Greenhouse Addition to ATP's Backyard Nurseries Program

An Interactive Qualifying Project Report

Submitted to the faculty of Worcester Polytechnic Institute in partial fulfillment of the requirements for the Degree of Bachelor of Science in cooperation with Armenia Tree Project and AUA Acopian Center for the Environment.

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Abstract

We collaborated with the AUA Acopian Center for the Environment and Armenia Tree Project (ATP) to address deforestation through successful tree growth in Armenia. We researched and conducted interviews on ideal seedling growth conditions, greenhouse structures, material availability, and biogas digesters for CO_2 supplementation. From these results, we proposed feasible greenhouse designs and recommended ventilation, insulation, heating and irrigation additions for successful seedling growth within ATP's Backyard Nurseries Program.

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Executive Summary

Deforestation has become increasingly prevalent worldwide since the era of industrialization. Deforestation in Armenia became a major issue in the 1990's as the cutting of trees for fuel was unregulated, overlooking the need for the renewal of forest resources. This resulted in negative impacts on the society and environment of Armenia. To combat these effects, there have been various reforestation efforts carried out. This is primarily done through forest preservation and reforestation initiatives by a variety of Armenian organizations including our project sponsors, the AUA Acopian Center for the Environment and the Armenia Tree Project (ATP).

Since the establishment of ATP in 1994, ATP's various initiatives have contributed to providing a sustainable method for tree growth in Armenia. ATP maintains various tree nurseries and promotes growing efforts focused on reforestation. In addition to its large nurseries and community planting, ATP also has the Backyard Nursery Micro-Enterprise Program; a program that employs families to grow seedlings on their own land. ATP provides seeds to participants and then monitors the seedling growth process until they are ready for transplanting into the forest. The seedlings that are ready for transplanting and have been raised into high-quality seedlings are then bought back by ATP.

The backyard nurseries program that aids in the reforestation of Armenia is facing challenges with its success rate. There is a high workload placed on ATP staff as they must train all new participants and oversee active sites. This ultimately limits the number of participants. Although there is a high dedication level of the participants and staff within the program, Armenia's unique climate threatens the rate at which new trees can be produced. This is due to the inability to have a consistent, high success rate of seedlings per family. Ultimately, this creates an insufficient supply of trees for ATP's reforestation effort. The establishment of a method that requires less oversight and results in higher outcomes for healthy seedlings will allow this program to better contribute to reforestation efforts.

The goal of this project was to propose a design for a greenhouse that supports tree seedling growth and is feasible for the ATP backyard nurseries program. This greenhouse will help ATP address deforestation in Armenia. To achieve our goal, we identified the following objectives:

1. Determination of ideal environmental conditions for seedling growth
2. Determination of a feasible greenhouse structure
3. Identification of materials that can be purchased that are feasible for greenhouse construction in Armenia
4. Evaluation of a biogas system for a small-scale greenhouse

To carry out Objective 1, we utilized the AUA Acopian Center for the Environment website to determine which subspecies of the target tree seedlings are naturally occurring in Armenia. A web search was then carried out to find botanical knowledge, arboretum websites, and scholarly plant growth studies. These helped determine the sunlight, temperature, soil conditions, altitudinal range, and appropriate carbon dioxide (CO_2) supplementation levels. We also used the ATP website and scholarly studies to determine the environmental conditions for each village the greenhouse will be implemented.

To carry out Objective 2, we investigated the various shapes of existing and well performing walk-in and small-scale greenhouse structures through gardening specific websites and scholarly articles. Specifically, we determined the design as well as the benefits and disadvantages of each structure. We also used instructional websites and inspected figures of small-scale greenhouses in order to determine the necessary structural elements. Additionally, the team carried out an interview with Vitaly Aoun, a forestry and environmental engineer, who offered feedback on the various greenhouse design options and additions to the greenhouse to support seedling growth.

To carry out Objective 3, we looked up material prices on the Alibaba website, which provided us with an idea of how expensive each material is. Adding to this, the GrantaEdu Pack 2020 WPI material database was used to examine if the materials met the specific transparency, durability, and thermal requirements needed to allow the greenhouse to function properly. A meeting was held with our IQP advisors, Aaron Sakulich and Norayr Ben Ohanian to discuss the relevance and definitions of each material property. Aaron is a civil and environmental engineering associate professor at WPI, and Norayr Ben Ohanian is an adjunct professor at the AUA. We also discussed how material families, such as metals, typically have similar material properties, with some exceptions.

To carry out Objective 4, we interviewed Alen Amirkhanian, the director of the AUA Acopian Center for the Environment, who provided clarifications on biogas use and answered questions on the goals and expectations for the project. A technical product review of current biogas digesters was also completed, focusing on those that have already been implemented using various university studies. We researched open-access university studies and online scholastic journals to investigate how biogas is pumped through a house for cooking and heating purposes as well as the necessary piping and its effects on the carbon dioxide. This was used to understand what type of connection system can be utilized for gas exchange between a biogas digester and the greenhouse. We also utilized online resources on the properties of combustion and types of gas to determine the amount of organic waste necessary to provide the optimal temperature and CO_2 levels determined in Objective 1.

We wanted to support the growth of oak, maple, ash, beech, and birch trees within the greenhouse. Out of these trees there were 11 species of focus that were determined to grow naturally in Armenia for our environmental considerations. The greenhouse design accounts for disparities found between the optimal environmental conditions of each tree species and those of villages in which they will be used. The use of individual pots for growing the seedlings was ruled out due to their adverse effects on the hardiness of the tree in unideal weather and the binding of roots. Exploring the soil pH of the regions, there was found to be an appropriate amount of nutrients and minerals to support seedling growth with the exception of the village of Aghavnavank, as the soil there has a slightly more acidic composition. Also, the effects of altitude changes were not considered for the greenhouse as there was not an overwhelming disparity between the elevation ranges where the tree species tend to grow and the villages that the seedlings will grow in.

A comparison of the ideal growing temperature conditions shows that the average minimum temperature withstood by the trees will not be exceeded. However, the ideal growth temperature is not achieved year-round, so the greenhouse must compensate for the weather fluctuations that exist throughout the rest of the year. Additionally, there is not adequate rainfall to support seedling growth year-round, which is why alternative sources of water for seedling irrigation are necessary. In terms of carbon dioxide supplementation an increase of CO_2 concentration to 1,000 – 1,300 ppm increases the rate at which photosynthesis takes place in plants, but this level decreases to 400 – 600 ppm during the process of ventilation inside the greenhouse. The last condition of interest was sunlight, for which we found that all the target tree species are shade tolerant, meaning that they can grow under low light conditions as well as full sun.

These growing conditions were taken into consideration for the overall design of the greenhouse structure. Since the seedlings will only be grown to a height of roughly 20 to 35 cm (0.67 to 1.15 ft) in the greenhouse, smaller-scale greenhouses were decided upon for implementation. These greenhouses were compared to walk-in greenhouses of similar designs and features. There were three small-scale greenhouse structures and three walk-in structures that were considered. The small-scale greenhouses that were considered were the single-winged cold frame, double-winged cold frame, and the low tunnel.

There were seven different materials that were considered for greenhouse framing: cedar wood, steel, flexible steel wire, aluminum, PVC pipe, polyethylene pipe, and cellulose acetate. Each of these materials fall under an overarching material family, which in this case is either wood, metal, or plastic. There were also six materials considered for the covering options: soda lime glass, polycarbonate, polyethylene terephthalate (PET), GFRF epoxy matrix (isotropic), polymethyl methacrylate (PMMA), and polyvinyl chloride (PVC). These were separated into three material families: glass, plastic, and epoxy resin. Since pricing has such a significant role in the feasibility of greenhouse implementation and our project was focused on building multiple backyard greenhouses, the material prices were identified from the Alibaba website, which is a site that has materials available in bulk and for industrial use, for a general pricing comparison. All materials were then compared based off their durability and thermal properties, and covering materials were also compared based off transparency.

We considered the use of a biogas digester in conjunction with the greenhouse in order to supply the seedlings with an increased CO_2 level. An increase in CO_2 directly correlates to increased sugars and carbohydrates for plant growth. A biogas digester is a system in which organic materials, which in this case would be cow manure, are broken down and made into biogas. The biogas is then combusted producing the CO_2 needed for seedling growth within the greenhouse. Biogas digesters come in two categories of designs, being either above- or below-ground. The variation in the two designs is that the below-ground design uses the ground as a constant insulator, meanwhile the above-ground design is cheaper and easier to build as it does not require digging.

The main components of the biogas digester system in conjunction with the greenhouse are the main tank, which stores the slurry and holds the biogas, and the combustion chamber. The tank is the largest having three openings: one opening for the input of slurry, which is composed of equal parts of manure and water, one for the output of biogas, and the last opening for the output of fertilizer. The combustion chamber is where the biogas is converted into CO_2 through the process of combustion. All components of the biogas system will be ideally made of steel because of its high corrosion resistance when properly treated. The biogas digester will be connected to the combustion chamber through piping. The combustion chamber will be placed closest to the greenhouse and will be attached through a pipe leading directly into the side of the greenhouse. The regulation of the complete biogas system is carried out with valves at the beginning of each opening.

Our primary recommendation for a small-scale greenhouse structure is a single-winged cold frame over a double-winged cold frame as it requires less material, making it more cost effective. A single-winged cold frame also offers varying degrees of sunlight throughout the day which promotes growth while also preparing these shade-tolerant seedlings for sunlight conditions in the forest. If the resources needed for a single-winged cold fame are not available, then the structure can be substituted with our secondary recommendation of a low tunnel greenhouse structure.

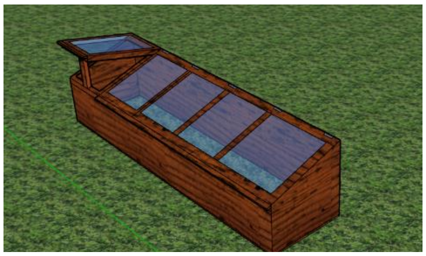

Figure 1: Single-Winged Cold Frame Greenhouse Design

For the frame of the cold frame structure, we recommend that it be composed of wood and that a protective paint coat being applied before utilization. However, if the wood used is redwood this step is not needed. For the covering material that would be used for the angled roof we recommend a polycarbonate sheet, or any other transparent plastic sheet that allows at least 70 % of light to pass through.

