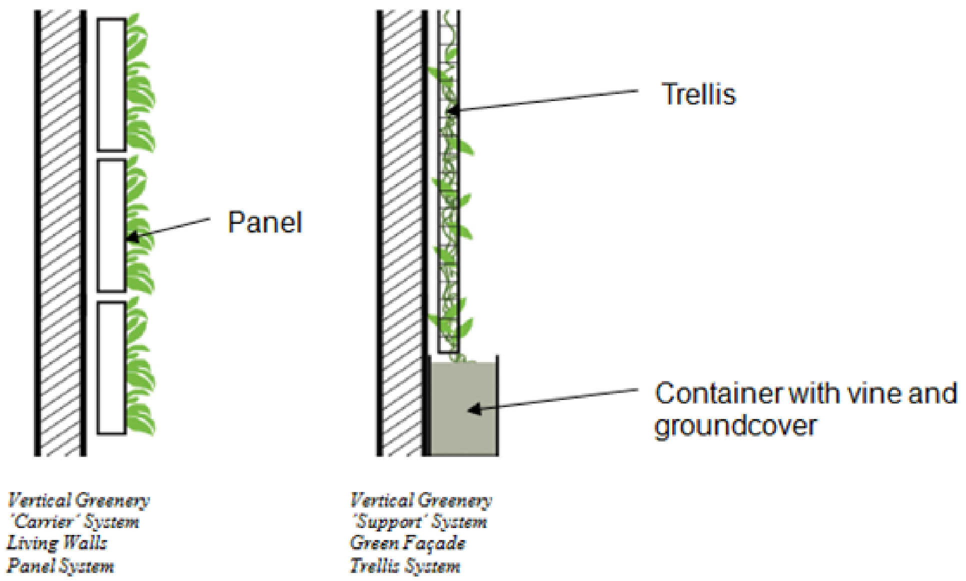


Figure 1. Living Wall and Green Façade Systems definitions (Wong, 2009).

In a definitive paper produced at the Queensland University of Technology Centre for Subtropical Design, *Living Walls – A Way to Green the Built Environment* (Loh, 2008), three basic green wall systems are defined, as shown in Figure 2:

- Panel Systems (like the Carrier System described above).
- Felt Systems, with pockets hung from a backing support.
- Container and/or Trellis Systems, with a ground container to support vine growth.

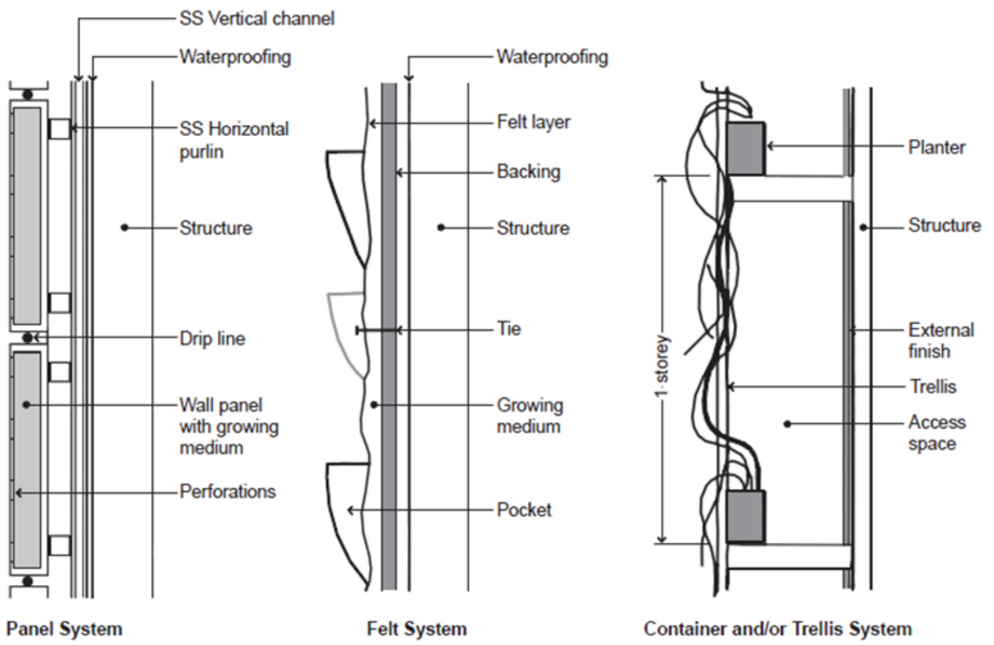


Figure 2. The three generic green wall systems (Loh, 2008).

The system used at this experimental research on the south and west façades of the Intelligent Workplace living lab in Pittsburgh was a hybrid panel and trellis system, with the soil panels providing the fabricated soil mix to grow the polyculture of plants used in this study. The research installations used a diversity of food and ornamental plants, captured rainwater for irrigation, vines for air filtration and seasonal transparency of the glazed areas, and photovoltaics to power the automated drip irrigation system. The experimental installation was evaluated over six growing seasons, using a range of instruments to quantify the performance benefits of living, food producing walls, highlighted in green in Table 2.

Table 2. Performance Metrics.

Performance Metrics						
Thermal Qualities	Air Qualities	Water Qualities	Visual Qualities	Acoustic Qualities	Material Qualities	Spatial Qualities
Shade	Air Quality	Stormwater	Daylight	Sound Transmission	Food & Flower Production	Size
Cooling Load Ratio	Oxygen	Greywater	Shade	White Noise	Biophilia	Ergonomics
Heating Load Ratio	Carbon Sequestration	Blackwater	Glare	Habitat	Soil Nutrient Cycle	
Evapotranspiration	Bio-Filtration		Color		Public Relations/ Marketing	
Urban Heat Island						
Energy Production						

Background Literature on Living Food Producing Façades

Twenty-one papers of precedent research on living façades, and more significantly food producing façades, were reviewed to determine critical test bed configuration and performance measurements for food, heat, air and water impacts, with an identification of the climate region where these studies were conducted.

Table 3. Table of major green wall research authors and areas of focus.

