Building-Integrated Carbon Sequestration Techniques: Towards Mitigating Climate Change

JAYATI CHHABRA
Georgia Institute of Technology

TAREK RAKHA
Georgia Institute of Technology

Keywords: Carbon, Climate Change, Carbon Sequestration, Mitigation, Sustainable Design

This paper provides an overview of building-integrated Carbon Sequestration (CS) techniques focusing on their potential environmental impact and associated costs. CS techniques are classified into three categories: 1) Biotic (Green Roofs, Vertical Greenery Systems (VGS), and Algae Facades); 2) Materials (carbon-negative and carbon absorbing building materials); and 3) Equipment (filter towers). Preliminary literature review shows that Green Roofs and VGS can capture 150gC/m2 – 650gC/m2, while algae facades go up to 2430gC/m2 - 2970gC/m2. Biomass and filter towers could absorb a relatively high amount of approximately 1 x 10^15 gC and 687.5 x 10^9 gC, respectively (without normalization). By analyzing and summarizing each CS technique based on performance indicators like prerequisites, CS potential, costs and area required, it was found that Biotic techniques can be applied to a structure's roof and facades for a large range of projects having low to high budgets. Biomass must be highly encouraged to be mixed with all the construction materials which can sequester up to 10^15 gC. Equipment, which has one of the highest potentials to sequester carbon and are highly expensive, can be used in urban spaces like parks and markets. A comparative analysis is finally done specifically showing the CS potential associated with the Biotic CS techniques to allow architects and designers to evaluate these technologies and analyze their integration potential in architectural practice.

BACKGROUND

Anthropogenic climate change is a reality of our times (Cawley 2011). The greenhouse effect which has made life on Earth possible by absorbing the sun's radiation and keeping the Earth's surface warm is now becoming one of the causes of climate change. A number of greenhouse gases (GHG) such as methane (CH4), carbon dioxide (CO2), water vapor, ozone (O3) contribute to this process (Farrelly et al. 2013), out of which CO2 is the most dominating absorber after water vapor and clouds. (Schmidt et al. 2010). Due to anthropogenic activities, the amount of CO2 has seen a drastic rise in the last two centuries estimated to result in a temperature rise of 3-5 deg C by the year 2100 (IPCC 2014). Such increase in emissions of carbon might push our planet to cross a threshold beyond which Earth's stabilization could not be achieved by human actions (Oreskes 2004). Thus, the fate of this planet may lie predominantly on mastering the ability to cycle carbon efficiently and avert it from becoming the reason for the destruction of humankind (Antonietti and Müllen 2010).

NEED FOR CARBON SEQUESTRATION

Carbon Sequestration (CS) is the process of capturing carbon from the atmosphere and storing it securely (Jain et al. 2012). This is largely undertaken to reduce the excessive CO2 concentration in the air caused by industries, burning of fossil fuels, automobiles, which otherwise lead to heat being trapped, resulting in global warming (Sood and Vyas 2017).

Moreover, while forests, soils and oceans have been a major, as well as the oldest carbon sinks, there have been several evidences of their deterioration such as water acidification and changes in the soil content, due to increased anthropogenic carbon emissions (Sundquist et al. 2008). As per IPCC's report, it is required to halt the temperature rise 1.5 deg C above pre-industrial levels otherwise it would lead to worse heatwaves, drought and flooding. (Zhou 2018). To avert this, it is important that the structures which cover large areas of the earth start contributing to CS. The integration of CS techniques in architecture has increased significantly recently even though some of the techniques mentioned in this literature review, like Vertical Gardens and Green Roofs, were being used in buildings for a long time, however, for other purposes.

METHODOLOGY

What are various CS techniques that have been integrated in buildings? How much carbon can a structure capture after the application of CS techniques? To address these questions, this study employed an exploratory research method. Various precedent studies published in peer-reviewed journal and conference papers on building-integrated CS techniques which were retrieved by a database search were reviewed for a systematic literature review. This being a comparatively recent topic, information was also collected from articles and reviews of reliable governmental and organizational websites.