For the low tunnel greenhouse design, we recommend the frame be made of semicircular flexible steel wires spaced evenly apart. We also recommend that a powder or paint coat be added to the metal, as it will increase its corrosion resistance. For the cover we recommend using a material that is either polyethylene terephthalate (PET) or polyvinyl chloride (PVC) film.

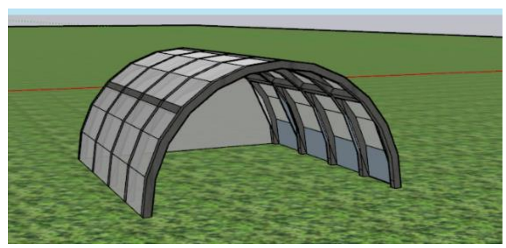

Figure 2: Low Tunnel Greenhouse Design

A biogas system can be used in conjunction with the greenhouse in order to supply carbon dioxide for the stimulation of seedling growth. The system of delivering CO_2 into the greenhouse using biogas is viable but will need to have a pilot program to test it as discussed later. Biogas would be better applicable to the cold frame design as the piping is supported off the ground by the rigid frame and a better seal can be applied to eliminate gas leakage. The biogas digester is cheap to maintain and is a renewable form of CO_2 for the greenhouse. Further testing with a pilot program will be needed to see if this novel idea is viable in practice. We suggest that a silo-style, which is an above-ground biogas digester be utilized over the below-ground design as it is the cheaper and easier to construction and maintain. It is recommended that sawdust be used as insulation to offset the drawback of not being insulated by the ground. As this sawdust retains heat well, we recommend that it be placed in between the two outer walls of the digester. Although if another material that has low thermal conductivity is more available that material can be used instead.

We recommend that a manual ventilation cycle be implemented for the greenhouse in order to mitigate the trapping of humidity as well as to aid air flow. Since the greenhouse will need to maintain a higher internal temperature than external temperature, it is recommended that additional heating sources outside of the potential heat benefits of biogas be utilized to help stabilize heat in the colder months. For additional heating, we recommend using a hot bed and thermal massing. A hotbed is a raised, above ground foundation for plants to grow in which decomposes organic waste such as straw, manure, and compost to create heat so that the internal greenhouse temperature stays around 23.9 °C (75 °F). Thermal massing uses materials such as water filled containers that absorb and hold in heat during the day that is released during the night.

For cold frame insulation, it is recommended that bubble wrap be used to line the interior of the cold frame during the colder months. Horticultural bubble wrap should be used, as it lasts longer due to higher durability than other types and can be easily obtained at most garden centers, but other bubble wraps can also be used. In order to make the bubble wrap stay in place an adhesive should be used. Plants should also be covered if the temperature goes below 0 °C (32 °F) (Volente, 2021). Plants can be wrapped in horticultural fleece or clothing and textiles to help keep heat in (Waddington 2020). For the cold frames, we also recommend that a thick layer of mulch is added on top of the plants, as it keeps in heat well. For the low tunnel structure, there should be a layer of straw or mulch added on top of the soil followed by a layer of fabric covering to keep heat in.

In order to maintain the optimal water levels for the plants, we recommend that an irrigation system consisting of tubing extending the length of the greenhouse be used. The tubing should be hooked up to an outside water source and should have openings at each seedling position to deliver water directly into the soil in a controlled manner. We also recommend exploring the use of a stand-alone rainwater collection mechanism or one used in conjunction with the greenhouse for use of recycled water for the seedlings.

We recommend that continued progress be made towards determining the appropriate methods for implementation of the greenhouse within the backyards of ATP's program participants. We recommend that interviews and focus groups be carried out with the target participants. We did not have the capabilities to carry out this communication within this project, but client feedback is a very important aspect of product development. We also suggest that the construction of a single-winged cold frame and a low tunnel greenhouse design be carried out by ATP in order to determine the appropriate steps and whether the structures are as sturdy and effective as they are currently assumed to be. It is also recommended that the greenhouses be piloted for at least one year so that weather fluctuations and seedling needs can be observed throughout all seasons. There should also be a pilot program for the implementation of biogas within the greenhouse, which can determine the benefits that biogas provides along with the exact heat and carbon dioxide levels produced. This will also need to be supplemented with research on the proper valve operations.

This greenhouse will provide a controlled growing environment, increasing the probability of growing successful seedlings. Since the participants earn a profit for each high-quality seedling, the overall yearly income for participants will be increased, in turn increasing motivation to participate in ATP's program expanding its influence and forestation impact. Beyond the scope of ATP's work, these individualized greenhouses will assist in reaching the country's goal of doubling the number of trees by the year 2050. An effective and affordable method for reforestation efforts that can be carried out in an individual manner can spark worldwide interest and adoption.

Introduction

Deforestation has become increasingly prevalent worldwide since the era of industrialization. Forested regions are constantly decreasing due to the cutting down of trees for re-purposing or clearance of land. This is driven by the growth of agricultural production and industry as well as large-scale farming. To help reverse the negative effects of deforestation, the establishment of forested regions through new tree growth is needed. Deforestation is a primary concern in Armenia.

Deforestation in Armenia became a major issue in the 1990's with negative impacts on society and the environment. It is a specific problem in Armenia as reforestation efforts are constantly challenged by the unique range of climatic conditions. Poor soil quality, severe weather, and insufficient water supply prevent the establishment of seedlings and saplings. In the social context, deforestation increases the rates of infectious diseases and premature death while decreasing water quality. To combat these effects, various reforestation efforts have been carried out. These efforts have been similar to those implemented worldwide and have consisted of fundraising and planting efforts. This is primarily done through agricultural methods by a variety of organizations including our project sponsors, the AUA Acopian Center for the Environment and the Armenia Tree Project (ATP).

ATP's Backyard Nursery Micro-Enterprise Program allows participants to grow seedlings and shrub cuttings on their land. Participants are educated on how to maintain the seedlings and shrubs over a two-to-three-year period and are only paid for the number of successfully grown seedlings. Therefore, their efforts are not always rewarded as there are detrimental weather conditions that can kill seedlings before they mature. Ultimately, this prolongs the tree planting effort, resulting in detrimental impacts on the Armenian government's goal of doubling forestry in the country by 2050. One way through which ATP can contribute to this goal is by using greenhouses to plant and grow high-quality seedlings at a faster rate.

An efficient and cost-effective greenhouse design will aid Armenia in their reforestation efforts. This is because it has the potential to improve seedling growth for ATP's backyard nurseries program participants. Greenhouses are designed to create a stable and ideal environment for plants by providing proper growing conditions consisting of light, temperature, and CO_2. An easy to use and cost-effective carbon supplementation method can be used in conjunction with the greenhouse as it can aid in plant growth through photosynthesis.

We aimed to positively impact the success of ATP's backyard seedling growing efforts through designing a greenhouse. This design was achieved through the following objectives: determination of ideal environmental conditions for seedling growth; determination of a feasible greenhouse structure; identification of local materials that are feasible for greenhouse construction in Armenia; evaluation of a biogas system for a small-scale greenhouse. The implementation of each objective helped ensure the best case for the adoption of a greenhouse proposal that will help ATP in their program development goals.

Background

In this chapter, we begin with a brief overview of the general problem of deforestation, a pressing environmental issue that is heightened by climate change. Next, we discuss the long-term reforestation efforts that are continuously being expanded upon to help improve environmental and societal conditions in Armenia. We conclude by introducing the Armenia Tree Project organization, their challenges, and their efforts in the adoption of a greenhouse design. Our goal for this design is that it can be easily constructed and maintained by local Armenian populations to increase the effectiveness of this Armenian reforestation program.

Deforestation in Armenia and its Effects

Deforestation started to accelerate after the 1988 Spitak earthquake, which was followed three years later by the dissolution of the Soviet Union, which marked the start of the war between Armenia and Azerbaijan. This combination of events placed stress on energy resources available to Armenians. This is because the country’s established importation of oil and gas for heating needs from Russia and former USSR republics was abruptly halted. Armenians' reliance on their surrounding forests then increased as wood was used to meet household energy needs (Sayadyan & Moreno-Sanchez, 2006). At that time, the cutting of forests for fuel was unregulated, overlooking the need for the renewal of forest resources. The clearing of forested land for urbanization also became more prevalent as the creation of more urban land through deforestation resulted in increased income from agricultural use (Andrée et al., 2019). This quickly heightened the amount of long-lasting deforested regions. Furthermore, the lack of forestation which provides wind protection, creates a positive feedback loop in which more fuel for heating such as firewood is needed due to the subsequent windier and colder weather conditions (Maddison, 2013).

Climate change is another main contributor to the increasing deforestation and its effects on environmental wellbeing. The reforestation of Armenia is challenged by the changing climate and topography across the country. The climate in Armenia is quite variable as a result of its complex terrain and unique positioning between the Black and Caspian Seas (Opala-Owczarek et al., 2021). These factors affect the movement of air masses across the region, resulting in seven distinct climate zones (Maddison, 2013). Armenia’s high level of biodiversity is supported by the range of climatic conditions (Maddison, 2013). Global warming adds to the complexity of the Armenian climate and thus is a concern for forestation efforts. The increased occurrence of droughts, higher air temperatures, reduced rainfall and water scarcity impact the ability to grow various plants successfully (Melkonyan, 2015).

One of the most concerning problems resulting from climate change is its effect on rainfall, as water is crucial for plant growth. If there is not enough water, then plants will not grow properly. The precipitation within Armenia ranges from about 0.2 m (7.87 in) in arid regions to 1 m (3.28 ft) in mountainous regions per year (Opala-Owczarek et al., 2021). The total rainfall is at a maximum in the spring and a minimum in the summer. Studies conducted in Armenia from 1966 to 2010 have shown that there has been a decrease of about 30 % of the April-to-October rainfall used for irrigation due to climate change (Melkonyan, 2015). This timeframe from April to October is vital for plant growth as it ensures that plants get appropriate amounts of water for their continued development. Increasing temperatures and decreasing precipitation rates due to climate change can cause periods of drought, significantly impacting the environment. Drought also increases the amount of stress placed on trees. This is demonstrated through the evaluation of tree-ring data in 2018 of juniper and oak trees from various regions of Armenia. The data show a distinct reduction of tree growth during periods of drought throughout the tree's lifespan (Opala-Owczarek et al., 2021). As climate change continues this course, experts predict that by 2100, rainfall will decrease 8 % – 27 % in Armenia (Melkonyan, 2015). This trajectory results in a significant reduction in the amount of rain, which will continue to result in detrimental losses to crop and plant growth. While climate change is an external threat to forestation, overall, the lack of forested regions presents a threat to its own ability to regenerate.