Author	Food	Temperature / Cooling	Air	Water	Climate		
					Temperate	Subtropical	Tropical
Akbari		✓	✓			✓	
Amir	✓						✓
Bass		✓			✓		
Cameron		✓			✓		
Connelly (BCIT)				✓	✓		
Davis		✓					✓
Eumorfopoulou		✓				✓	
Köhler		✓	✓		✓		
Kontoleon		✓			✓		
Kew				✓	✓		
Martensson	✓				✓		
Nagle	✓				✓		
Othman		✓					✓
Petit			✓			✓	
Perini		✓	✓		✓		
Schmidt		✓		✓	✓		
Stec		✓					
Susorova		✓			✓		
Tilley		✓			✓		
Wang				✓	✓		
Wong		✓					✓
Leininger	✓	✓	✓	✓	✓		

A majority of the research on green walls and living façades has been focused on the temperate climate region, which is the dominant climate type in the United States and in Europe. While there is a growing body of research on living façades, there is remarkably little research to date on food producing façades. At the time of this research, only two studies had been completed quantifying the benefits of food production on the vertical faces of buildings. At Penn State University, Nagle et al identified that a range of 1.5– 12.7 kg/m² of herbs and collard greens can be produced on panel based living façades in a temperate climate (Nagle et al., 2017). At the Swedish University of Agricultural Sciences, Martensson et al identified that edible perennials - Chives, Lesser Calamint and Wild Strawberry – could thrive over winter in a living wall system in Malmo, Sweden (Martensson et al., 2014). These two studies offer insight into the production capability of food producing walls and the potential durability and vitality of horticultural plants as components of a living façade in cold and temperate climates. Critical validation of the veracity and replicability of these results is one purpose of this study.

A review of more than a dozen green façade and living wall studies related to thermal performance benefits, these five illustrate the typical findings. Akbari et al. (2001), identified that "*urban trees and high albedo surfaces can…reduce national energy use in air conditioning by 20% and save over $10B per year in energy use and improvement in urban air quality*". A field study of trellis and panel Vertical Greenery Systems (VGS) by Wong et al, identified that living walls reduced surface temperatures by 5°C (9°F) on average. In a subsequent simulation study, Wong et al identified heat gain reductions of 10%-74% based on the extent of vertical greenery coverage (Wong, 2008).

A field study of green façade exterior surface temperature differentials on a building in Northern Greece determined the average reduction was 5.7°C (10.3°F) (Eumorfopoulou & Kontoleon, 2009). An energy simulation study on the same building identified cooling load reductions of 18% on the east façade, 8% on the south, 18% on the west and 5% on the north (Kontoleon & Eumorfopoulou, 2010). Tilley et al, identified an average façade surface temperature reduction of 11°C (20°F) in green façade test cells at the University of Maryland, with a maximum of 14°C (25°F) cooler than the bare wall control (Tilley, Price, Matt & Marrow, 2012). Perini et al, identified 17%-40% energy savings in cooling with vertical greenery systems on the south façade of an office building in Genoa, Italy (Perini et al., 2017). These findings show the surface temperature reduction and potential cooling load reduction benefit generated by green façades and living walls planted with non-edible plant varieties. Verifying that horticultural plants will yield similar façade surface temperature reductions is the second point of this study.

The four studies reviewed on the benefit of plants relative to small particulate reduction, illustrate the major findings in this area. Kohler identified a 4% reduction in annual dust-fall (PM_{10} and $PM_{2.5}$) through a maximization of green façades (trellis) and living walls (panel) in dense urban environments (Kohler, 2008). Variation in leaf texture and surface characteristics of three tree species, and the use of daily irrigation to increase the opportunity for wet deposition, are effective mechanisms for reducing $PM_{2.5}$ in urban environments (Wang, Gong, Liao & Wang, 2015). The performance of four different evergreen plant species to reduce fine and ultra-fine dust particles (PM_{10} and $PM_{2.5}$) when planted in a vertical greening system was studied by Perini, et al. Shrubby, non-edible plants indicated that waxy leaves (*T. Jasminoides*) collected the highest number of particulates, whereas plants with hairy leaves (*P. Frucitosa*) were less effective (Perini et al., 2017). Petit et al identified that fern species had a single pass removal efficiency of 46% for $PM_{0.3\text{-}0.5}$ and 92% for $PM_{5\text{-}10}$ when integrated into a bio-wall HVAC filtration system (Petit et al., 2017). These studies show that small tree and shrub species produce leaves that provide effective surface area for small particulate deposition, effectively reducing airborne levels. Verifying that horticultural plant leaves can provide similar benefits in terms of improving air quality by reducing $PM_{2.5}$, while producing measurable amounts of fresh produce, is the third important aspect of this study.

The two most relevant studies on rainwater absorption by living façades illustrate their potential value as green infrastructure. Living façade panels planted with sedum angelina, sedum ternatum, sempervivum tectorum, and ajuga reptans reduced rainwater runoff an average of 52-68% (Kew et al., 2014). Connelly et al identified that different vining plants will absorb different rain quantities, with Silverlace at 2.83 L/m^2 (0.07gal/ft^2), vine, Evergreen clematis at 4.28 L/m^2 (0.11gal/ft^2), and Oriental bittersweet at 5.58 L/m^2 (0.14gal/ft^2) (Connelly et al., 2012).

Food Producing Living Façades – System Design and Food Production Methods & Materials

After a review of living façade designs and precedent research, the design and implementation of the Intelligent Workplace food producing living façade project was developed to contribute a semi-controlled field experiment on the existing south and west façade areas of the Robert L. Preger Intelligent Workplace (IW) on the campus of Carnegie Mellon University (see Figures 3-7). The drawings illustrate the concept.