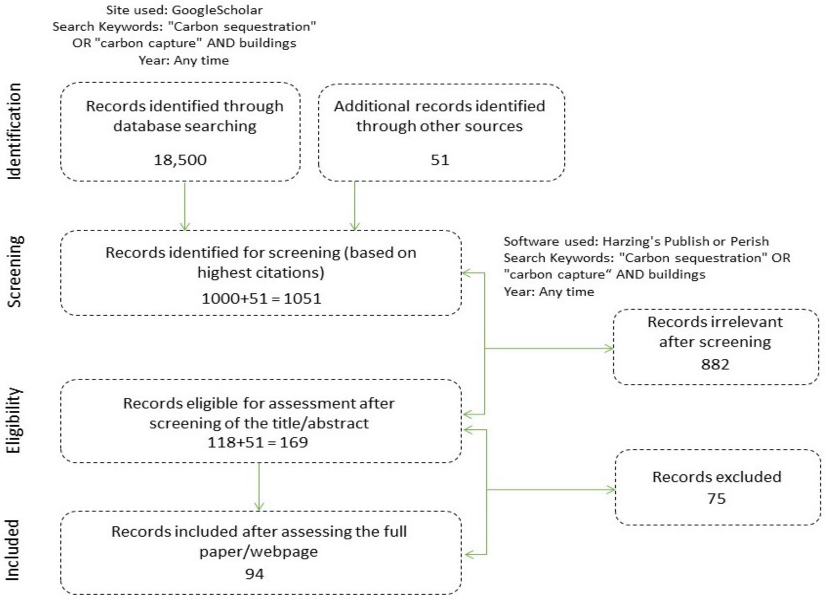
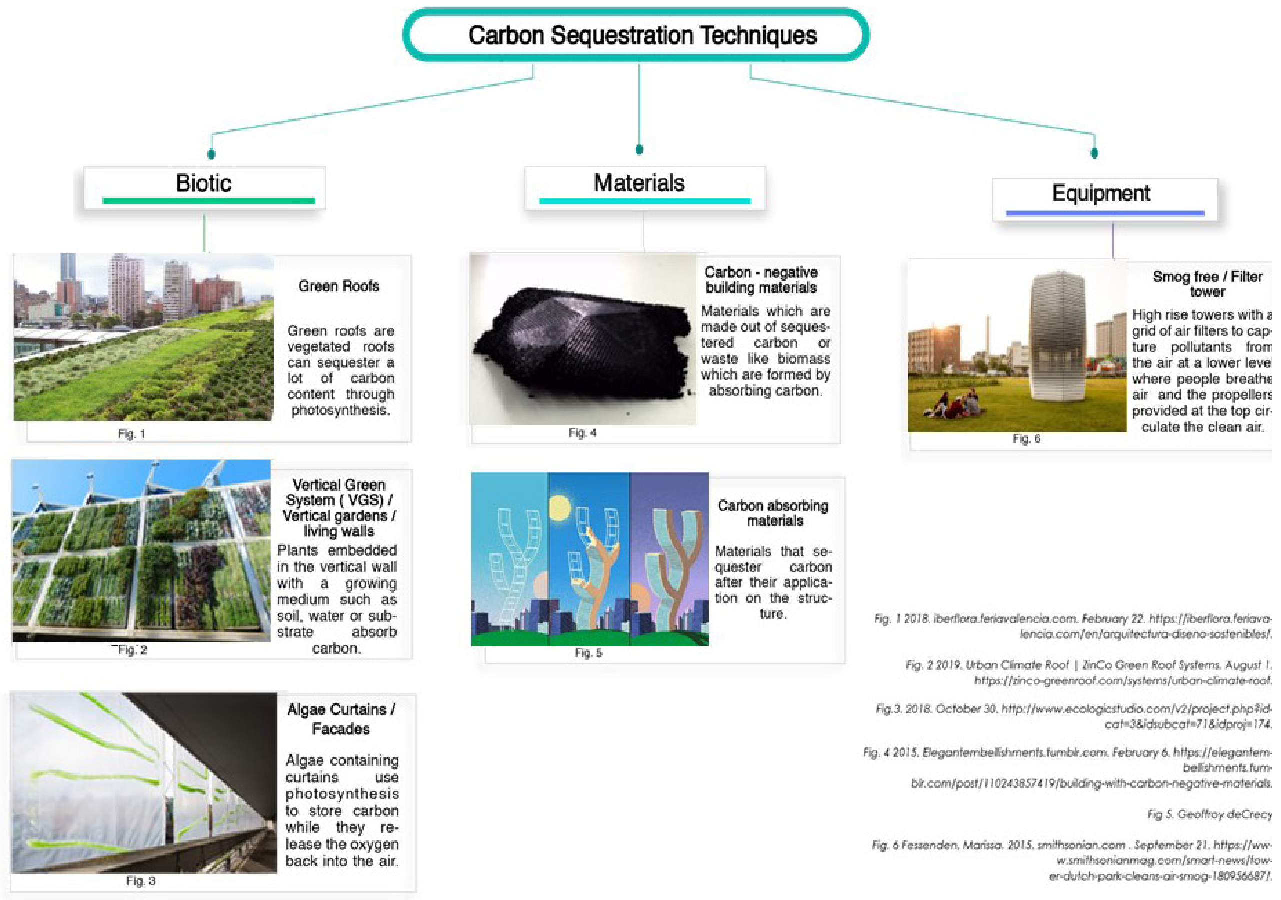


Figure 1. Literature review process for classification of Carbon Sequestration techniques. (Author).



Green Roofs

Green roofs are vegetated roofs can sequester a lot of carbon content through photosynthesis.

Vertical Green System (VGS) / Vertical gardens / living walls

Plants embedded in the vertical wall with a growing medium such as soil, water or substrate absorb carbon.

Algae Curtains / Facades

Algae containing curtains use photosynthesis to store carbon while they release the oxygen back into the air.

Carbon - negative building materials

Materials which are made out of sequestered carbon or waste like biomass which are formed by absorbing carbon.

Carbon absorbing materials

Materials that sequester carbon after their application on the structure.

Smog free / Filter tower

High rise towers with a grid of air filters to capture pollutants from the air at a lower level where people breathe air and the propellers provided at the top circulate the clean air.

Fig. 1 2018. iberflora.feriavalencia.com. February 22. https://iberflora.feriavalencia.com/en/arquitectura-diseno-sostenibles/.

Fig. 2 2019. Urban Climate Roof | ZinCo Green Roof Systems. August 1. https://zinco-greenroof.com/systems/urban-climate-roof.

Fig.3. 2018. October 30. http://www.ecologicstudio.com/v2/project.php?idcat=3&idsubcat=71&idproj=174.

Fig. 4 2015. Elegantembellishments.tumblr.com. February 6. https://elegantembellishments.tumblr.com/post/110243857419/building-with-carbon-negative-materials.

Fig 5. Geoffroy deCrecy

Fig. 6 Fessenden, Marissa. 2015. smithsonian.com . September 21. https://www.smithsonianmag.com/smart-news/tower-dutch-park-cleans-air-smog-180956687/.

Figure 2. Proposed classification of Building-integrated CS techniques.

CLASSIFICATION OF CS TECHNIQUES

After a systematic literature review (Figure 1), building-integrated CS techniques were proposed to be categorized into three major groupings – Biotic, Materials and Equipment (Figure 2). Materials and Equipment are in their emerging stages for the purpose of Carbon Sequestration when compared to Biotic techniques. Therefore, limited information was found when focusing on cost and maintenance. Consequently, they were both not reviewed as extensively as Biotic techniques in the sections to follow.

QUANTITATIVE LITERATURE REVIEW (BIOTIC TECHNIQUES)

Living organisms such as trees and plants, often termed as biotic (Lal 2008) are one of the major sources of CS (Getter et al. 2009). The process of photosynthesis that allows them to assimilate atmospheric CO2 and release back O2 falls under the biotic process of carbon sequestration. Biotic elements are, thus, used in various forms to sequester carbon, out of which Green Roofs and VGS are commonly used techniques (Pérez et al. 2014). To quantify the amount of carbon sequestered by each technique, a literature study was conducted for each.

GREEN ROOFS

Green Roofs are vegetated roofs which have been established for around 100 years. They are generally divided into three categories – Intensive Green Roofs, semi-intensive Green Roofs and extensive Green Roofs (Li and Yeung 2014).