Deforestation causes a soil quality issue by increasing erosion and altering land coverage. One soil analysis identified soil erosion and structural characteristics in three types of land - pasture, forest, and coppice. A coppice region consists of trees that were cut to stumps periodically to stimulate new growth (Willis et al., 2021). One study showed that "40 cm (15.74 in) of soil has been lost in the pasture and 20 cm (7.87 in) have been lost in the coppice compared to the forest in Hrazdan, Armenia" (Rhoades et al., 2011). This demonstrates that soil degradation in these areas goes 40 cm (15.74 in) deep in pasture and 20 cm (7.87 in) in coppice, making these areas harder to grow in and keep plants grounded. Although this study had a focus on the mountainous region of Hrazdan, these findings represent the trends in soil erosion that deforestation creates in all of Armenia's climate zones. One way that forested regions slow erosion is by creating soil stability through tree root anchorage (U.S.C., 2018).

Another factor contributing to the decrease in plant stability and growth is the carbon level within soil. The amount of natural carbon present in the soil has been negatively impacted by erosion caused by deforestation. The study mentioned in the previous paragraph also showed lower organic carbon percentages in the pasture and the coppice when compared to the forest (Rhoades et al., 2011). The decreased amount of organic carbon impacts the growth of plants in several ways. When soil carbon decreases, the oxygen in the soil also decreases. This erosion and soil nutrient decrease is also impacted by heavy rain conditions present in Armenia. Heavy rainfall was found to occur for 17 to 40 days a year between 1975 to 2006 and added to the continued threat of soil erosion within Armenia (United Nations Development Programme, 2013). This impacts the ability of plants to get their necessary intake of carbon to survive during the process of respiration. Since carbon adds to the structure of soil, its reduction equates to lessened stability for plants making it harder for them to stay grounded. Carbon also helps plant's water retention and the ability to expel water (Schwartz, 2014). It is crucial for air to be rich in carbon dioxide, otherwise the soil will not be able to provide enough carbon to plants which negatively impacts a plant's ability to cope with floods and droughts. Regardless, this erosion and loss of organic carbon in soil has a detrimental impact on plants' ability to receive the nutrients they need in order to grow.

The lack of soil nutrients and appropriate environmental conditions has an increased detrimental impact on seedlings. The act of reforestation begins with the emergence of new growth from the seedling stage, which is a tree's phase characterized by small size and lack of protective structures. At this stage, the roots are laid superficially in the soil, which makes them extremely sensitive to desiccation (Lett & Dorrepaal, 2018). Therefore, the level of moisture within the soil has a significant impact on the viability of these seedlings. The success of growing efforts is dependent on appropriate water levels, especially when the seedling is in the presence of intense sunlight. Above ground, seedlings must withstand varying wind, light, and temperature conditions. The feeble stem of seedlings creates sensitivity to intense wind, as they can easily be knocked over and have their stems snapped. The stem is the mechanism by which water and nutrients are carried to the plant, so damaging the stem ultimately leads to the tree's death (Keles, 2020). Seedlings can also die through the freezing of their roots in cold temperature conditions. Since the average air temperature in January within Armenia is 6.7 °C (19.94 ° F), freezing temperatures are a continued risk factor to new plant growth during the winter (Opala-Owczarek et al., 2021). Another consequence of freezing temperatures is hail, which occurred on 20 to 40 days out of the year between 1975 and 2006 (United Nations Development Programme, 2013). Hail falling onto fragile seedlings results in the breaking of the stem similar to the consequences of strong winds.

The desired sunlight conditions for optimal seedling growth are dependent on the type of tree species as there are various degrees of shade tolerance. This means that some seedlings will grow better in direct sunlight while others will face higher chances of survival in shaded locations. In soil and weather conditions that are not ideal for seedling growth, there is a decrease in growth rate in exchange for increased focus on survival mechanisms (Lett & Dorrepaal, 2018). Other external threats to plant growth lie within stem, leaf, and root consumption by small browsing and burrowing animals as well as fungal disease, which all vary depending on tree species. These various environmental threats present a challenge to reforestation efforts because they inhibit seedlings' ability to make it into full grown, healthy trees. This has created a sector of interest for organizations to step in and facilitate seedling and sapling growth to positively impact the Armenian way of life.

Reforestation Efforts

Reforestation will improve the quality of life for Armenians. These everyday impacts include lessened risk of disease, increased presence of clean water reserves, and increased household incomes. The efforts to reforest decrease the threats of disease to the population. According to the World Health Organization, "Deforestation increases the risk of infectious diseases including malaria, dengue fever, SARS, Ebola, Hantavirus, and Zika" (El-Sayed & Kamel, 2020). The one mosquito-borne disease that has been present in Armenia is malaria, which is endemic in the country. Malaria is part of the arbovirus family, which are animals that transmit diseases to humans by feeding off their blood (NBTI, 2020). Forests provide habitats for arbovirus animals and if taken away, these animals may move into populated areas such as villages in search for a new home and food source. This increases people's exposure rate, especially those more vulnerable to disease. Health risks, such as asthma, allergies, chronic obstructive pulmonary diseases, lung cancer, cardiovascular diseases and skin diseases are also mitigated by reforestation (Akopov et al., 2019). Trees act as natural air filters by providing clean air into the atmosphere, ultimately reducing air pollutants. "Urban greenery such as trees can effectively reduce air pollution in a natural and eco-friendly way" (Akopov et al., 2019).

Access to clean water is increased by forestation as well since trees act as natural water filters. They lessen the amount of rainfall runoff by absorbing water through their roots. Excessive rainfall runoff increases the volume of water that flows into water reserves, which increases the amount of animal waste and other contaminants that are picked up along the way. Another benefit of reforestation efforts is increased employment opportunities, since growing trees for increased forest cover can account for a part- or full-time job.

Land used for agriculture covers 68.8 % of Armenia and about 40 % of Armenians own land for cultivation. The demographic of farmers is 13 % urban communities and 84.2 % rural communities (N. et at., 2017). About 21 % of Armenia's Gross Domestic Product (GDP) comes from the agricultural sector (Melkonyan, 2015). This contribution to the GDP is significant as Armenia has a lot of different climates suitable for growing a variety of crops. It is generally known that many Armenians have a garden of their own that provides them with fruits and vegetables. Growing crops is both a part of the economy and the culture in Armenia. Local knowledge of agriculture used to grow crops in a variety of conditions also contributes to the ability to successfully plant and grow trees and are beneficial to reforestation efforts to grow healthy trees in an effective way.

Armenia has many programs and organizations for tree growing efforts, which are centered on the protection and restoration of forests and community involvement. An example of a governmental organization that aids in reforestation is the Ministry of Environment in Armenia, which was formed to increase appreciation and protection of the country's environmental resources (Ministry of Nature Protection of the Republic of Armenia, 2002). In particular, the Ministry emphasizes the protection of the country's air, water, and land resources (Policy Forum Armenia, 2010). One division of the Ministry of Environment is the Committee of Forest of Ministry of Environment. The forest committee strives to maintain forests and their productivity in a sustainable way. This includes monitoring the biodiversity of forest ecosystems and ensuring that illegal or non-sustainable logging does not occur (Aslanyan, 2018). Due to the abundance of logging, Armenia has established certain forest protection organizations such as the Forest State Monitoring Center. This center identifies illegal activities related to logging and wood transportation. Efforts like these are important as they help prevent the continued decline of trees. While these organizations are primarily focused upon the elimination of threats to forested regions, there are also organizations which primarily focus on regenerating forested regions.

One program is ArmForest also known as HayAntar, where people from ten communities of the Tavush region are hired to plant and grow trees (UNDP, 2020). This program can provide its participating members, referred to as foresters, with full-time careers. Some of the tree species that are grown by this initiative are ashes, oaks, and beeches (UNDP, 2020). These trees take about four to five years to mature to a point where they can grow independently. This past June, 120 foresters worked on increasing the Noyemberyan Forest tree coverage by growing 3,000 additional trees per hectare (2.47 acres) (UNDP, 2020).

Another organization called My Forest Armenia employs local villagers for afforestation efforts in surrounding areas. Afforestation differs from reforestation as it is the planting of trees in areas that were previously forested a long time ago or are completely barren (My Forest Armenia, 2021). This not only creates more forests but also builds biodiversity in Armenia. Some villages with which they work are Shirakamut and Jrashen, which were approved for forestry efforts in October 2020. The forest location in Shirakamut is 86 hectares (212.5 acres), and for Jrashen it is 350 hectares (865 acres). It is estimated that afforestation will be completed in about three years for both regions (My Forest Armenia, 2021).

The American University of Armenia's Acopian Center for the Environment is another organization that restores and protects the environment through community outreach initiatives, research, education and project work (AUA Acopian Center for the Environment, 2019). The

Acopian Center has participated in many research opportunities conferences and workshops related to forestry. Examples of some research topics include reforestation, afforestation, and biodiversity in the forests of Armenia (AUA Acopian Center for the Environment, 2021). An example of a workshop they held was on wildfire prevention in 2019, where governmental and societal planning for wildfire prevention was discussed (AUA Acopian Center for the Environment, 2019, *Multi-Stakeholder Workshop on Wildfire Prevention and Community Contributions to Wildfire Management*). They also co organized a conference called the Forest Summit in Armenia. The goal of this conference was to "facilitate and open rigorous discussions on policy decisions on Armenia's forests" (Forest Summit, 2019). The other organization involved in this conference was the Armenia Tree Project (ATP).

ATP is responsible for carrying out one of the main reforestation efforts in Armenia. ATP was established by an Armenian-American philanthropist Carolyn Mugar in 1994. It was prompted by the noted decline of forestry in Armenia during the late twentieth century (Gharibyan, 2009). Since 1994, ATP's various initiatives have contributed to providing a sustainable method for tree growth in Armenia. The Armenia Tree Project maintains various tree nurseries and promotes growing efforts focused on reforestation.

The Armenia Tree Project has been contributing to the greening of land throughout villages and communities in Armenia. ATP owns four different tree nurseries: one in Margahovit considered as the reforestation nursery and three community planting nurseries in Aragatsotn, Ararat, and Vayatz Dzor. The nurseries serve as field research centers for environmental education of students, professionals, and local farmers. Tree propagation, grafting techniques, and irrigation methodologies are taught in these centers. They promote the planting of forests along with providing a means for greening villages and communities. ATP has successfully planted 50 varieties of trees and shrubs, some of which are fruit trees and therefore provide the added benefits of produce (Armenia Tree Project). The benefits of nurseries also extend to the individual level through ATP's other growing initiatives.