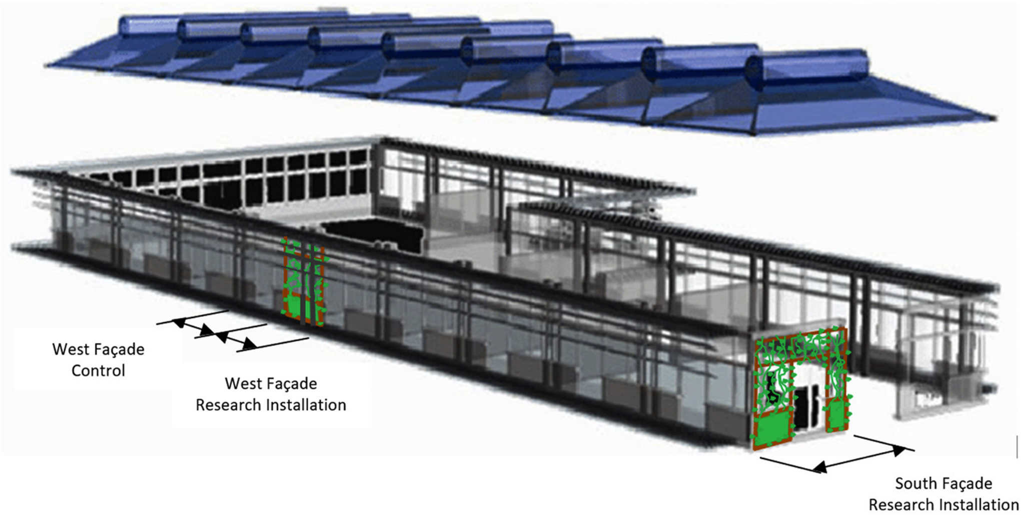


Figure 3. Axonometric of IW showing Living Façade Research Areas.

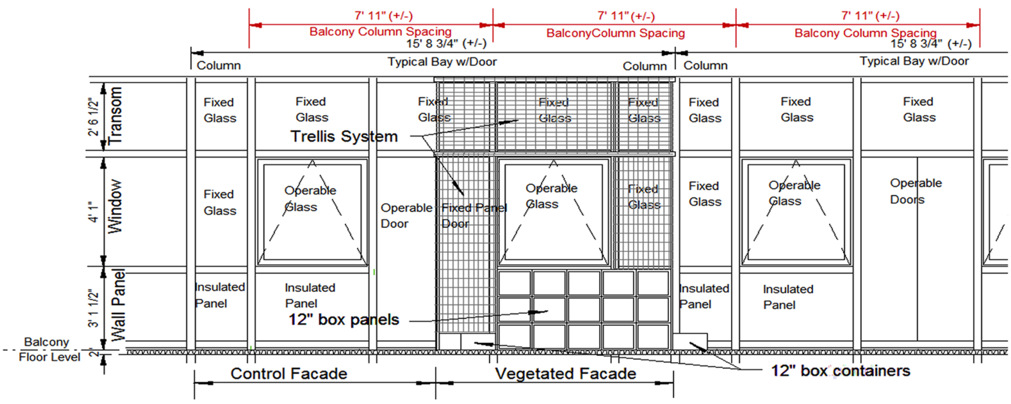
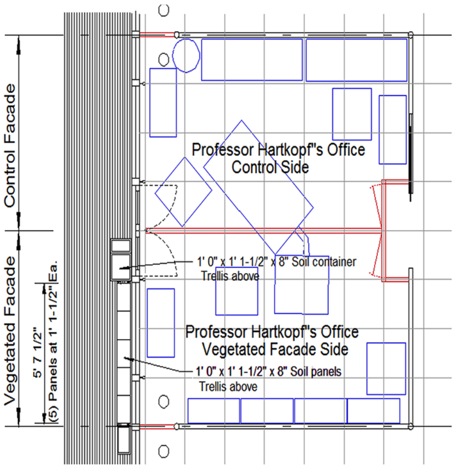


Figure 4. Food producing living façade installation, Intelligent Workplace west façade elevation

The IW is a 7,000 square foot living and lived-in laboratory dedicated to the research, demonstration and development of building systems integration for increasing energy efficiency and environmental effectiveness within the built environment. It is designed to be a flexible platform for building systems research and innovation, while occupied with faculty, staff and graduate student researchers (Hartkopf et al., 2005). The system was designed as a panel and trellis hybrid Living Façade system planted with food producing plants. The west façade research bay elevation and floor plan show the research façade and control façade. The details drawings and step by step assembly and planting images illustrate the individual soil panels. The photo shows the south façade system in place.



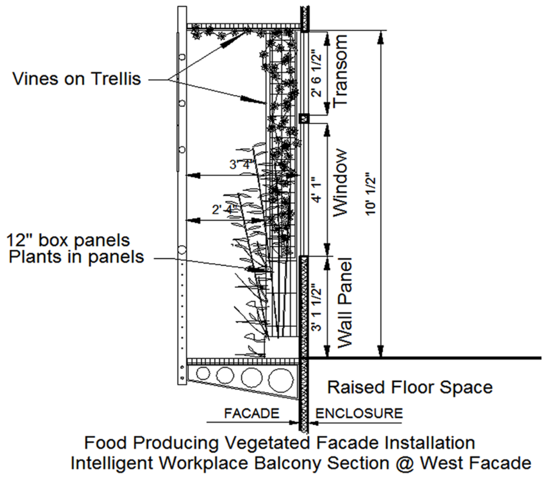


Figure 5. West façade research bay floor plan.
Figure 6. West façade section @ living facade.

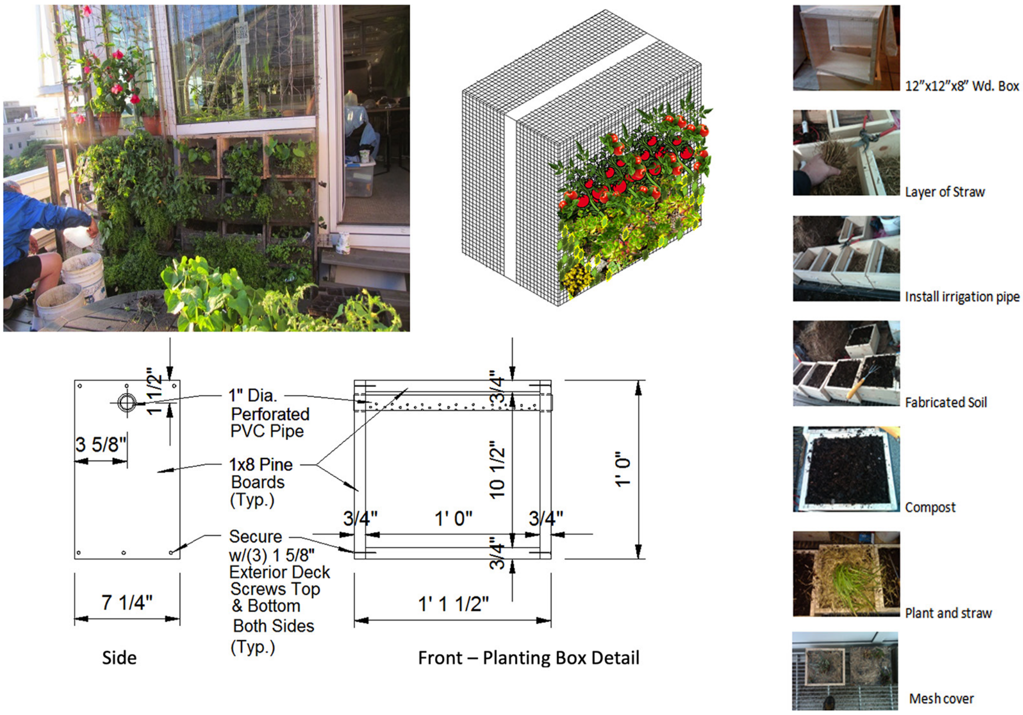


Figure 7. Planting box configuration and details.