Working Mechanism and Prerequisites

Imitating landscape on a part of a structure may be a challenging process. Specifically, with having to deal with the extremities on the rooftop, it takes 9 layers to fabricate a working Green Roof which includes the vegetation layer followed by the growth substrate layer where the growing medium is laid. The type and properties of the substrate chosen has a huge influence on the growth rate of vegetation and the Green Roof's performance. Other layers include filter layer, drainage layer, protection layer, root barrier, insulation layer and the water proofing membrane. These layers might not contribute to the CS potential of a Green Roof, but they have a critical role. Any issue with these layers like leakage leads to the failure of the Green Roof. Rectification in these layers also increases the maintenance cost significantly (Vijayaraghavan 2016).

CS Potential

Green Roofs have been used for various purposes such as improving stormwater management, energy saving, mitigating urban heat island effects, but not mainly for CS (Getter et al. 2009). The first study, which was conducted by Getter et al, was performed on 13 roofs in Michigan and Maryland. All the roofs (1-6 years old) primarily comprised Sedum species and substrate depths ranging from 2.5 to 12.7 cm. After continuous evaluation for 2 years, they found that the above ground plant material sequestered an average of 168gC/m^2, with the average being 107gC/m^2 and 913gC/m^2 for belowground biomass and substrate carbon content, respectively. It was concluded that the entire extensive Green Roofs could sequester 375gC/m^2 (Getter et al. 2009). The second research was performed by Kuronuma in 2018. They calculated the annual CS potential of Green Roofs by three species to be 459.3gC/m^2 - 681.9gC/m^2. The study shows how carbon capture depends on various factors such as the plant species, substrate, the age of the Green Roof, wind speed (Kuronuma et al. 2018). While most of the studies recorded CS values on the lower side of the spectrum, a study by Whittinghill showed enormously high values of 4.67gC/m^2 – 65.25gC/m^2 (Whittinghill et al. 2014). Although, the values might be correct due to varying factors, the results have been considered an anomaly for this study.

Cost

Setting up of a Green Roof requires a significant initial investment. Vijayraghavan has documented and summarized in their paper the findings of various scientists and researchers who have tried to calculate the initial cost of creating a Green Roof as well as performed the cost benefit analysis. The results have varied because of different factors such as the type of Green Roof, the location, substrate and vegetation used, equipment used and the labor (Vijayaraghavan 2016). The initial cost is approximated to be $129/m^2-$161/m^2 for British Columbia and Canada (Bianchini and Hewage 2012), $107.64/m^2-$161.46/m^2 for extensive Green Roofs in Chicago whereas it is $161.46/m^2-$269.1/m^2 for intensive Green Roofs (Yang, Yu, and Gong 2008). For Chennai, India, the Green Roof cost varies between $33.33m^2 - $55.5/m^2 (Vijayaraghavan 2016).

Though setting up of a Green Roof is expensive, there has been research where future cost savings have been calculated and incorporated to view an overall return on investment (ROI). Various factors are included such as energy saving costs, property appreciation value, air quality and carbon costs, which are still difficult to be included to their precise values. While some have proved the overall valuation to be positive (Rowe 2011) (Niu et al. 2010), others have presented contrasting results (Carter and Keeler 2008). Thus, this aspect needs further study and has not been fully considered in this study.

Maintenance

Green Roofs require attention and care, especially during the first two years of their installation. Maintenance costs include irrigation costs, labor costs and a few other comparably smaller costs (such as removing seedlings). According to a Life Cycle Cost (LCA) assessment done in 2003 for Germany, USA, and Brazil, the annual maintenance cost is $1/m^2 for extensive Green Roofs and $8/m^2 for intensive Green Roofs (Porsche and Köhler 2003). The prices for the resources keep increasing, thus, a more recent study by Sproul in 2014 for the United States mentions the annual maintenance cost for the same situation as $2.90/m^2 (Sproul et al. 2014). It is less expensive to maintain extensive Green Roofs than intensive Green Roofs (Porsche and Köhler 2003).

VERTICAL GREENERY SYSTEM/VERTICAL GARDENS/ LIVING WALLS

Vegetation has often been used in structures for exterior as well as interior walls for aesthetic purposes. VGS are "relatively light structures anchored on building facades with plants embedded on felt layers and nurtured by a hydroponic watering system" (Pulselli et al. 2014).

Working Mechanism and Prerequisites

VGS has four main considerations - 1) Climate type 2) Plant species used 3) Construction System and 4) Mechanism of operation (Pérez et al. 2014).

Though, being a vertical element makes the implementation of vertical facades and walls difficult, it has been found from various studies that their effect is greater than Green Roofs due to the larger surface area of walls as compared to roofs. With increasing numbers of skyscrapers being constructed in the world, the surface area covered by the walls is approximately 20 times greater as compared to the roofs (Pérez et al. 2014).

There are several construction methods for VGS. Green facades have been classified into double-skin green façade, grid system, cable wire system, mesh system, whereas living/ green walls have been classified into pocket system, geotextile felt system, modular system, and many others (Radić, Dodig, and Auer 2019). They all have a growing medium and a panel system, but the prerequisites as well as the working mechanisms differ for each construction method.

CS Potential

Vertical greenery system Carbon Sequestration and Living walls Carbon Sequestration were the phrases used for the search. A life cycle assessment (LCA) of VGS was carried out in Italy as a part of a project named "GREENED." A VGS installation was hypothesized on a 98m^2 facade for simulation. The results showed that plants used (herbaceous perennial) in VGS capture carbon from the atmosphere at a rate of 250gC/ m^2 (Pulselli et al. 2014). Another simulation experiment was performed by Marchi in 2015. The carbon captured was in the range from 37.32gC/m^2 - 270gC/m^2 with the average being 169gC/m^2 approximately. A species of S.nemorosa also showed some exceptional CS potential in the range of 610gC/ m^2 - 4565.6gC/m^2 (Marchi et al. 2015).

Cost

A VGS consists of various components and has a considerable initial cost. According to Perini and Rosasco, who performed a Cost Benefit Analysis in 2013, $41.1/m^2 – $61.67/m^2 was the cost of direct greening system. With plants and supporting material it increases to a range of $54.8/m^2 – $102.75/m^2, with planter boxes, to $205.5/m^2, and even $1097/m^2 for plastic material. For living walls, the cost varies between $548/ m^2 - $1644/m^2 (Perini and Rosasco 2013).