In addition to its large nurseries and community planting, ATP also has the Backyard Nursery Micro-Enterprise Program. The backyard nurseries program is currently present in the villages of Aghavnavank, Margahovit, and Keti. This program employs families to grow trees on their own land by providing seeds to participants and then monitoring the seedling growth process until they are ready for planting. Once these families or individuals have raised them into high-quality seedlings that can be replanted, ATP buys back each individual seedling (Armenia Tree Project). Households can boost their annual income by either taking an employment opportunity with ATP or participating in their family reforestation programs. Providing 70 full-time and 150 seasonal jobs, ATP has become one of the largest employers among non-governmental organizations in the country due to its employment opportunities within rural areas (Armenia Tree Project & AUA Acopian Center for the Environment, 2019). The inclusion of seasonal and full-time workers creates a diverse job pool that can appeal to a large demographic. This is particularly important for Armenians in rural areas as they can remain within their communities and still earn income as there is no requirement for job relocation. This offer of employment is a driving factor in the reforestation of Armenia.

Reforestation can seem like a daunting task, which makes incentivization a key aspect. The growing process can be frustrating for individuals as it tends to take anywhere from two to three years and seedling survival is not always guaranteed (Armenia Tree Project). The establishment of the background nurseries program by ATP has increased Armenians' efforts and ability to participate in the reforestation of their country. Individuals are influenced to participate in part because they are not required to make an initial investment, since ATP provides households with the necessary seedlings. This means that the compensation they receive for each healthy seedling at the end of the growing period is solely repayment for their effort. Insurance of a successful harvest by these individuals is driven by the fact that ATP only provides compensation for high-quality seedlings. These are classified based on whether they can be replanted. There are about 30 families in this program with each family growing around 1,500 to 2,000 saplings at a time (Armenia Tree Project, 2021). While this program has been widely successful, it also faces various obstacles.

The backyard nurseries program which aids in the reforestation of Armenia is facing challenges with its success rate. There is a high workload placed on ATP staff as they must train all new participants and oversee active sites. The program is limited to a certain number of participants as it must be manageable for oversight by ATP staff. Although there is a high dedication level of the participants and staff within the program, Armenia's unique climate still threatens the rate at which new trees can be produced. This is due to the inability to have a consistent, high success rate of seedlings per family. Ultimately, this creates an insufficient supply of trees for ATP's reforestation effort. The establishment of a method that requires less oversight and better outcomes for healthy seedlings will allow this program to reach its optimal reforestation contributions.

Greenhouses can be established as a method for achieving these goals. A greenhouse is a building or covering for plants that protects them from harsh weather while providing a more ideal growing environment. A greenhouse is beneficial because it supplies a consistent climate which helps plants grow year-round. This helps boost tree yield and reforestation efforts as there is no seasonal restriction for growth. Greenhouses can also be aided by carbon dioxide (CO_2) supplementation to achieve optimal CO_2 levels for maximum plant growth. CO_2 supplementation is necessary within an enclosed environment as the air will become stripped of CO_2. This will happen overtime as the plants will convert all the available CO_2 into oxygen through the process of photosynthesis. This will cause the plants to start dying as there is a lack of the necessary inputs for photosynthesis, which is the method by which plants create energy to survive. One option for CO_2 supplementation is the burning of biogas which is the product of anaerobic digestion of organic waste, such as cow manure. Anaerobic digestion is the process whereby organic waste is broken down and gases are released. It is a renewable energy source that has a low manufacturing cost, making this a potentially valuable component of a greenhouse.

Importantly, greenhouses are a proven approach to mitigating seedling death from unideal climatic challenges and have the potential to contribute to Armenia Tree Project's goal of fighting deforestation. This can be achieved through increasing the percentage of tree yield for families participating in their backyard nurseries program. A greenhouse design for ATP must account for proper above- and below-ground conditions through regulating an optimal growing environment for the desired seedlings with a low-complexity and low-cost design. This puts greenhouse technology in reach and would eliminate the issues that ATP currently faces with harsh weather conditions allowing for more reliable returns for growers and potential program expansion.

Summary

Deforestation in Armenia has become prevalent as the practice of unsustainable cutting of trees for firewood and clearing of land for urbanization increased. Climate change has also negatively impacted forested regions by decreasing rainfall and creating soil erosion. This lack of water and nutrients along with the unideal weather conditions in Armenia makes it difficult for seedlings to mature. Reforestation is important as it benefits both society and environment through the reduction of disease, the increase of air and water quality, and the increase of jobs available in forestry. Reforestation efforts are being conducted through organizations such as ATP, ArmForest also known as HayAntar, My Forest Armenia, and the AUA Acopian Center for the Environment, which restore and protect forested regions through community outreach and tree growing initiatives. Specifically, ATP has struggled with producing a large yield of high-quality seedlings within their backyard nurseries program. As greenhouses can provide a consistent climate to support plant growth year-round, a greenhouse addition can be beneficial to the success of ATP’s program and the reforestation of Armenia.

Methodology

Our goal was to propose a design for a greenhouse that supports tree seedling growth and is feasible for the ATP backyard nursery program. This greenhouse will help ATP address deforestation in Armenia. To achieve our goal, we identified the following objectives:

1. Determination of ideal environmental conditions for seedling growth
2. Determination of a feasible greenhouse structure
3. Identification of materials that can be purchased that are feasible for greenhouse construction in Armenia
4. Evaluation of a biogas system for a small-scale greenhouse

To meet these objectives, we used a combination of meetings with the sponsors, interviews with experts, technical and market assessments, and secondary research. This was completed remotely due to the COVID-19 restrictions that were in place worldwide. This knowledge that was gained ensured a desirable greenhouse that will have a high potential for future adoption and implementation.

Objective 1: Determination of ideal environmental conditions for seedling growth

The determination of the ideal environmental conditions for seedling growth shaped the greenhouse design process. The material selection of structural components, and design of the biogas digester element were based on their ability to aid in the maintenance of an ideal growing environment for seedlings. As every plant has necessary light, water, and nutrient levels for optimal growth, it was important to determine these levels for each species of seedlings that will be grown in the greenhouse. The greenhouse was designed to accommodate the specific needs of oak, maple, ash, beech, and birch seedlings.

To obtain information on the appropriate environmental conditions, we conducted research on the ideal growing conditions of the tree species specified by ATP. The AUA Acopian Center for the Environment website was utilized to determine which specific species of the target trees are naturally occurring in Armenia. Secondary research was then carried out to find botanical knowledge, arboretum websites, and scholarly plant growth studies. These helped determine the sunlight, temperature, and soil conditions as well as the natural altitude range for each tree species. In addition, these sources helped identify general water and moisture levels for overall seedling growth and the difference between growing seedlings in pots versus directly in the soil.

The greenhouse will first be implemented by the backyard nurseries program participants who have been with the program for many years and have successfully grown high-quality seedlings; therefore, the regions in which they live were identified, and their climatic conditions were determined. News articles and the ATP website were used to determine the villages in which the backyard nurseries program is currently taking place. Scholarly studies conducted in Armenia were found to provide the temperature, annual precipitation, soil type, and altitude of each of these regions.

We also obtained information on the appropriate levels of CO_2 that can be supplied to the plants within the greenhouse in order to stimulate seedling growth. This information was obtained from Ontario's Ministry of Agriculture, Food, and Rural Affairs website. It provided the appropriate fluctuations in CO_2 supplementation levels during ventilation and varying sunlight conditions of the greenhouse as well.

The ideal environmental conditions required for optimal seedling growth of the specified species were taken into consideration when deciding greenhouse design components. We created various tables in order to compare the ideal conditions that were determined for each tree species and those that occur in each backyard nursery region. For the sunlight and temperature conditions, we determined that they did not need to be broken up by tree species and could be discussed as one condition that needs to be met for all target species. The optimal growing conditions along with the proper CO_2 supplementation levels were used to make a conclusion about the environmental conditions in the greenhouse. The greenhouse characteristics were decided based on the levels of disparity that exists between the ideal environmental conditions and those that are naturally occurring within the Armenian regions of interest.

There were limitations in determining whether each environmental condition had a direct correlation to the success of the seedling growth and survival. This is because these environmental conditions often occur synergistically, so it is not clear whether the combination or the individual characteristic is creating overall results on the growth of the plant. There also is some variation in the ideal growing condition depending on from where the information is obtained, as there can be unidentifiable sources of influence on the plant growth. These could consist of regional influences, short term weather fluctuations, and different measurement methods.

Objective 2: Determination of a feasible greenhouse structure

It was important to make decisions about the structural design of our greenhouse as it had to be feasible for the program participants. The structural design specifies the overall shape and the individual structural elements of our greenhouse, ensuring its durability and feasibility.

We investigated the designs of working walk-in and small-scale greenhouse structures through websites by organizations focused on gardening and construction, such as Novagric and Garden and Greenhouse. Scholarly articles from Science Direct, Texas A&M University, the University of Massachusetts Amherst, the University of Georgia, and the University of Illinois were also utilized. These sources provided us with details on design as well as the benefits and disadvantages of each structure. The descriptions of the walk-in structures were utilized in order to draw conclusions about smaller-scale structures of similar shape. These smaller-scale structures were of interest to us since the target tree species do not reach a substantial height after a two-to-three year growing period. We compared the information on the benefits and disadvantages of the walk-in structures and the related smaller scale structures. Depending on the number of disadvantages or advantages for each small-scale structure we identified which structures were feasible for the ATP participants.

The structural elements and figures of each structure were obtained from instructional sources such as DIY Network and the sources listed above. We inspected the visuals of the specified greenhouse and instructions provided in order to determine the necessary structural elements. Specifically for the smaller scale structures, we used these visuals and instructions to determine how each element should be connected and the general placement of each element as well as the slope of the window coverings for the cold frame structures.

We also conducted in interview with Vitaly Aoun, a Forestry and Environmental Engineer. He offered advice on various greenhouse design options and additions to the greenhouse to support seedling growth.

Objective 3: Identification of materials that can be purchased that are feasible for construction in Armenia

We designed a feasible greenhouse through the identification of readily obtainable materials from local suppliers. Price is an important factor of consideration as it impacts the probability that the materials will be adopted by locals. It is important to have viable options for designs that can work for those who do not have excess funds for nonessential investment. Material properties were also important, as they indicated how well the greenhouse would be able to maintain the ideal environment needed for seedlings.