The steps necessary to conduct this experiment were to design, test, analyse and conclude the system installation, operation, performance, and disassembly, outlined in Table 4 below. The aim of this research study was to measure, record and verify performance, comparing the field data results to existing research and contributing original results not previously collected or recorded. The four sections that follow outline the data sets, analysis methods, and results that confirm food producing living façades contribute measurable food production, heat gain reduction, air quality improvement and rainwater redeployment.

Objectives	Methods	Details
DESIGN Design, Fabricate, Install, Operate, and Maintain a Food Producing Living Facade	Proof of Concept Design Installation and Operation	Soil Based Panel and Trellis System
		Temperature Sensor Installation
		Particulate Sensor Installation
		Rain Barrel and PV solar irrigation system Installation
TEST Building Performance MRV	Semi-Controlled Field Experiment Data Collection	Food Production
		Façade Temperature (Exterior & Interior)
		Small Particulates
		Rainwater Irrigation
ANALYZE Data Analysis	Descriptive and Inferential Analysis	Food Weight, Quantity & Nutritional Value
		Hobo Sensor Façade Temperature Monitoring & Infra-Red Photography
		Small Particulate Monitoring
		Average Rainwater Usage
CONCLUDE Cradle to Cradle Dismantle System	Design for Disassembly	Biological Components to be composted
		Technical Components to be reused or recycled

Table 4. Conceptual Diagram of Research Objectives, Methods and Details.

FINDINGS/RESULTS

Food Producing Living Façades – Façade fruit and vegetable production
Food Producing Living Façades generate an average of 2 kg/m² of nutrition per growing season.

The primary hypothesis of this dissertation is that building façades can produce measurable amounts of fresh produce when updated with living façade assemblies planted with food producing plants. Quantification of fresh produce harvested from the south and west façade research installations was systematically documented to test this hypothesis. The same number and type of food producing crops planted on both façades each year included:

- 6 Cherry Tomato plants
- 6 Roma Tomatoes plants
- 2 Heirloom Tomato plants
- 6 Sweet Banana Pepper plants
- 6 Hot Pepper plants
- 18 Green Bean plants

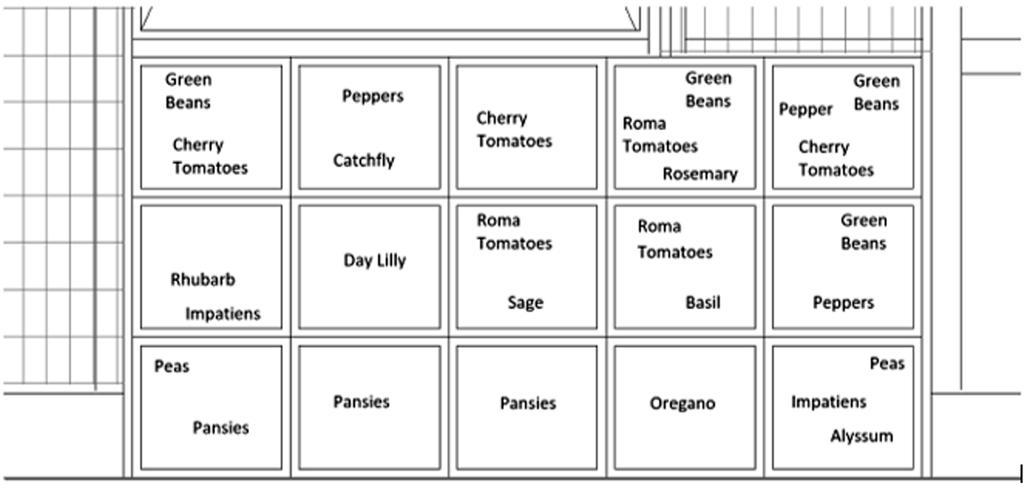


Figure 8. West façade planting diagram (May 2014).

Production was broken down by weight, quantity, and façade orientation. Replicability and fluctuations in productivity over the six growing seasons were captured and graphed as well. The goal was to quantify potential production levels attainable on a consistent basis with this type of system in this climate region, as well as to look at the potential for variety in the production output of such a system, in terms of the diversity of potential future plantings. Vegetables, herbs, and fruit grown on the living façade system were harvested as they ripened. Every vegetable and piece of fruit, and small bundles of herbs, were arranged on single letter sized (8.5" x 11.5") sheets of white paper, numbered and then weighed. Each sheet of paper was photographed, and then weight and quantity were recorded in a spreadsheet database.

Figure 9. Fresh produce weight and quantity, measured, verified, and recorded.

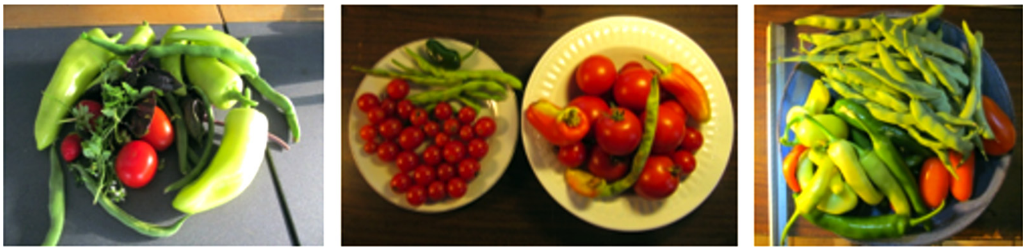


Figure 10. Harvested vegetables and herbs.