Rosasco in their paper calculates the initial cost for indirect green façade. One made with high density polyethylene (HDPE) costs around $140/m^2, with steel mesh costs $268.8/m^2 and with planter boxes, it ranges from $184.8/m^2 - $369.6/ m^2. The initial cost for living walls is $207.2/m^2 - $560/m^2 (Rosasco 2018). Similar results have been achieved in another study by Huang in 2019 (Huang et al. 2019).

Maintenance

The maintenance requirements for VGS differ for each construction system. While for direct and indirect green facades, only pruning is required, planter box system additionally requires substitution of water tubes and plant species. Living walls also require a change of panels. Pruning is approximately $3.84/m^2 annually, plant species replacement is $1.9/m^2 – $3.76/m^2 annually and annual panel replacement for living walls can cost up to $8.28/m^2. Irrigation is required to be done annually at a rate of $1.31/m^2. There can be further other costs such as cladding renovation, irrigation system costs that might differ from case to case (Perini and Rosasco 2013).

ALGAE FACADE/CURTAINS

Algae is often seen in a negative light due to its less aesthetically pleasing characteristics as compared to other plants, but it is considered to be an essential plant in the world since it generates approximately 50% of the total oxygen produced (Chapman 2013). For the same reason algae is being considered in recent years as a sustainable alternative to the predominantly used glazed facades to address climate change (Kyoung-Hee 2013).

Working Mechanism and Prerequisites

Algae can be grown by two methods – open pond and closed system known as photobioreactor. While the open pond system is more economical, it faces a lot of challenges in terms of external contaminants, whereas the photobioreactor prevents cross contamination by encapsulating algae in tubes (Kyoung-Hee 2013). The latter method is being used to integrate algae with structures in the form of facades and curtains. Algae utilize photosynthesis for CS. (Aouf 2018).

Algae curtains introduced by EcoLogic Studio are made up of 16 (2m by 7m long) bioplastic modules. It has embedded serpentine tubes which contain algae. When the unfiltered air enters the curtains from the bottom and start moving upwards, the micro-algae in the tubes capture CO2, releasing O2. They further grow biomass from the absorbed CO2 (Aouf 2018)

CS Potential

The keywords used to determine the records measuring the CS potential of microalgae were, Microalgae Carbon Sequestration, Algae facades Carbon Sequestration and Algae CO2 sequestration. According to a survey conducted by The Naval Research Lab in Washington, DC, an algae facade of 1.524m x 3.657m having 6.5 liters of algae solution can sequester around 2.43kgC/m^2 (Kyoung-Hee 2013).

The algae curtain invented and displayed by EcoLogic Studio of 2 m^2 absorbs 1 kilogram of CO2 every day, which is equivalent to the carbon sequestered by 20 large trees (Aouf 2018). When this is calculated in terms of amount of carbon sequestered annually gives a value of 2.970kgC/m^2. The huge anomaly that can be observed in the algae curtain might be due to varying amounts of algae solution used in the curtain.

The first house built using algae facades is in Hamburg, Germany. According to their estimation, algae facades can sequester 2.500kg C/m^2 in a year (Colt International, Arup 2013). The value demonstrated by the BIQ house is closer to the value estimated by EcoLogic studio.

Cost

Although algae can be found and grown easily, the costs associated with incorporating it in facades is not yet clear. There have been proposals and demonstrations of algae facades and curtains by globally influential architectural firms, for instance, HOK proposed an algae facade for the U.S. General Services Administration (GSA) retrofitted project in Los Angeles (Kim 2013), EcoLogic displayed a prototype of algae curtains in the Climate Innovation Summit 2018 in Dublin and also proposed an Algae Urban Farm in Tehran, Iran (Kim 2013). Evidence for the initial installation cost for this technique cannot be found easily on the available sources. BIQ house in Hamburg, Germany built in 2013, the first house to integrate an algae façade, (although not used with the objective of sequestering carbon) (Kim 2013) is the only project which indicates the cost of building an algae facade as $2200-2300/m^2 (Wilkinson et al. 2017). The cost is substantially high, but it is expected that with the rapid advancement of technology, prices may change to be more affordable.

Maintenance

Various issues have been raised with respect to algae facades including maintenance issues such as cleaning of facades and algae carrying tubes, associated costs with continuous supply of water and nutrients to the algae façade as well as removal of the grown algae (Wilkinson et al. 2017). Odor, structural retrofitting, harmful toxins are some of the other issues related to it. While the issues are known, a clear description of the maintenance costs is not available.

COMPARATIVE STUDY

After a detailed literature review, the biotic techniques with respect to different design criteria – prerequisites, design factors and CS potential have been summarized in the Figure 3.

QUALITATIVE LITERATURE REVIEW

Materials

A considerable number of materials have been explored, tested and proven to capture carbon, such as alkaline earth metals, calcium and magnesium oxides (Huntzinger et al. 2009), biochar, titanium dioxide, solidia cement (Chawla 2018) (Ćurĉić 2018).

Carbon–negative building materials are products with less than neutral carbon footprint. Such materials have an effect of removing CO2 from the atmosphere (Chawla 2018). One of a similar working material is developed by Berlin based – Elegant embellishments. It uses biomass (organic waste) which absorbs and stores CO2 (Ayoubi 2018).

Working Mechanism and Prerequisites

Biomass is created by plants that absorb CO2 and sunlight throughout its life. To make a carbon negative material, the process of pyrolysis is used to bake biomass to a stable form of carbon in an oxygen free environment. Further, it is mixed with a bio-degradable binder. This carbon negative material is then shaped into the products to be used in building facades and the interiors (Chawla 2018). Faceted panels have been created using this material for experimentation stage. 'Charscraper' is one of the first instances of a projection made from thermoplastic "Made of Air" – a carbon negative building material.

CS Potential

The amount of CS that has been approximated in the lab is based on the percentage of manufactured goods. It has been reported that if 10% of all manufactured goods in the construction industry are made up of the carbon negative material, it can capture up to 10^15gC annually from the atmosphere (Biddulph Jim 2017).

EQUIPMENT - FILTER / SMOG ABSORBING TOWERS

Carbon emissions by vehicles, factories, construction industry have increased to such extreme levels that Direct Air Capture (DAC) is being considered and discussed largely throughout the world. One method of DAC is through equipment which can be integrated with structures. Dubai-based architectural studio Znera has proposed to create high rise towers with a grid of air filters (Page 2018). In Switzerland, carbon is being sucked directly by a giant new machine developed by Climeworks (Marshall 2017). Also, Daan Roosegarde has been working on a smog free tower that is being known as the world's largest air purifier (Verma 2015).