We found all material prices on the Alibaba website. As price was the most important factor of consideration for materials, this helped us decide which materials were best for greenhouse construction. The materials also had to meet specific transparency, durability, and thermal requirements in order to maintain an ideal greenhouse environment. The ability to meet these requirements was researched using the GrantaEdu Pack 2020 WPI material database. This materials database is open to the WPI community and contains a wide variety of materials and their properties. These were obtained in order to understand whether materials filter the ideal amount of light into the greenhouse and if they have the proper thermal properties which would make them suitable for constructing a greenhouse.

The identified materials and their corresponding properties were compared within an Excel spreadsheet, which was separated into two separate portions for covering and framing materials as well as pricing tables. These tables were made for the comparison of materials for greenhouse framing and covering use based on their price ranges. In the Excel spreadsheet, the columns identified each material type, and the rows included the material properties. This Excel spreadsheet was used to rank suitable materials on their durability and thermal properties. A meeting was held with our IQP advisors, Aaron Sakulich and Norayr Ben Ohanian, who are both professors and engineers that have previously worked with material properties for construction. Aaron is a civil and environmental engineering associate professor at Worcester Polytechnic Institute, and Norayr Ben Ohanian is an adjunct professor at the American University of Armenia. In this meeting, we discussed the relevance and definitions of each material property. We also talked about how material families, for example metals, typically have similar material properties with some exceptions. This meeting helped us carry out the material comparison and interpret the meaning of each material property value correctly.

The spreadsheet and meeting were used to decide which materials were going to be included in our final greenhouse design based off price and their material properties. In choosing materials best for greenhouse construction, we assessed materials based on their material families of wood, metal, plastic, and glass. This allowed for a larger probability of the materials' availability in Armenia's market as material families are less selective than individual materials, therefore adding more material options.

Objective 4: Evaluation of biogas system for a small-scale greenhouse

An optimal system for temperature regulation and CO_2 levels within the greenhouse can support maximum plant growth. It was important for us to determine an effective and low-cost method to carry this out as it will contribute to the likelihood of the greenhouse application by ATP.

We conducted an interview with Alen Amirkhanian, the director of the AUA Acopian Center for the Environment, who provided clarification on biogas use and answered questions on the goals and expectations for the project. He provided clarification on how the AUA Acopian Center for the Environment is mainly interested in CO_2 production and not the heating element, as well as only focusing on biogas instead of other supplementations.

We also completed a technical product review on current biogas digesters, focusing on those that have already been implemented. We used various university scholarly studies conducted under the University of Missouri, the University of Illinois, and Pennsylvania State University. These sources provided us with information on the process by which organic material is converted to biogas and then combusted to produce CO_2. We focused on the benefits and downfalls of each type of digester, fuel type and method of combustion, CO_2 levels produced, and production of other gases.

We used the university studies mentioned above to investigate how biogas is pumped through a house for cooking and heating purposes. This gave us an understanding of what type of connection system can be utilized for gas exchange between a biogas digester and the desired source of output, such as a gas stove or combustion chamber. We used online scholastic journals to find the material and length required for piping as well as the temperature effects of carbon dioxide movement through it. We also utilized online sources on the properties of combustion and types of gas to determine the amount of cow manure necessary to provide the optimal temperature and CO_2 levels determined in Objective 1.

Information gained on biogas digesters was used to determine the feasibility and effectiveness of CO_2 supplementation from combusting biogas. The information from our research allowed us to determine if biogas is a viable form of CO_2 supplementation for each of the greenhouse designs. We also utilized the information about connection systems in order to determine how the biogas digester would be set up with the greenhouse.

There were limitations on the research for CO_2 supplementation in the greenhouse as this is a novel concept. Most biogas digesters are used for energy production limiting the information available on using the CO_2 byproduct of the digester to aid in plant growth. There has been very limited information on the specifics of CO_2 production from a biogas digester as most of the time it's only mentioned as a byproduct. This made it difficult to determine how much CO_2 would be released at a time into the greenhouse.

Results

Our methodology resulted in findings on the ideal conditions for seedling growth, possible greenhouse structures and options for their material composition, as well as the utilization of a biogas digester for greenhouses. These findings were focused on information that was relevant to the Armenian population and climate.

Objective 1: Determination of ideal environmental conditions for seedling growth

The Armenia Tree Project's goal is to improve the growth of oak, maple, ash, beech, and birch seedlings by incorporating greenhouses for individual use within their backyard nurseries program. The species of each desired tree type that naturally occur within Armenia are those of focus (Table 1), avoiding the need for the importation of trees outside of Armenia. This is of utmost importance as invasive species can out-compete native trees and increase the risk of pests and disease, destroying forested regions and reversing reforestation efforts (Armenia Tree Project & AUA Acopian Center for the Environment, 2019).

Table 1: Target Tree Types (Acopian Center for the Environment, 2019)

Tree Type	Common Name
Quercus castaneifolia	Chestnut-leaved oak
Quercus macranthera	Caucasian oak
Quercus pontica	Armenian Maple
Acer platanoides	Norway maple
Acer pseudoplatanus	Planetree maple, Sycamore maple
Acer tataricum	Tatarian maple
Acer trautvetteri	Red-bud maple
Fraxinus excelsior	European ash
Fagus orientalis	Oriental beech
Betula pendula	Downy birch, Moor birch, White birch, European white birch, Hairy birch
Betula litwinowii	Litwinow Birch

The proposed greenhouse was designed to be piloted first by backyard nurseries program participants who have been with the program for many years and have successfully grown high-quality seedlings. These participants live in the villages of Aghavnavank in Tavush Province, Margahovit in Lori Province, and Keti in Shirak Province (Armenia Tree Project, 2021). The greenhouse design accounts for disparities found between the optimal environmental conditions for seedling growth and those of villages in which they will be used. The environmental factors that we focused on dictate plant growth and include soil nutrients, altitude ranges, average temperature, water availability, carbon dioxide levels, and sunlight.

The method by which seedlings will be grown in the greenhouse was explored to determine the necessity of studying the region's ability to supply proper soil conditions. Studies conducted on growing nursery trees in pots rather than directly in the ground proved that this method could have adverse effects on the trees' tolerance of less ideal weather conditions and on their future survival. The seedling roots dry up the moisture in the containers at a faster rate than field grown seedlings, making them extremely sensitive to drought which can cause injury to the plant by killing its cells (UF, 2015). Thus, the seedlings would require more frequent irrigation, which causes reliance on ideal conditions and increases sensitivity to water scarcity when planted in the ground at another location. Another downfall of growing in containers is that root growth gets constrained, which is also referred to as becoming rootbound. When trees are grown in pots, the roots wind around one another unlike the branching that would naturally occur in open soil. When the tree gets removed from and planted outside of the pot, it often faces difficulty with the expansion of its root system and often a girdling root appears within 20 years after transplanting (Silver, n.d.). A girdling root is one that grows near the top of the soil into the main tree trunk, which ultimately places pressure on the trunk and prevents the movement of water and nutrients necessary for tree survival.

Table 2: Ability of Tree Species to Grow in Target Villages based on Soil pH

Tree Type	**Soil pH**	**Village**		
		Aghavnavank	**Margahovit**	**Keti**
Quercus castaneifolia	6.1 – 7.8 (National Gardening Association, 2021)			
Quercus macranthera	> 6.5 (Ebben, 2021, *Quercus macranthera - Caucasian Oak, Persian Oak*)			
Quercus pontica	> 5.5 (Ebben, 2021, *Quercus pontica - Armenian Oak, Pontine Oak*)			
Acer platanoides	6 – 8 (CABI, 2021, *Acer platanoides (Norway maple)*)			
Acer pseudoplatanus	5 – 8 (CABI, 2021, *Acer pseudoplatanus (sycamore)*)			
Acer tataricum	5 – 8 (Cornell University, 2021)			
Acer trautvetteri	5.5 – 8.5 (The Morton Arboretum, 2021)			
Fraxinus excelsior	6 – 8 (Thomas, 2016)			
Fagus orientalis	3.5 – 8.5 (Turkis, 2018)			
Betula pendula	< 6.5 (Plants for a Future, 2021)			
Betula litwinowii	> 4 (Hughes et al., 2009)			

The soil pH has effects on the solubility of minerals and nutrients, which ultimately affects the resources to which seedlings get access. The range of pH that a plant can withstand dictates the nutrients that the plant needs. Thus, a soil pH out of this range won't provide adequate nutrients for the plant to absorb and use to grow properly. The comparison between target growth regions and the ideal soil types indicate that these regions have the appropriate amount of nutrients and minerals to support seedling growth (see Table 2, where green cells indicate suitability, and red cells indicate unsuitability). This excludes the village of Aghavnavank, as it has a slightly more acidic characteristic and therefore is not ideal for the growth of all target seedlings. However, raising the soil pH to a level within the optimal growing pH range will be discussed in recommendations as an option for planting.

Trees also have specific elevations at which they grow, which can influence their exposure to soil nutrients, solar radiation, air temperature, and wind speeds. Growing trees in regions similar to their naturally occurring altitude ensures that that the tree will not undergo unnecessary stress due to an altitudinal change. This is especially important as a tree that is placed under stress allocates its energy to survival mechanisms rather than growth, which will ultimately jeopardize the growth rate and overall quality of the seedling. The altitudes of the specific regions for greenhouse implementation fall between the ranges of growing altitudes for most of the target tree subspecies (see Table 3, where green cells indicate suitability, and red cells indicate unsuitability). This excludes *Q. pontica*, *A. plantanoides*, and *B. litwinowii*, which will require extra consideration regarding whether they can be grown in certain greenhouses. As there is not an overwhelming disparity between the ideal altitude and those at which the trees will be grown, it was not a consideration during the greenhouse design process.

Table 3: Ability of Tree Species to Grow in Target Villages based on Altitude.