There are several significant conclusions drawn from this 6-year experimental study that confirm that living food producing façades can produce an average of 2 kg/m2 of nutritious fruits and vegetables for south and west orientations in the temperate climate of Pittsburgh (see Table 5).

- Food Producing Living Façades can produce a maximum of 2.64 kilograms/ m^2 of fresh produce (0.54 lbs./ft^2) and a six-season average of 2.04 kg/m^2 across south and west façades in a temperate climate.
- To achieve 400 grams daily of fresh fruit and vegetable, approximately 37 m^2 (400 ft^2) of façade would be needed per person to provide for a nutritional diet that meets WHO standards, during the growing season.
- Food producing living façade produce showed similar nutrient levels as store bought produce, but will support local economies and reduce embodied energy – and tastes better.

Table 5. Living Façade Food Production Totals by Weight per Unit of Area per Year.

	2013	2014	2015	2016	2017	2018	Avg
Total West Façade Food Production (kg/m^2)	**2.66**	**1.61**	**1.82**	**1.34**	**2.61**	**1.56**	**1.93**
Total West Façade Food Production (lbs/ft^2)	0.54	0.33	0.37	0.27	0.53	0.32	0.40
Total South Façade Food Production (kg/m^2)	**2.51**	**1.41**	**2.70**	**1.70**	**2.68**	**1.91**	**2.15**
Total South Façade Food Production (lbs/ft^2)	0.51	0.29	0.55	0.35	0.55	0.39	0.44
Total Food Production (kg/m^2)	**2.59**	**1.51**	**2.26**	**1.52**	**2.64**	**1.74**	**2.04**
Total Food Production (lbs/ft^2)	0.53	0.31	0.47	0.31	0.54	0.36	0.42

Food Producing Living Façades – Façade surface temperatures reduction

Food producing living façades reduce exterior façade surface temperatures 5.56°C-20.53°C (10°F-36.95°F).

A second research question is that food producing living façades will measurably reduce façade surface temperature, compared to a control of that same façade, which in turn will reduce conductive heat gain and total cooling load. Temperature data was collected for the research and control façade areas over two one-week periods in August and September 2013 to show typical summer conditions.

- Air temp 1 meter away from west façade – indoors and outdoors (HOBO and Omega sensors)
- Exterior and interior surface temp - opaque west façade (HOBO U12 data logger and sensors)
- Exterior and interior surface temp - glazed west façade (HOBO U12 data logger and sensors)
- Thermographic Imaging of exterior façade (FLIR Thermal Imaging Camera)

Figure 11. Hobo U12 data logger, temperature sensor and Omega air temperature sensor.

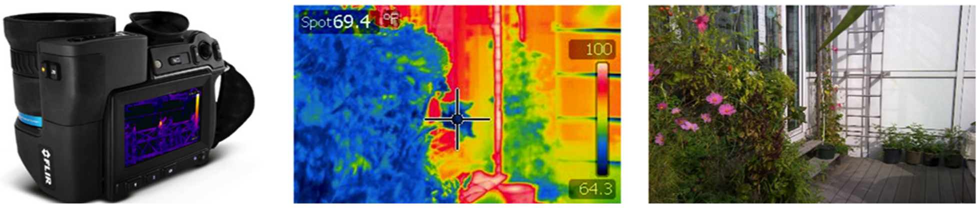


Figure 12. FLIR T1020 HD Thermal Imaging camera, south façade installation photos.

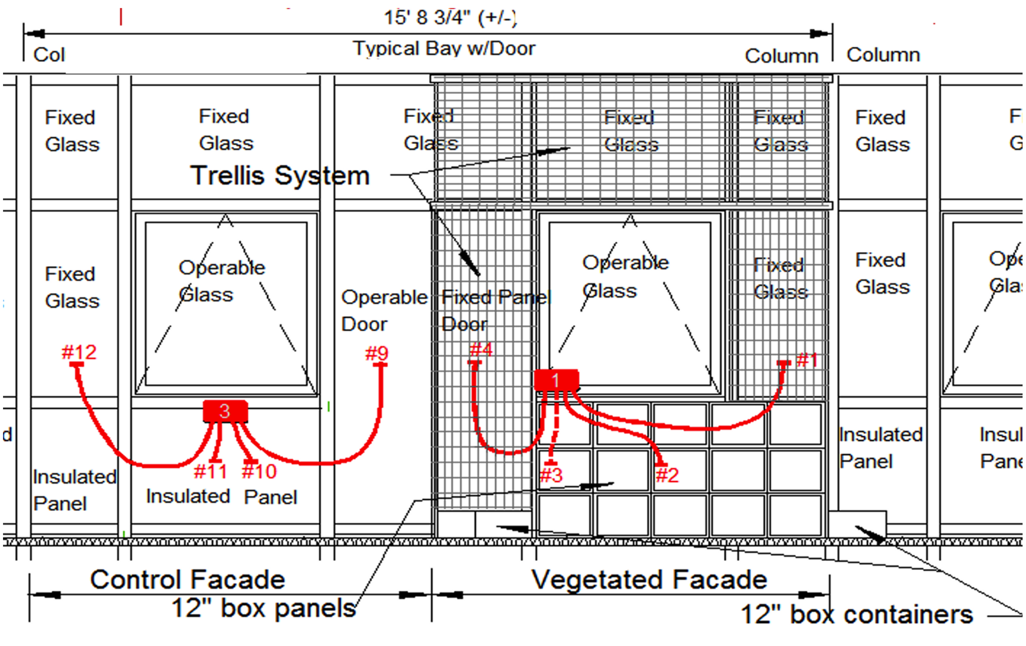


Figure 13. Surface temperature sensor locations, Intelligent Workplace west façade elevation.

The opaque façade temperature measurements for the week of August 5-11, 2013, reveal a number of statistically significant findings:

- The average temperature differential (ΔT) during heat gain periods was reduced by 40% to 79% for the living façade compared to the control.
- Peak exterior façade surface temperature was reduced by 20.5°C (37°F) on the hottest day.
- At night, the living façade kept the façade surface temperature an average 4.74°C (3.77°F) warmer than the control façade as temperatures dropped below comfort.
- The food producing living facade reduced the length of heat gain periods for the living façade 23% to 94% on hot days.
- The length of heat gain periods was shorter for the control façade on the cooler days, due to the thermal lag of the living façade.