Working Mechanism and Prerequisites

The smog project developed by the Znera Space has filtration pods at the bottom of the tower to capture pollutants from the air at a lower level where people breathe air and the propellers provided at the top circulate the clean air. To power the towers, hydrogen fuel cells along with solar panels are to be used. Carbon particles collected would then be converted into graphene, concrete and even ink (Page 2018).

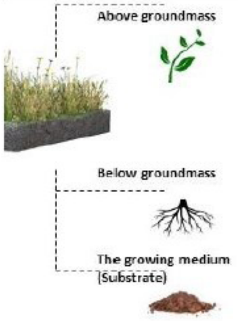
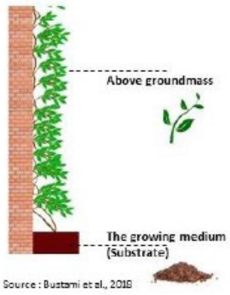
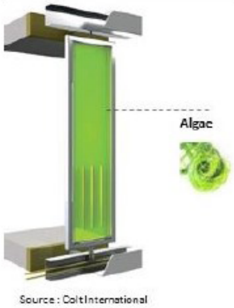
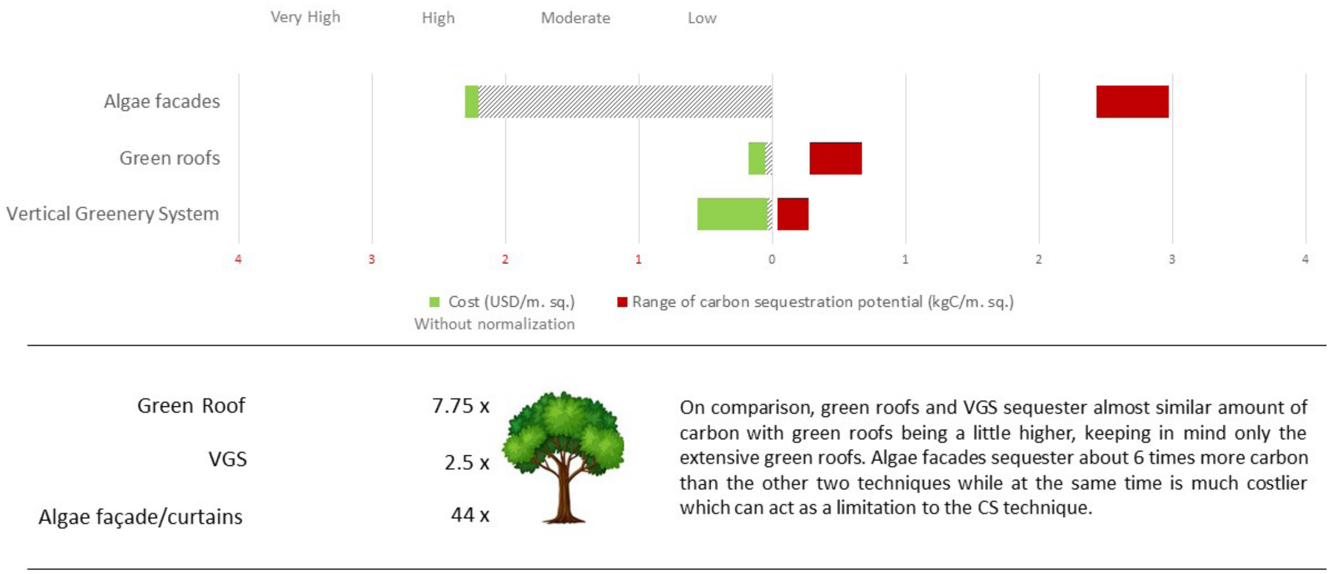
	Green Roofs 	**Vertical Greenery System (VGS)** 	**Algae Facades** 
CS Method	Photosynthesis	Photosynthesis	Photosynthesis
Types	Extensive Semi-intensive Intensive	Green facades Double-skin green façade Grid system Cable wire system Mesh system Living/green walls Pocket system Geotextile felt system Modular system and many others	Flat plate Annular Tubular
Components	Vegetation layer Growth substrate layer Filter layer Drainage Layer Protection mat Waterproof membrane Insulation Root barrier	Vegetation layer Growing planter layer Irrigation layer Steel structure Waterproof layer	Algae Medium inlet Water inlet Gas (CO2) inlet Water outlet Algae culture harvesting outlet
Components contributing to sequestering carbon		 Source : Bustami et al., 2018	 Source : Colt International
Annual Carbon Sequestration range (kg C/m. sq.)	0.276 – 0.670 (Extensive Green Roof)	0.037 – 0.270	2.43 – 2.970
Average annual Carbon Sequestration	0.473	0.154	2.70
Tree equivalent of 100 m. sq. of the technique (Average carbon sequestered by 1 tree annually = 6.1 kg)	7.75	2.5	44

Figure 3. Summary of CS techniques based on the performance indicators (Biotic techniques). (Author).



On comparison, green roofs and VGS sequester almost similar amount of carbon with green roofs being a little higher, keeping in mind only the extensive green roofs. Algae facades sequester about 6 times more carbon than the other two techniques while at the same time is much costlier which can act as a limitation to the CS technique.

Figure 4. Comparison of CS potential and cost for biotic techniques. (Author).

The Dutch designer Daan Roosgaarde's works also depict similar concepts. It includes air filtering tower which absorbs carbon and creates diamonds by compressing the pollutant. It claims to run on 1400 watts of green energy. A small positive current is used to send positive ions into the air through an electrode. These ions attach themselves to the fine dust particles which are then drawn towards the negatively charged surface. It allows the fine dust particles to collect and store inside the tower ("Kengo Kuma and Daan Roosegaarde Show Pollution-Absorbing Architecture" 2018).

The giant machine sequestering carbon in Switzerland uses a similar mechanism but it has a waste heat recovery facility that powers the entire machine. The filter system located underground collects CO2 with the help of fans. CO2 is occasionally separated at temperatures above 1000 Celsius when the filter is saturated.