Tree Type	**Growing Altitude**	**Village**		
		Aghavnavank	**Margahovit**	**Keti**
Quercus castaneifolia	0 – 2400 m (0 – 7874.02 ft) (Zale, 2018)			
Quercus macranthera	1000 – 1900 m (3280.84 – 6233.60 ft) (Kargioglu et al., 2011)			
Quercus pontica	1200 – 1300 m (3937.01 – 4265.092 ft) (Strijk & Carrero, 2020)			
Acer platanoides	0 –1400 m (0 – 4593.18 ft) (Crowley & Barstow, 2017)			
Acer pseudoplatanus	500 – 1900 m (1640.42 – 6233.60 ft) (CABI, 2021, *Acer pseudoplatanus (sycamore)*)			
Acer tataricum	500 – 1700 m (1640.42 – 5577.43 ft) (Fern, 2016, *Acer tataricum*)			
Acer trautvetteri	900 – 2200 m (2952.76 – 7217.85 ft) (Crowley, 2020)			
Fraxinus excelsior	0 – 1800 m (0 – 5905.51 ft) (Khela & Oldfield, 2018)			
Fagus orientalis	200 – 2200 m (656.17 – 7217.85 ft) (Rivers & Barstow, 2017)			
Betula pendula	500 – 3050 m (1640.42 – 10006.56 ft) (Stritch et al., 2014)			
Betula litwinowii	1800 – 2300 m (5905.51 – 7545.93 ft) (Akhalkatsi et al., 2018)			

The subspecies of trees that will be grown within the greenhouse can withstand an average minimum temperature of -31.95 °C (-5.51 °F) with an optimal growth temperature between 12 – 20 °C (53.6 – 68 °F) (CABI, 2021; FAO, n.d.). A comparison of the ideal growing temperature conditions with those common for the regions in which the greenhouse will be used

(Table 4) shows that the average minimum temperature withstood by the trees will not be exceeded, but the ideal growing temperature is not provided year-long. The ideal growth temperature is only achieved in the summer months, meaning that the greenhouse must compensate for the weather fluctuations that exist throughout the rest of the year.

Temperature regulation within the greenhouse can be aided through greenhouse material selection based on optimal thermal properties. A biogas system can also be used as a secondary source of heat for the regulation of the greenhouse's internal temperature. The implementation of a biogas system in conjunction with the greenhouse is discussed in more detail in Objective 4. According to the temperatures in the regions of interest, the greenhouse will have to account for a maximum temperature difference of approximately 24.8 °C (44.64 °F) in order to provide an average optimal growth temperature of 16 °C (60.8 °F) in the greenhouse. This is because the average lowest temperature outside the greenhouse will be -8.8 °C (16.16 °F).

Table 4: Temperature Conditions within Backyard Nursery Program Regions

Village	Average Winter Temperature	Average Annual Temperature	Average Summer Temperature	Source
Aghavnavank	-6 °C (21.2 °F)	9 – 12 °C (48.2 – 53.6 °F)	22 °C (71.6 °F)	(Vardanyan, 2016; Hudson Institute of Mineralogy, 2021)
Margahovit	-6.17 °C (20.89 °F)	0.5 – 9.25 °C (32.9 – 48.65 °F)	15 °C (59 °F)	(Weather WX, 2021)
Keti	-7.9 – -8.8 °C (17.78 – 16.16 °F)	2.2 – 5.6 °C (35.96 – 42.08 °F)	14.6 – 17.5 °C (58.28 – 63.5 °F)	(Ghazaryan et al., 2018)

Water availability is especially important because although seedlings may be able to survive short periods of dryness, they grow best in moist soil. The average rainfall of the greenhouse adoption regions is not adequate for maintaining ideal moisture levels, and thus irrigation must be considered. Regions that can support plant growth year-round are considered tropical and have an annual rainfall amount of 175 – 250 cm (65 – 100 in) (NASA, n.d.). The regions of interest are classified as semi-humid and semi-arid with an annual rainfall amount ranging between 135 – 700 mm (5.31 – 27.56 in) (Ghazaryan et al., 2018; Weather WX, 2021; Vardanyan, 2016). Most of the annual rainfall in Armenia occurs during the rainy season from April to October, meaning that during these months there may be sufficient water supply for the seedlings. However, this is not true year-round, which is why alternative sources of water for seedling irrigation are necessary to supplement the lack of adequate rainfall as will be discussed in the recommendations.

Another component for consideration is the availability of CO_2. In an outdoor environment, seedlings receive appropriate amounts of CO_2 while off-putting oxygen, but a greenhouse enclosure cuts off the natural air circulation needed for this cycle. The concentration of CO_2 naturally occurring in the outside air is around 340 parts per million (ppm) which is sufficient to support quality plant growth (Blom et al., 2016). An increase in CO_2 directly correlates to increased sugars and carbohydrates for plant growth. In an enclosed greenhouse environment, it has been proven that increasing the CO_2 concentration to 1,000 – 1,300 ppm increases the rate at which photosynthesis takes place in plants (Blom et al., 2016). A biogas system (see Objective 4) can be used to provide this optimal concentration of CO_2. This CO_2 concentration increase assumes that there is adequate light being applied to the seedlings within the greenhouse. This 1,000 – 1,300 ppm ideal CO_2 level is considered to be a plant's saturation point and therefore higher levels will not have added benefits. However, exceeding the ideal level would result in the slowing of photosynthesis, and at 10,000 ppm the photosynthetic rate will be zero. This occurs because the pores in plants close and there is an exclusion of air into the leaf, which ultimately leads to plant death (Manitoba, n.d.). Also, the ideal CO_2 concentration is only applicable for a greenhouse that is entirely separate from the outside air. In the case that the greenhouse is open for ventilation, the CO_2 should be supplemented to a level within the range of 400 – 600 ppm (Blom et al., 2016). Overall, the level of CO_2 within the greenhouse should not go below 340 ppm as this will have strong negative impacts on the photosynthesis rates of the seedlings.

Sunlight is another limiting factor in seedlings' ability to reach maximum growth. The target tree species are shade tolerant, which means that they can grow under low light conditions as well as full sun. Full sun can be classified as the seedling being in direct sunlight for six or more hours a day, while partial shade means that the seedling would get around two hours of direct sunlight per day. As the length of daylight hours changes throughout the year, ranging between 9 and 15 hours, the seedlings having a characteristic of being shade intolerant is a benefit during winter days when the daylight hours are shorter. When seedlings grow in nature, they are often shaded by the canopy of the existing trees. Therefore, exposing the seedlings growing in greenhouses to a range of sunlight conditions early on will prepare them for the conditions that will exist when they are transplanted into the forest.

Objective 2: Determination of feasible greenhouse structures

The determination of a feasible greenhouse structure for ATP's Backyard Nursery Program is pertinent for successful seedling growth and program participation. The shape and orientation of the greenhouse affects the temperature in the greenhouse as solar radiation is reflected from the ground and roof of the greenhouse (Sethi, 2008). An overall consideration when looking at the temperature within the greenhouse is that an enclosed environment traps humidity. This indoor humidity level must be controlled as it can create a refuge for pests and can result in disease among the plants. As the focus was on the greenhouse design, openings in the greenhouse structure were minimized as they present a method for pest infiltration and zones for heat loss. To control the humidity level within the greenhouse, ventilation was incorporated, which lowers the threat of disease. Warm air with a higher level of moisture escapes from the greenhouse when ventilation occurs and is replaced with cooler air that has a lower relative humidity. As the ventilation creates a cooler environment within the greenhouse, it must be used in conjunction with heating in order to reach an equilibrium of temperature that is optimal (according to Objective 1) and that will ensure proper seedling growth (University of Massachusetts Amherst, 2015).

There are multiple designs that are commonly used for greenhouses. These designs can range in size from walk-in to non-walk-in structures that are smaller in scale. There are three walk-in greenhouses, and they are called lean-tos, post and rafter structures, and high tunnels or Quonsets.

The lean-to greenhouse is a structure with a single sloped roof and three walls that are attached to an existing building (Garden and Greenhouse, 2018). The front wall is usually longer in length compared to the other two side walls. Since the lean-to is placed against an existing building with a shared back wall, it is likely to have better insulation and heat retention due to the material and thickness of the wall. As this greenhouse shares a wall with a house that uses heating in the winter, some of the heating may indirectly transmit through the shared wall and heat the greenhouse. Since the lean-to structure is placed closer to the home, it makes maintenance of the greenhouse much easier. This is because the seedling caretaker will not have to travel far during severe weather conditions. It may also be easier to configure the connection for water sources, electricity, or heat if these components are included in the greenhouse (Pennisi & Worley, 2006). Some flaws of the lean-to are its limited orientation and height due to its attachment to an existing building. In the context of the participants for the backyard nurseries program, the properties may not have available wall space facing south, which is the optimal overall orientation of the greenhouse as it allows the most sunlight to hit the seedlings. The unavailability of an optimal orientation would ultimately affect plant growth. The height of a house may also interfere with the ability to create a greenhouse with an optimal slope for the roofing (Garden and Greenhouse, 2018). A photograph of a lean-to structure is shown in Figure 3.

Figure 3: Lean-to Greenhouse Structure (adapted from SturdiBuilt, 2020)

The post and rafter greenhouse design is one of the strongest existing greenhouse structures due to its shape (Waterworth, 2020). Since it is an A-frame, it is a very sturdy design. The three structural elements that make up the post and rafter design are posts, rafters, and purlins. The posts are the vertical components that hold up the entire roof structure. The roof is then supported by angled rafters that are connected to the posts and sit parallel to each other. Sometimes, purlins that are horizontal structural elements and sit on top of the rafters are used to ensure the structural integrity of the design. The roof is connected at the top by a ridge. The setback to having all these elements is the amount of material being used. Since the goal is for this greenhouse to be low cost, we are avoiding the excess materials. A photograph of a post and rafter greenhouse is shown in Figure 4.

Figure 4: Post and Rafter Greenhouse (adapted from Cedar Built Greenhouses, n.d.)

The high tunnel structure, also known as a Quonset, is constructed from arched rafters and a plastic covering (Texas A&M Agrilife Extension, n.d.). There are various arch shapes including asymmetrical arc, gothic arc, or the semicircular arch that can be used for the high tunnel (Novagric, 2016). The asymmetrical arch has a point that is not in the center, which creates an uneven arch. The gothic arc has a point in the center of the structure making it evenly arched. We focused on the semicircular shape, which is a smooth arch that does not have a pointed roof, as it offers better rain deflection, a higher air volume for better air flow, and optimal light transmission (Novagric, 2016). However, wind is an issue for this structure as it is not the most stable. The thin plastic covering that is applied could easily be ripped off the structure in stormy conditions by strong winds. This could be mitigated by setting the arch elements closer to each other creating better support for the covering, however constructing this type of greenhouse on a larger scale could be time-consuming and would require more material. A photograph of a high tunnel is shown in Figure 5.