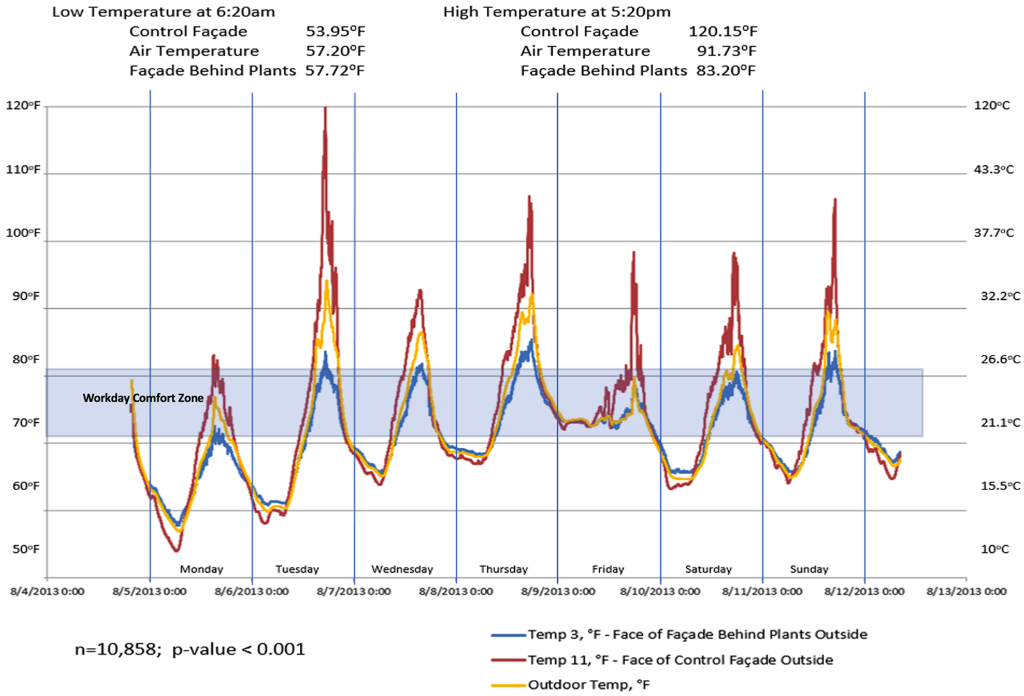


Figure 14. Exterior Opaque Façade Surface and Air Temperatures, Aug. 5-11, 2013.

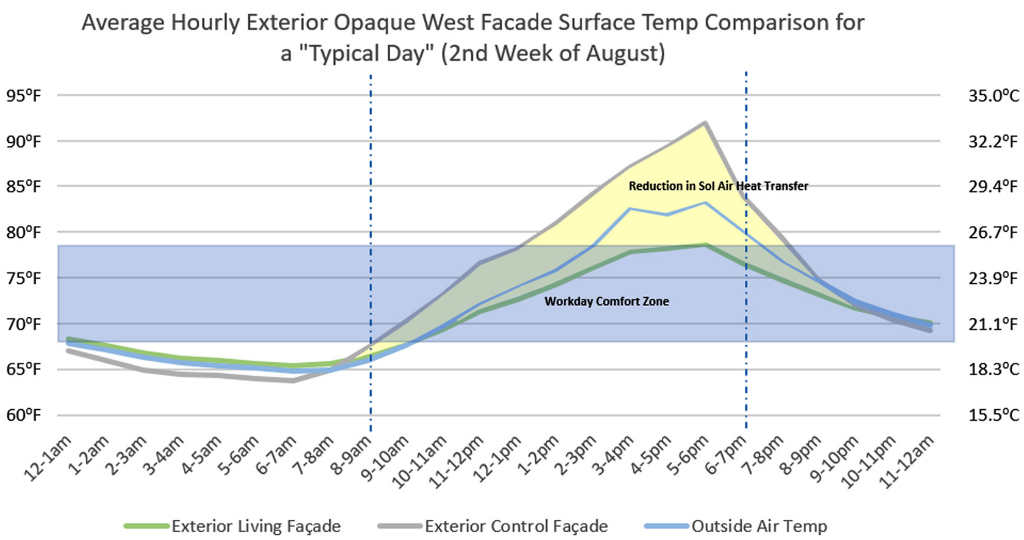


Figure 15. Average Hourly Exterior Opaque West Façade Surface and Outside Air Temperatures, "Typical Day".

To understand the implication of these temperature differentials for a buildings cooling load, the hour-by-hour comparison of the temperature changes for an averaged typical summer day are shown in Figure 15.

On an averaged "Typical Summer Day" living façade temperatures never exceed the comfort zone upper limit of 25.6°C (78°F), while the control façade exceeds the comfort zone from 1 to 8 pm. The highlighted area between the exterior surface temperatures of the living façade compared to the control represent the potential contribution to the cooling load.

As a field research study in an occupied building, it was not possible to fully isolate the control and living façade test areas from the mechanical systems. However, the continuous minute by minute monitoring of interior and exterior surface temperatures for two summer weeks with a mix of sun and overcast days allowed for a statistically significant profile of surface temperatures and temperature differentials to be developed for living façades in a temperate climate. Other researchers have identified that reductions in surface temperatures and temperature differentials correspond to a reduction in air conditioning loads of 20% (Stec et al., 2005) (Akbari et al., 2001) or greater, between 35%-68% in various cities globally (Alexandri & Jones, 2008).

Food Producing Living Façades – Air quality improvement via small particulate reduction

Food producing living facades generate 3.2%-5.6% reductions in $PM_{2.5}$ at the exterior façade.

The third research question on the value of food producing façades was the ability to reduce outdoor air pollutants. Measurement of air quality performance focused on small particulate levels ($PM_{2.5}$) critical for improving the air quality of cities with high traffic and industrial pollution, such as Pittsburgh. (Figures 16-18). The small particulate data was collected with the IW Aircuity Optinet™ system that utilizes nanotube technology to take air samples every few minutes. Samples were pulled to a robust central sensor suite from locations on the exterior and interior of the façade.

Analysis of the exterior data for the entire seven-month period, from February to August 2014, revealed statistically significant but modest improvements in air quality due to the living façade.

- Over the monitoring period from February to August, $PM_{2.5}$ levels were 3.2% to 5.6% lower at the surface of the living façade (p<0.001).
- Neither façade exceeds the federal National Ambient Air Quality Standards (NAAQS) levels of 35µg/m³ over 24 hours, or 15µg/m³ as an annual mean (USEPA, 2020).