CS Potential

The Smog Free Tower created by Daan Roosegarde is 7-meter-tall and at the time of writing this thesis, is the only tower in development. It can provide 255.5 million m3 of clean air annually (Thompson 2016). Another installation by Berlin-based Green City Solutions, which is named "CityTree" is 13-foot by 10-foot tall and is made up of moss culture. It is claimed to capture carbon equivalent to 275 trees (Page 2018) in a year, which on conversion, taking carbon sequestered by 1 tree as 2.5 tons, is equal to 0.58 million m^3C. The giant machine in Switzerland developed by Climeworks captures 0.5 million m^3 of carbon which is equivalent to carbon emissions by 200 cars (Marshall 2017).

DISCUSSION AND CONCLUSION

Based on the literature review and the comparative analysis of biotic techniques, it is observed that Green Roofs and VGS capture carbon in the range of 150gC/m^2 – 650gC/m^2, while algae facades perform better and sequester up to around 2430gC/m^2 - 2970gC/m^2. They all require an initial investment, but there is a possibility that their future benefits overcome the initial cost. Carbon captured by materials is dependent on the percentage of products using those materials, whereas equipment could absorb a high amount of approximately 687.5 x 10^6gC – 250.65 x 10^9gC without normalization, but it is significantly expensive. It is not possible to normalize both materials and equipment without further understanding of the system; for instance, the ability to capture carbon by filter towers is not proportional to the size of the equipment, as is the case with Green Roofs, VGS, algae facades. Therefore, Figure 4 focuses only on visualizing biotic potentials, with the aim to aid in the quantification of CS potential. Cost is shown with dashed lines to signify its subjectiveness (not normalized).

FUTURE RESEARCH SCOPE

As was seen in the keyword search, CS techniques have been researched extensively in various disciplines, however, the state of the art lacks a significant amount of work when it comes to the integration of CS techniques in the built environment. With very little time left for the humankind to prevent permanent climate change damages, it is imperative to build a database of building - integrated CS techniques and evaluate their impacts and consequences as early as possible. An attempt to do so was made in this paper. While a lot of published quantitative research could be found regarding the CS potential of biotic techniques, materials and equipment were seen as the emerging class of techniques calling for more demonstration projects as well as scientific published literature. Further, along with a realization to bring more awareness regarding these techniques, an indispensable need to facilitate the implementation of CS techniques in the built environment became evident from the lack of resources available for architects, designers and engineers to use as a reference. Thus, an in-depth investigation of factors affecting the Carbon Sequestration potential of biotic techniques, and a simulation-based work-flow to quickly measure and analyze the CS potential of built environment projects through the application of various techniques appropriate for their building based on region, cost, and area is being worked upon in the second part of this research.

In conclusion, an overview was presented, but advances in building-integrated CS techniques are still needed in order for buildings to not just limit the catastrophic effects of climate change, but also mitigate it for a better future for our built environment.