Figure 5: High Tunnel Greenhouse (adapted from FarmTek, 2021)

In order to minimize the amounts of materials used and the initial and operational costs of the greenhouse, we decided to investigate small-scale, non-walk-in greenhouse structures that correlate to the structures described above. These small-scale structures would be more cost effective since our sponsors explained that the seedlings will only be grown at most to a height of roughly 35 cm (1.15 ft). These small-scale greenhouse structures include the single-winged cold frame, double-winged cold frame, and low tunnel. The seedlings in these structures will be planted directly in the soil, which has benefits as discussed in Objective 1, meaning that an earth floor would be a component of the greenhouse design. Laying a concrete or cement foundation for greenhouse flooring would require more construction materials and pots for each individual seedling, which ultimately increases the overall price.

One option for a smaller-scale greenhouse design would be a single-winged cold frame. A cold frame is essentially a rectangular box enclosed by a sloped cover that can be lifted (Crezo, 2020). Since the cover is transparent, it allows sunlight to go through and heat the soil during the day. While speaking to a forestry and environmental engineer Vitaly Aoun, he stressed that the single-winged cold frame allows the trees to adapt to different amounts of sunlight throughout the day rather than direct sunlight all day. These lighting conditions can be compared to canopy conditions in forests, which make it easier for the trees to survive in forest conditions when transplanted. Compared to the lean-to greenhouse, the single-winged cold frame usually has a shorter height of approximately 0.914 m (3 ft), which means it requires less material to construct and has a smaller volume (Crezo, 2020). Due to its smaller volume, heating from the sun tends to happen more rapidly.

Since the smaller volume may lead to seedlings overheating on hotter and sunnier days, ventilation is a necessary component that needs to be implemented. There are automatic venting options and manual venting options for cold frames. For automatic venting there is a simple solution that involves the expansion of wax which causes the covering to open. This is a system where the cold frames "have a metal cylinder containing compressed wax that expands when heated. As the wax expands, it pushes a piston that opens the vent, letting in air from the outside. As the temperature cools the wax contracts and the spring closes the vent" (Enroth, 2020). This would be a simple and useful component to add when constructing a cold frame however it may limit the amount by which the covering is opened, making it hard to plant. The manual ventilation process would be opening the covering by hand and placing a supporting element under it to ensure it stays open.

There are usually four framing pieces that make up the base of a single-winged cold frame. In order to create the rectangle shape for the base, two pieces are usually cut longer, and two of them are cut shorter. These pieces are connected by L brackets. There are also framing pieces called furring strips that are thinner and lighter in weight that are attached to the covering for support (Pennisi, & Worley, 2006). There are usually ten furring strips per window covering. The furring strips that are placed on the front edge of the structure have a slight overhang, which would be used as a handle. There would also be a central furring strip placed along the center of the window covering to ensure that the material of the translucent covering does not cave in or crack during the process of expansion or contraction. This can happen in the winter, where the material shrinks and is more prone to cracking since the cold air makes it more brittle. This can also occur during the summer, as direct sunlight causes the material to get soft and overtime can droop in the middle and become concaved in shape. In both scenarios, without the middle furring strip the material can fall through the frame and crush the seedlings.

The number of windows depends on the length of the backside of the cold frame. The furring strip of the window frame is hinged to the back of the base frame. The number of hinges needed depends on the width of the covering. For the attachment of the covering to the window frame, a strong and weatherproof adhesive in the form of glue is usually applied (DIY Network, 2021). This is not the only option for attaching the covering to the framing, as it can also be screwed on, or slits can be created in the frame for the window to sit in rather than be placed on top. Both the furring strips and the window coverings are usually sized according to the dimensions of the slope and base framing. A photograph of a single winged cold frame is shown in Figure 6.

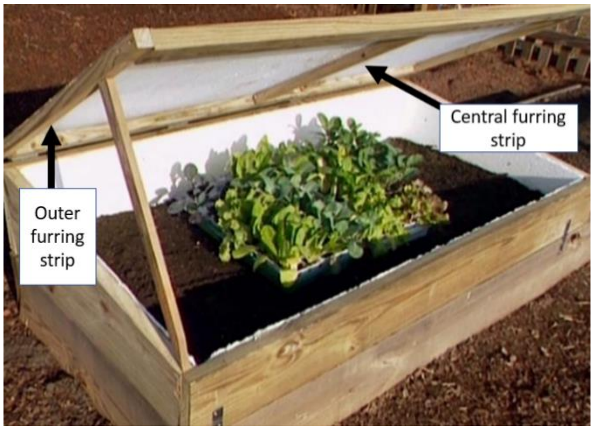

Figure 6: Single-Winged Cold Frame Structure (adapted from DIY Network, 2019)

Another cold frame design is the double-winged cold frame. This design is a smaller scale of the post and rafter design, as they have a similar triangular roof shape. Since this design is also a cold frame, it contains the same structural elements as the single-winged cold frame. However, since the double-winged cold frame requires more framing pieces and window coverings than the single-winged cold frame, more material will be required. Another issue this design may pose is cold air leaking through the windows in the colder months. Since this design would have two sides of windows, more heat could escape, thus making heat retention more challenging. However, in the summertime the higher ventilation area will aid in the minimization of overheating. Additionally, the use of more window space and base framing allows for more planting room for the seedlings. A photograph of a double-winged cold frame is shown in Figure 7.

The last small-scale structure for consideration was the low tunnel, which is a smaller version of a high tunnel. Similar to the high tunnels, light transmission is evenly balanced within a low tunnel design. This also allows for evenly distributed heat and airflow. According to Vitaly Aoun, this option is cost effective. However, it only lasts for about five years and is not as stable as the cold frame. For both high tunnel and low tunnel, in order to ensure that there is more stability within the structure, the hoops should be placed fewer than six feet apart and the connections between the covering and the skeleton of the structure should be fully secured (Enroth, 2020).

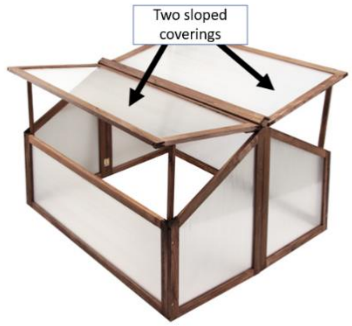

Figure 7: Double-Winged Cold Frame Greenhouse (adapted from Primerose.co.UK, 2016)

The low tunnel requires bent wire or pipe, which create hoops or the skeleton and a flexible plastic covering. The ends of the hoops are usually fastened in the ground on opposite sides of the growing area (DIY Network, 2015). They are also connected to the ridge that is the straight piece of unbent pipe that sits at the top of the arch. This would be placed at the highest point of the low tunnel while connecting the individual hoops together and keeping them in place (Proctor, 2021). Some designs have two additional ridges placed lower on both sides of the structure, which provide better structural integrity. The plastic covering is usually wrapped around the skeleton. The design also incorporates rails, which are metal pieces that sit on both sides of the greenhouse frame and latch on to the plastic covering during ventilation. The ventilation process can either be carried out in a roll up or a drop-down manner. The roll up process involves rolling up the plastic halfway from the bottom of the structure and attaching it to the rails and tubing with clips (University of Massachusetts Amherst, 2016). The drop-down process involves rolling down the plastic halfway from the top of the structure. Both processes could be done by hand or by a crank that rolls the material when the handle is turned (University of Massachusetts Amherst, 2016). A photograph of a low tunnel is shown in Figure 8.

Figure 8: Low Tunnel Greenhouse (adapted from Cathy, 2014)

Objective 3: Identification of local materials that are feasible for construction in Armenia

The identification of affordable and feasible materials for use in Armenia was completed based off a collection of material options which ranged in availability and cost. These materials were analyzed based on their use for the framing or covering of the greenhouse. Since materials within these families generally have the same material properties with the occasional deviation, feasibility for the greenhouse use was analyzed based on material groupings. Although we discuss specific materials that fall within these families, it can be assumed that any material within the same family would be a viable substitute. This will allow for a better chance in finding a cheaper material that can be locally sourced. These materials all cost varying amounts due to availability, supply, and demand.

Since pricing has such a significant role in the feasibility of greenhouse implementation and our project was focused on building multiple backyard greenhouses, the material prices were obtained from Alibaba for a general pricing comparison. This is a website that has materials available in bulk and for industrial use and is assumed to be accessible to Armenia. It should be recognized that the prices listed in this paper were obtained on the 19th of April 2021 and are subject to change at the time this paper is read, and do not include shipping and handling costs. We also used material properties to compare the material choices and to decide on which are the best for greenhouse use. The purpose of obtaining all the material properties was to choose the material that best suits the projects needs when compared with the other possible materials.

Environmental factors of wind, snow, and hail were taken into consideration for the material selection of the greenhouse. The greenhouse was designed to withstand the loading that these conditions will apply to it. The wind speed throughout the year ranges from 6.92 – 11.10 kph (4.3 – 6.9 mph) (Dieble et al., n.d.). During winter, when the temperature drops, there tends to be on average 5.08 mm (0.2 in) of snowfall with an upper limit of 17.78 mm (0.7 in). This is a relatively small amount of snowfall and therefore does not apply a substantial load onto the greenhouse structure. Hail is of severe concern when it exceeds a size of 25.4 mm (1 in). A severe hailstorm only occurs approximately once every three to four years, during which they apply a loading of 80 – 90 kg (176.37 – 198.42 lbs) when they fall onto objects (Arakelyan, 2018). Since severe hailstorms are rather rare, we did not take into consideration the load that severe hail will place upon the greenhouse, but rather we focused on it providing a basic barrier between the hail and seedlings.

Greenhouse Framing Materials

There were seven different materials that were considered for greenhouse framing use: cedar wood, stainless steel, flexible steel wire, aluminum, PVC pipe, polyethylene pipe, and cellulose acetate, which were compared based on material durability and thermal properties. These materials and their properties can be seen in Table A of Appendix A.

A material's durability is its ability to withstand elevated levels of stress. This can include its ability to handle additional weight, debris falling on it, and harsh weather conditions. This is important as it ensures the material will last a longer time with minor damage. Material durability is determined from the density, yield strength, fatigue strength, and fracture toughness. Density, defined as "mass per unit volume" (GrantaEDU, 2020), indicates how heavy a material is and can indicate its ability to withstand wind without being moved by it. This weight can also dictate the need for a stronger foundation; because if the materials are very heavy, they can sink into the ground over time and decrease the overall height of the greenhouse. This can create gaps between the greenhouse and the ground, increasing the amount of heat loss and effectiveness of the greenhouse. A material with a high yield strength, fatigue strength, and fracture toughness indicates durability when exposed to stress placed upon the greenhouse by loading or extreme weather conditions such as heavy rain and wind. Yield strength can be defined as the stress at which irreversible damage occurs to a material under a loading while fatigue strength dictates the highest stress point the material can be cyclically exposed to without breakage. Fracture toughness is the "resistance of a material to the propagation of a crack" that may be caused by severe weather (GrantaEDU, 2020).