Figure 16. PM2.5 sensors @ control façade.
Figure 17. PM2.5 sensors @ living façade.

• Rarely does either façade exceed the American Lung Association's recommended level of 3.2µg/m³. (American Lung Association, 2020).

Food Producing Living Façades – Rainwater Runoff Reduction
Food producing living façades can absorb 14 litres of water per m2 per day.

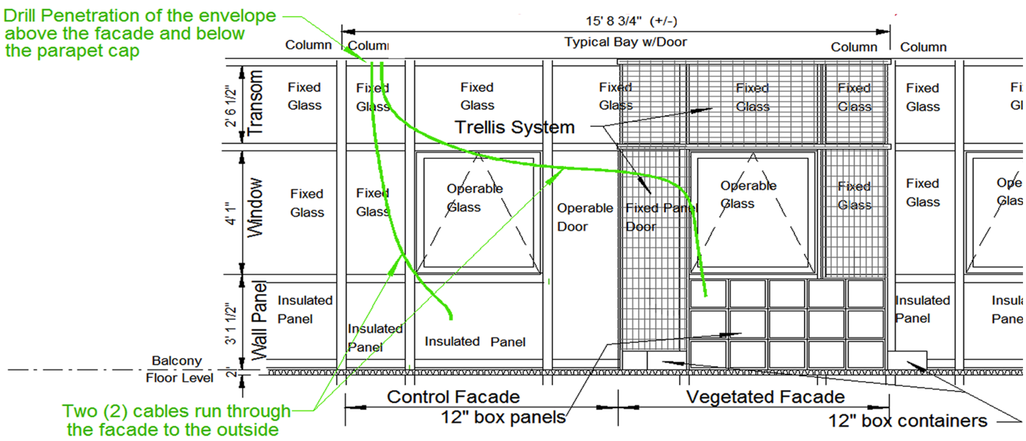


Figure 18. PM2.5 sensor locations @ living and control façades, IW west façade elevation.

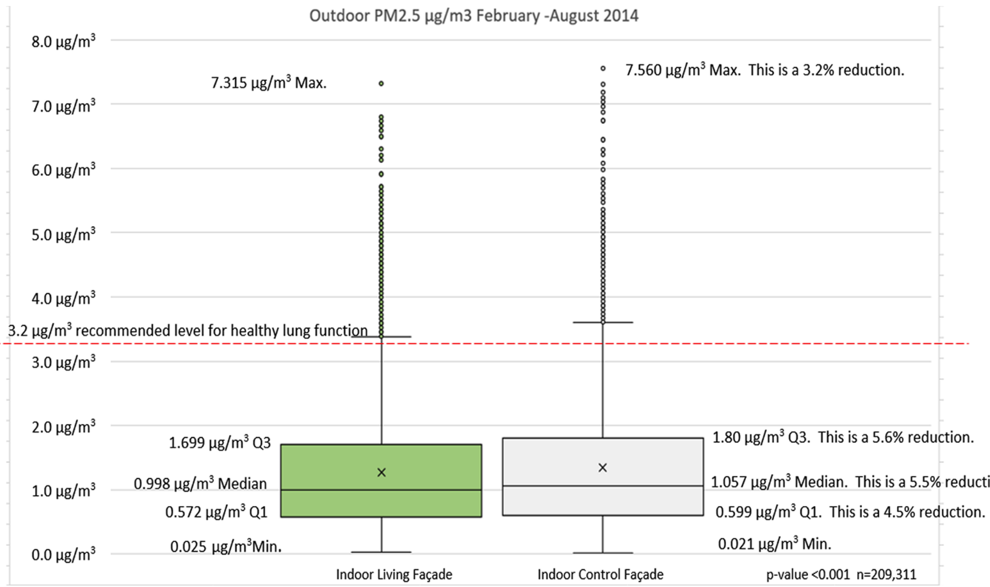


Figure 19. Outdoor West Façade PM2.5 µg/m3 at Living and Control Façades February – August 2014, n=209,295, p<0.001.

To benefit the significant number of temperate climate cities with challenges of storm-sewer overflow in heavy rains, quantifying irrigation water usage relative to surface area of food producing living façade is an important aspect of this study. The average irrigation requirements were measured in litres (gallons) per day throughout the growing season from May 1 to December 1, over six growing seasons. Irrigation for the living façade assemblies was integrated with rainwater capture and storage to address predictable periods of no rain. Since rainfall is never consistent, roof rainwater capture was stored in two 45-gallon rain barrels, with an overflow capability to the building drains. To establish water requirements of the living food producing façade, Echo EC-5 moisture sensors were attached to a HOBO U30 monitor system which triggered the pump to turn on and off as required, and established the optimum watering quantities for the remaining seasons (see Figures 20-22).

The pattern of readings for irrigation demand suggested that watering once every 24 hours was adequate for keeping the food producing plants sufficiently moist, but two days without irrigation caused the plants leaves to begin to wilt.

Figure 20. Irrigation system components.
Figure 21. Hobo U30 Monitoring System.
Figure 22. ECHO EC-5 Soil Moisture Sensor.

Although solar panels were added to power the pumps for the drip irrigation system, an uneven pattern of irrigation through the automated system led to an undesirable condition called "blossom end rot" on the bottom of the Roma tomatoes. As a result, daily hand watering of the system was implemented during the growing season.

The results are significant: Food Producing Living Façades in temperate climates can effectively redeploy 14.26 litres/m^2 (0.35 gallons/ft^2) per day of rainfall for the 214-day growing season, from May 1st to Dec 1st each year (see Table 6) in the Pittsburgh climate.

This means that every 1 m^2 of living façade can absorb the rainwater from 5 m^2 of roof (54 ft^2 of roof), in combination with on-site water storage to address rainfall variability, significantly reducing stormwater runoff. In the Pittsburgh climate, rainwater Storage should be sized at 28.6 gallons storage per m^2 façade.