ENDNOTES

1. Amir, Atikah F, Foong S Yeok, and Abdul M A Rahman. 2014. “Estimation of Annual Carbon Sequestration in Psophocarpus Tetragonobulus Used as Biofacade in Tropical Environment,” 31–37. https://doi.org/10.17758/ur.u1214310.
2. Antonietti, Markus, and Klaus Müllen. 2010. “Carbon: The Sixth Element.” Advanced Materials 22 (7): 787. https://doi.org/10.1002/adma.200904091.
3. Aouf, Rima. 2018. “Algae Curtain by EcoLogicStudio Could Make Buildings More Eco-Friendly.” 2018. https://www.dezeen.com/2018/12/10/ecologicstudio-algae-curtain-photo-synth-etica/.
4. Auld, Douglas, and Jeremy Wright. 2018. “Carbon Sequestering and Green Roof Technology: A Benefit Cost Analysis.” Environmental Management and Sustainable Development 7 (1): 85. https://doi.org/10.5296/emsd.v7i1.12396.
5. Ayoubi, Ayda. 2018. “This Week in Tech: A Carbon-Negative Façade Panel That Absorbs CO2 | Architect Magazine.” 2018. https://www.architectmagazine.com/technology/this-week-in-tech-a-carbon-negative-facade-panel-that-absorbs-co2_o.
6. Banta, Gary. 2018. “Estimation of Green Roofs ’ Carbon Sequestration Potential by Supervised by,” no. June.
7. Bianchini, Fabricio, and Kasun Hewage. 2012. “How ‘Green’ Are the Green Roofs? Lifecycle Analysis of Green Roof Materials.” Building and Environment 48 (February): 57–65. https://doi.org/10.1016/J.BUILDENV.2011.08.019.
8. Biddulph Jim. 2017. “In Conversation with Made of Air | Material Lab.” 2017. https://www.material-lab.co.uk/journal/conversation-made-air/.
9. Carter, Timothy, and Andrew Keeler. 2008. “Life-Cycle Cost–Benefit Analysis of Extensive Vegetated Roof Systems.” Journal of Environmental Management 87 (3): 350–63. https://doi.org/10.1016/J.JENVMAN.2007.01.024.
10. Cartwright, Mark. 2018. “Hanging Gardens of Babylon - Ancient History Encyclopedia.” 2018. https://www.ancient.eu/Hanging_Gardens_of_Babylon/.
11. Cawley, Gavin C. 2011. “On the Atmospheric Residence Time of Anthropogenically Sourced Carbon Dioxide.” Energy & Fuels 25 (11): 5503–13. https://doi.org/10.1021/ef200914u.
12. Chapman, Russell Leonard. 2013. “Algae: The World’s Most Important ‘Plants’—an Introduction.” Mitigation and Adaptation Strategies for Global Change 18 (1): 5–12. https://doi.org/10.1007/s11027-010-9255-9.
13. Charoenkit, Sasima, Suthat Yiemwattana, and Ninnart Rachapradit. 2020. “Plant Characteristics and the Potential for Living Walls to Reduce Temperatures and Sequester Carbon.” Energy and Buildings 225: 110286. https://doi.org/10.1016/j.enbuild.2020.110286.
14. Chawla, Purva. 2018. “A Case for Carbon–Negative Materials: Made of Air — MaterialDriven.” 2018. https://www.materialdriven.com/home/2018/12/3/a-case-for-carbonnegative-materials-made-of-air.
15. Colt International, Arup, SSC GmbH. 2013. “SolarLeaf: Bioreactor Façade,” 3. https://www.coltinfo.co.uk/files/pdf/UK/SolarLeaf bioreactor facade.pdf.
16. Ćurĉić, Aleksandra A. 2018. “Photocatalytic Self-Cleaning Facades” 16: 425–36.
17. ecoLogicStudio. 2019. “SYSTEM | PhotoSynthetica.” 2019. https://www.photosynthetica.co.uk/system.
18. Fan, Liangqian, Jingting Wang, Xiaoling Liu, Hongbing Luo, Ke Zhang, Xiaoying Fu, Mei Li, et al. 2020. “Whether the Carbon Emission from Green Roofs Can Be Effectively Mitigated by Recycling Waste Building Material as Green Roof Substrate during Five-Year Operation?” Environmental Science and Pollution Research, July, 1–14. https://doi.org/10.1007/s11356-020-09896-6.
19. Farrelly, Damien J., Colm D. Everard, Colette C. Fagan, and Kevin P. McDonnell. 2013. “Carbon Sequestration and the Role of Biological Carbon Mitigation: A Review.” Renewable and Sustainable Energy Reviews 21: 712–27. https://doi.org/10.1016/j.rser.2012.12.038.
20. Getter, KL, DB Rowe, GP Robertson - … science & technology, and undefined 2009. 2009. “Carbon Sequestration Potential of Extensive Green Roofs.” ACS Publications 43 (19): 7564–70. https://doi.org/10.1021/es901539x.
21. Getter, Kristin L., D. Bradley Rowe, G. Philip Robertson, Bert M. Cregg, and Jeffrey A. Andresen. 2009. “Carbon Sequestration Potential of Extensive Green Roofs.” Environmental Science & Technology 43 (19): 7564–70. https://doi.org/10.1021/es901539x.
22. Harzing, Anne-Wil. 2016. “Publish or Perish.” 2016. https://harzing.com/resources/publish-or-perish.
23. Huang, Ziyou, Yujie Lu, Nyuk Hien Wong, and Choon Hock Poh. 2019. “The True Cost of ‘Greening’ a Building: Life Cycle Cost Analysis of Vertical Greenery Systems (VGS) in Tropical Climate.” Journal of Cleaner Production 228 (August): 437–54. https://doi.org/10.1016/J.JCLEPRO.2019.04.275.
24. Huntzinger, Deborah N., John S. Gierke, Lawrence L. Sutter, S. Komar Kawatra, and Timothy C. Eisele. 2009. “Mineral Carbonation for Carbon Sequestration in Cement Kiln Dust from Waste Piles.” Journal of Hazardous Materials 168 (1): 31–37. https://doi.org/10.1016/J.JHAZMAT.2009.01.122.
25. IPCC. 2014. “Climate Change 2014: Mitigation of Climate Change - Intergovernmental Panel on Climate Change - Google Books.” 2014. https://books.google.com/books?hl=en&lr=&id=JAFEBgAAQBAJ&oi=fnd&pg=PT19&ots=dAyEpAU758&sig=gMyMYMqMvIswl2nB61orBdcPhW0#v=onepage&q&f=false.
26. Jain, Ravi, Lloyd Urban, Harold Balbach, M. Diana Webb, Ravi Jain, Lloyd Urban, Harold Balbach, and M. Diana Webb. 2012. “Contemporary Issues in Environmental Assessment.” Handbook of Environmental Engineering Assessment, January, 361–447. https://doi.org/10.1016/B978-0-12-388444-2.00013-0.
27. Kell, Douglas B. 2012. “Large-Scale Sequestration of Atmospheric Carbon via Plant Roots in Natural and Agricultural Ecosystems: Why and How.” Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences 367 (1595): 1589–97. https://doi.org/10.1098/rstb.2011.0244.
28. Kim, Kyoung-Hee. 2013. “Beyond Green: Growing Algae Facade.” The Visibility of Research Sustainability: Visualization Sustainability and Performance, 500–505. https://www.brikbase.org/sites/default/files/ARCC2013_UNCC_Conference_Proceedings_518.pdf.
29. Kuronuma, Takanori, and Hitoshi Watanabe. 2017. “Relevance of Carbon Sequestration to the Physiological and Morphological Traits of Several Green Roof Plants during the First Year after Construction.” American Journal of Plant Sciences 08 (01): 14–27. https://doi.org/10.4236/ajps.2017.81002.
30. Kuronuma, Takanori, Hitoshi Watanabe, Tatsuaki Ishihara, Daitoku Kou, Kazunari Toushima, Masaya Ando, and Satoshi Shindo. 2018. “CO2 Payoffof Extensive Green Roofs with Different Vegetation Species.” Sustainability (Switzerland) 10 (7): 1–12. https://doi.org/10.3390/su10072256.
31. Kyoung-Hee, Kim. 2013. “A Feasibility Study of an Algae Façade System.” Conference: SB13 Seoul-Sustainable Building Telegram toward Global Society, no. Doe 2010: 333–41. https://doi.org/10.1049/iet-gtd.2016.1418.
32. Lal, Rattan. 2008. “Carbon Sequestration.” Philosophical Transactions of the Royal Society B: Biological Sciences 363 (1492): 815–30. https://doi.org/10.1098/rstb.2007.2185.
33. Li, W. C., and K. K.A. Yeung. 2014. “A Comprehensive Study of Green Roof Performance from Environmental Perspective.” International Journal of Sustainable Built Environment. Elsevier B.V. https://doi.org/10.1016/j.ijsbe.2014.05.001.
34. Luo, Hongbing, Xiaoling Liu, Bruce C. Anderson, Ke Zhang, Xiaoting Li, Bo Huang, Mei Li, et al. 2015. “Carbon Sequestration Potential of Green Roofs Using Mixed-Sewage-Sludge Substrate in Chengdu World Modern Garden City.” Ecological Indicators 49 (February): 247–59. https://doi.org/10.1016/j.ecolind.2014.10.016.
35. Marchi, Michela, Riccardo Maria Pulselli, Nadia Marchettini, Federico Maria Pulselli, and Simone Bastianoni. 2015. “Carbon Dioxide Sequestration Model of a Vertical Greenery System.” Ecological Modelling 306: 46–56. https://doi.org/10.1016/j.ecolmodel.2014.08.013.
36. Marshall, Christa. 2017. “In Switzerland, a Giant New Machine Is Sucking Carbon Directly from the Air.” Science, June. https://doi.org/10.1126/science.aan6915.
37. Nasa. 2016. “Global Climate Change: Evidence.” NASA Global Climate Change and Global Warming: Vital Signs of the Planet. 2016. https://climate.nasa.gov/faq/16/is-it-too-late-to-prevent-climate-change/.
38. National Academies of Sciences, Engineering, and Medicine. 2019. Negative Emissions Technologies and Reliable Sequestration. Washington, D.C.: National Academies Press. https://doi.org/10.17226/25259.
39. Niu, Hao, Corrie Clark, Jiti Zhou, and Peter Adriaens. 2010. “Scaling of Economic Benefits from Green Roof Implementation in Washington, DC.” Environmental Science and Technology 44 (11): 4302–8. https://doi.org/10.1021/es902456x.
40. Oreskes, Naomi. 2004. “The Scientific Consensus on Climate Change.” Science

306 (5702): 1686–1686. https://doi.org/10.1126/science.1103618.