Research Installations	Area	Irrigation/Day	Irrigation/Day/Area
West Façade	1.39 m^2 (15 ft^2)	18.9 liters (5 gallons)	13.60 liters/m^2 (0.333 gal/ft^2)
South Façade	1.76 m^2 (19 ft^2)	26.5 liters (7 gallons)	15.06 liters/m^2 (0.368 gal/ft^2)
Totals	3.15 m^2 (34 ft^2)	45.4 liters (12 gallons)	14.26 liters/m^2 (0.353 gal/ft^2)

Table 6. Daily Irrigation Totals and Total per Unit of Area per Façade and Overall.

Food Producing Living Façades - Increase Biodiversity

Food producing living façades provided additional habitat where a mix of species were observed.

Food producing living façades support biophilic advantages and biodiversity. The food producing living façades developed provided increased access to nature. Across the six seasons studied in this thesis, a variety of birds, spiders and insects were observed:

- American Robin
- Hawk
- Grasshopper
- Praying Mantis
- Yellow Garden Spider
- European Paper Wasp
- Northern Paper Wasp

Considering the extent of work and living environments that have no visual or physical connection to nature, in spaces too deep or too tall, the introduction of food producing living façades that bring full sensory experience to every floor is an important contribution to the quality of the indoor environment.

Figure 23. American Robin Turdus migratorius.
Figure 24. Hawk Species Unknown.
Figure 25. Robin's nest
Figure 26. Yellow Garden Spider Agriope aurantia bruary – August 2014, n=209,295, p<0.001.

DISCUSSION

Throughout the United States and around the world, major cities have been utilizing vacant lots and flat or low slope roof tops to develop urban farms, education programs and jobs training to support this expanding sector of urban agriculture. The surface area of urban building rooftops is only a small proportion of the overall area of the building façade on multi-story buildings. Transforming building façades into food producing vertical gardens would, in effect, create "new land" drastically increasing the area for food production within the urban environment.

Food Producing Living Façades could provide the 400g/day of fresh vegetables needed per person to 8-10% of the occupants of a residential or commercial building floor, entire building, or group of buildings, during the 214-day growing season in Pittsburgh. Application of the food producing living façade to three façades of the IW (a single-story building) would yield 190Kg's (832 lbs.) of produce. This is enough to provide 400g/day of fresh fruit and vegetables for 2 individuals out of 22 occupants or 9% of that population.

Application of the food producing living façade to all four façades of Donner House (a six-story building when renovated) would yield 1,756 kg's (3,720 lbs.) of produce; enough for 20 individuals out of 239 occupants to meet their nutritional needs or 8.4% of that population. When applied to thirty-three buildings of the same scale on campus, the yield would be 57,912 kg's (122,779.80 lbs.) of produce; enough for 676 individuals out of 6947 occupants or 9.7% of the campus undergraduate population.

Application of the food producing living façade to 70 ten-story Buildings in Downtown Pittsburgh would yield 2,160,000 kg's (4,762,000 lbs.) of produce. This is enough for 25,000 individuals to meet their nutritional requirements out of 15,060 downtown residents or 168% of that population, or out of 457,000 workers downtown or 5.5% of that population. When applied to 25% of commercial building façades in the United States, 186 million m^2 of façade, would yield 490,528,050 Kg's (1 billion lbs) of produce which is enough for 5.7 million individuals to meet their nutritional needs out of 64 million working professionals in the U.S. (DPE, 2020) or 8.9% of that population.

The annual production from food producing living façades could meet 8-10% of the nutritional needs of the population locally, nearly equal to the 9-12% of Pennsylvanians who are food insecure.

Food Producing Living Façades could absorb 0.003 inches of rainfall per m^2 of roof per day for each m^2 facade throughout the 214-day growing season in Pittsburgh. Application of the food producing living façade to three façades of the IW (a single-story building) would absorb 465 gallons per day over 122.25 m^2 of facade (3.8 gal/m^2) utilizing 100% of the rainfall on the IW roof per day (on average). Applied to all four façades of Donner House (a six-story building when renovated) would absorb 4,902 gallons per day over 1,290 m^2 of facade utilizing 100% of the rainfall on the IW roof /day.

The annual rainwater absorption from food producing living façades would utilize 100% of rainfall falling on roofs of buildings with extensive living façade installations.

This research study was limited by the variability in plant availability, due to seasons fluctuations in the local retail supply of horticultural plant starts. Additional limitations of the study included the inability to control for variables such as the unique geometries creating installation configuration differences between the south façade at the lower roof deck, without automated solar shading louvres, and the west façade at the balcony, at the same level as the interior floor level, which did feature the automated solar shading louvres. A multi-variable air quality analysis was not conducted to limit the complexity and quantity of the variables collected to a singular focus on small particulates ($PM_{2.5}$).

CONCLUSION AND RECOMMENDATIONS

There are a number of areas that could become the focus of future research immediately if funding was available now. The research results presented here provides a baseline of data in the areas of urban food, heat, air and water, upon which numerous future research studies could expand. Maximizing food production for specific species and demographics to address food insecurity tailored to specific regional and cultural tastes is a great area for additional investigation. Investigating vegetation variability for shading, including maximizing leaf area index (LAI), dynamic bioshading, and total cooling load calculations, in both energy simulation modelling and field verification is an important area for additional research. Design development of a commercially viable, modular, food producing living façade system with integrated irrigation, closed loop water applications, including aquaphonics, and automated operation with building robotics and controls could elevate this approach to the scale of urban vertical farming.

In addition, full scale human health implications related to reduced mortality linked to malnutrition, heat waves, small particulate related respiratory health, and CSO's should be investigated at the community scale. Integration with ongoing initiatives such as the Pittsburgh Downtown 2030 District (2030 Districts Network, 2021), P4 Initiative (P4 Pittsburgh, 2021), the investigation of applications of the United Nations Sustainable Development Goals within Pittsburgh by Covestro and other industry partners (Covestro North America, 2019), and specific project applications such as in Aliquippa, Pennsylvania, as identified in an EPA USDA funded Local Foods, Local Places workshop in 2019 (EPA, 2020). There are existing opportunities to apply the baseline results from this dissertation at the local, state and federal levels right now. Each of these applications should be a field research project gathering appropriate performance data to verify the results of this study. Applications at a large enough scale would reach a critical mass that would begin to change the energy and environmental performance of the built environment, replacing fossil fuel energy and materials, with biology and design intelligence, providing ecosystems services to urban populations.

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In this research, the necessary permissions were obtained from the relevant participants (individuals, institutions and organizations) during the survey, in-depth interview, focus group interview, observation or experiment.

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