41. Page, Thomas. 2018. “Giant Filter Towers Proposed to Eliminate Delhi Smog - CNN Style.” 2018. https://www.cnn.com/style/article/znera-air-filter-tower-delhi/index.html.
42. Pérez, Gabriel, Julià Coma, Ingrid Martorell, and Luisa F. Cabeza. 2014. “Vertical Greenery Systems (VGS) for Energy Saving in Buildings: A Review.” Renewable and Sustainable Energy Reviews 39 (November): 139–65. https://doi.org/10.1016/J.RSER.2014.07.055.
43. Perini, Katia, and Paolo Rosasco. 2013. “Cost–Benefit Analysis for Green Façades and Living Wall Systems.” Building and Environment 70 (December): 110–21. https://doi.org/10.1016/J.BUILDENV.2013.08.012.
44. Porsche, U, and M Köhler. 2003. “LIFE CYCLE COSTS OF GREEN ROOFS - A Comparison of Germany, USA, and Brazil.” RIO 3 - World Climate & Energy Event, no. December: 1–5.
45. Pulselli, R. M., F. Saladini, E. Neri, and S. Bastianoni. 2014. “A Comprehensive Lifecycle Evaluation of Vertical Greenery Systems Based on Systemic Indicators.” WIT Transactions on Ecology and the Environment 191: 1017–24. https://doi.org/10.2495/SC140862.
46. Radić, Mina, Marta Brković Dodig, and Thomas Auer. 2019. “Green Facades and Living Walls-A Review Establishing the Classification of Construction Types and Mapping the Benefits.” Sustainability (Switzerland) 11 (17): 1–23. https://doi.org/10.3390/su11174579.
47. Rosasco, Paolo. 2018. “Economic Benefits and Costs of Vertical Greening Systems.” Nature Based Strategies for Urban and Building Sustainability, January, 291–306. https://doi.org/10.1016/B978-0-12-812150-4.00027-6.
48. Rowe, D. Bradley. 2011. “Green Roofs as a Means of Pollution Abatement.” Environmental Pollution 159 (8–9): 2100–2110. https://doi.org/10.1016/j.envpol.2010.10.029.
49. Schmidt, Gavin A., Reto A. Ruedy, Ron L. Miller, and Andy A. Lacis. 2010. “Attribution of the Present-Day Total Greenhouse Effect.” Journal of Geophysical Research Atmospheres 115 (20). https://doi.org/10.1029/2010JD014287.
50. Shafique, Muhammad, Xiaolong Xue, and Xiaowei Luo. 2020. “An Overview of Carbon Sequestration of Green Roofs in Urban Areas.” Urban Forestry and Urban Greening 47 (May 2019): 126515. https://doi.org/10.1016/j.ufug.2019.126515.
51. Sood, Akash, and Savita Vyas. 2017. “Carbon Capture and Sequestration- A Review.” IOP Conference Series: Earth and Environmental Science 83 (1): 012024. https://doi.org/10.1088/1755-1315/83/1/012024.
52. Sproul, Julian, Man Pun Wan, Benjamin H. Mandel, and Arthur H. Rosenfeld. 2014. “Economic Comparison of White, Green, and Black Flat Roofs in the United States.” Energy and Buildings 71 (March): 20–27. https://doi.org/10.1016/J.ENBUILD.2013.11.058.
53. Sundquist, Eric, Robert Burruss, Stephen Faulkner, Robert Gleason, Jennifer Harden, Yousif Kharaka, Larry Tieszen, and Mark Waldrop. 2008. “Carbon Sequestration to Mitigate Climate Change.” Carbon Sequestration to Mitigate Climate Change. Reston, VA. https://doi.org/10.3133/fs20083097.
54. Thompson, Cadie. 2016. “Daan Roosegaarde Smog-Free Tower Turns Pollution into Fine Jewelry - Business Insider.” 2016. https://www.businessinsider.com/daan-roosegaarde-smog-free-tower-turns-pollution-into-fine-jewelry-2016-6.
55. Verma, S. 2015. “Smog Free Tower|Scientific India Magazine.” Environment. 2015. http://www.scind.org/214/Environment/smog-free-tower.html.
56. Vijayaraghavan, K. 2016. “Green Roofs: A Critical Review on the Role of Components, Benefits, Limitations and Trends.” Renewable and Sustainable Energy Reviews 57 (May): 740–52. https://doi.org/10.1016/J.RSER.2015.12.119.
57. Whittinghill, Leigh J., D. Bradley Rowe, Robert Schutzki, and Bert M. Cregg. 2014. “Quantifying Carbon Sequestration of Various Green Roof and Ornamental Landscape Systems.” Landscape and Urban Planning 123: 41–48. https://doi.org/10.1016/j.landurbplan.2013.11.015.
58. Wilkinson, Sara, Paul Stoller, Peter Ralph, Brenton Hamdorf, Laila Navarro Catana, and Gabriela Santana Kuzava. 2017. “Exploring the Feasibility of Algae Building Technology in NSW.” Procedia Engineering 180 (0): 1121–30. https://doi.org/10.1016/j.proeng.2017.04.272.
59. Yang, Jun, Qian Yu, and Peng Gong. 2008. “Quantifying Air Pollution Removal by Green Roofs in Chicago.” Atmospheric Environment 42 (31): 7266–73. https://doi.org/10.1016/J.ATMOSENV.2008.07.003.
60. Zhou, Wenji. 2018. “IPCC 2018, Cap2.” Global Warming of 1.5°C. An IPCC Special Report [...].