In our context, thermal properties are a material's ability to retain heat inside the greenhouse with little escaping back into the external environment. Material thermal capabilities were rated based on thermal conductivity and specific heat capacity values. Thermal conductivity is the "rate heat is conducted through a solid at a steady state" (GrantaEDU, 2020). Specific heat capacity is the energy it takes to heat one unit of a material by a certain amount (GrantaEDU, 2020). These properties tell us how fast a greenhouse will heat up during the day, and how well the heat will be retained inside the structure during colder temperatures such as at night and in winter months. It is important that a greenhouse keep in heat since the subzero months in Armenia could span from November to end of April, and seedlings should not be exposed to below freezing temperature as this will result in their death.

Wood materials are the cheapest and some types are naturally rot resistant and can support the weight of most covering materials. The best material option for the greenhouse within the wood family is soft cedar wood. This material is appropriate for outdoor use due to its high rot threshold when compared to other wood options. Rot threshold applies solely to wood, as other materials like metal rust while plastic degrades. Its lower yield strength is a downfall of this material, but it is outweighed by the benefit of being low in cost. Soft cedar wood is the cheapest material option, as seen in Table 5, making it the most feasible. If cedar is not available, it can be substituted by other types of wood as long as they undergo treatment for rot prevention. This treatment, such as paint, is added to protect against the materials increased probability of rot when it is exposed to wet weather conditions such as rain, snow, and humidity. This is a simple addition to the material, as it is a low-cost process.

Table 5: Framing Material Descriptions and Prices (Alibaba, 2021)

Materials	**Size / Description**	**Price**
Soft cedar wood	95 x 12 x 2100 mm (3.74 x 0.47 x 82.7 in)	\$0.75 – \$0.76 a meter
Y-shaped stainless steel fence posts	0.8 – 7.5 m (31.5 – 295.3 in) long and 2 – 3 mm (0.08 – 0.12 in) thick	\$1.30 – \$3.70 a piece
L-shaped aluminum profile posts	5.8 m (3.3 ft) long and have a powder coat surface treatment	\$2.25 a kilogram
Galvanized steel wire	5 mm diameter, high carbon steel wire, comes in 300-meter rolls, has zinc coating	\$38 a roll
Cellulose Acetate	4 x 8 feet acrylic plastic sheet	\$1.60 - \$2.18 a piece
U Polyvinyl Chloride (UPVC) pipe		\$0.40 – \$1 per square meter
Polyethylene tubing	1/16" - ½"	\$0.125-\$1.25 per square meter

In general, materials that are part of the metal family are dense, corrosion resistant, and good conductors. Corrosion resistance indicates if the material would corrode or decompose over time when exposed to water, such rain or humidity and can decrease longevity. Metals are also able to support heavier covering materials. The specific metals that were analyzed for the greenhouse were aluminum, stainless steel, and galvanized high carbon steel wire.

Aluminums have a good tensile strength, yield strength, and fracture toughness, making them a good fit for a greenhouse. The setbacks lay in the high price range (Table 5) and the fact that they do not fare well in acidic soil (peat). Since Armenia can have acidic soil as shown in the village of Aghavnavank, and we are using an earth flooring, there would not be a contact barrier between the frame and the ground which makes this an unviable option.

Stainless steel requires a paint treatment or powder coating prior to use to decrease corrosion and increase longevity. It also has a high price point as seen in Table 5. Stainless steel posts require more labor to bend and are the most difficult framing materials to weld. This would make putting holes and screws in a frame that requires steel pieces to be connected to one another a daunting, costly task.

Galvanized high carbon steel wire is affordable (Table 5), flexible and can behave well under stress without breaking or shape shifting as it has a high density, yield strength, fracture strength, and tensile strength. This material is also durable in both alkaline and acidic soil, which was an important factor discussed in Objective 1, making it a desirable choice for a greenhouse that will have a soil foundation. This is because it comes with an added zinc coating which protects the metal from corrosion.

Materials from the plastics family, including polyvinyl chloride (PVC) piping, polyethylene piping, and cellulose acetate (resin) were considered for the greenhouse framing as they are ideal for use in conjunction with lighter weight covering materials. One important characteristic of these materials is their low thermal conductivity, which indicates that they are good insulators. Plastics are also very versatile, and some are inexpensive. Another advantage of these materials is that they have durability when exposed to water. This means they have a higher resistivity to moisture such as rain and humidity build up in the enclosed environment. They even have a satisfactory level of durability against UV radiation, increasing their longevity. Although these materials do well in UV radiation and fresh water, it is best to add a protective coat onto them. This protection can decrease material ageing and increase its life span. These materials are also all available in colors and transparencies that let at least 70 % of light pass through them, and do not absorb much heat. This is beneficial as it allows light into the greenhouse, heating it up, but will make ventilation a requirement as discussed in Objective 2 in order to offset the chance that the saplings will overheat.

In terms of pricing for the plastics, cellulose acetate was much more expensive than PVC and polyethylene piping, as seen in Table 5. Cellulose acetate and PVC piping also had the second lowest thermal conductivity of these materials, which adds to its ability to keep heat in well. Meanwhile, polyethylene piping had the highest heat capacity, letting out heat far too much to be used in winter weather. Another benefit PVC pipe holds over polyethylene pipe is that its yield strength, tensile strength, fracture toughness, and fracture strength are higher.

In conclusion, for the low tunnel greenhouse that uses lighter cover materials, there were three materials examined for framing. The materials decided against were polyethylene pipe and

PVC pipe. Polyethylene was much less durable, and although PVC piping was a good low-cost option, it is harder to shape it into the semicircular structure of a low tunnel. The most ideal material for this structure was flexible steel. This material was the most ideal option as it had the highest durability out of all materials in this section and is the cheapest choice. This material also only had a few non-crucial negatives for framing, such as not letting light pass through and releasing heat at a quicker rate.

For the cold frame, there were four framing materials examined: cellulose acetate, aluminum, steel, and wood. Cellulose acetate was far more expensive than the other materials and its benefits did not outweigh the costs. It also could not withstand being in contact with acidic or alkaline soil for extended periods of time. Aluminum also does not fare well in acidic soil, making it less ideal for a greenhouse that has an earth floor. Steel was commonly used for hinges and screws, but outside of this use was not a material used for this type of framing. Making a frame out of steel would also be very costly. Wood was selected as the best option for the framing of this structure as it had the lowest cost, was the most used material for this structure, and is abundant, making it easily available in all locations.

Greenhouse Covering Material

The second component of a greenhouse is the covering. This is the clear part of the greenhouse that creates a barrier between internal and external environment. Six different cover materials were considered: soda lime glass, polycarbonate, polyethylene terephthalate (PET), GFRF epoxy matrix (isotropic), polymethyl methacrylate (PMMA), and polyvinyl chloride (PVC). These materials were compared based off thermal and durability properties as well as transparency (See Table B of Appendix A). These were divided into three material types: glass, plastic, and epoxy resin.

These materials were analyzed using the properties that helped determine thermal and durability capabilities for framing. One important factor for greenhouse coverings was price, followed by transparency, which is an optical property. Transparency can be defined based on three different types of light diffusion. One is reflectivity, which is the amount of light that gets reflected by a material. Another type is absorptivity, which is the amount of light that gets absorbed by the material and converted into internal heat. Lastly, there is transmittance, which is the amount of light that gets into the greenhouse, is absorbed by the earth, and supplies most of the heat generated inside the closed structure. Ideally, a greenhouse covering material must have a transmittance of 70% or higher, otherwise there will not be enough heat and light to provide plants with the ideal growing temperature. The materials that are used for the covering of the greenhouse were designed to maximize transmittance of sunlight onto the seedlings that are growing within. Thus, all covering materials examined reached the minimum light transmittance threshold.

Soda lime glass was the material used to determine the feasibility of glass use in the greenhouse. This material was the most expensive, as seen in Table 6. However, the material is transparent, which allows light to enter the greenhouse. The few benefits of this material are outweighed by the number of downfalls, such as low yield strength, low fracture toughness, and being a poor insulator. These indicate that the materials are more prone to bending and cracking, and that cracks that form will spread rapidly indicating need for frequent replacement. Glass in general is also a poor insulator, adding to its inability to keep in heat, which can jeopardize plant health in colder months. Adding to this, the material has the highest thermal conductivity, which makes heat move in and out of the greenhouse at a faster rate. Due to this material's poor insulation ability, low fracture toughness, and high thermal capacity, it is not an ideal material for the greenhouse.

Table 6: Covering Material Descriptions and Prices (Alibaba, 2021)

Material	**Size/ Description**	**Price**
Soda lime glass	2 – 20 mm (0.08 – 0.79 in) thick	$20 – $200 a square meter
PVC film	0.12 – 0.30 mm (0.005 – 0.012 in) thick	$0.75 a square meter
PET film		$2.30 – $2.80 a square meter ($0.21 - $0.26 a square foot
Twin wall polycarbonate		$2.50 – $4 per square meter ($0.23 – $0.37 per square foot)
GFRF Epoxy matrix		$33.73 - $36.60 per kilogram ($15.30 – $16.60 per pound)

The materials belonging to the plastic family that were examined included polycarbonate, PET, PVC, and PMMA. This material family is generally cheaper than epoxy matrix and glass (Table 6). All four of these materials also have a yield and tensile strength that allows the material to stay in good condition without bending or breaking, decreasing the probability of material deformation or breakage due to additional stress such as added weight from snow or rain. Polycarbonate has an advantage over the other plastic options because it has higher yield strength as well as a low-price range. These plastics did have lower values for fracture toughness, but this is less of a concern since plastics can handle a lot of weight before cracking. PVC had slightly lower fracture toughness: however, the difference was not big enough to impact material selection as it was also very affordable. Although the fatigue strength for plastics is on the lower side, it is not a concern. Plastic is also a good insulator and has a low heat capacity, allowing it to retain heat well with little heat loss during sundown and colder temperatures, which is common in the Armenian climate.

The specific type of epoxy resin that we explored material properties for was GFRF epoxy matrix. This material was the most expensive, as shown in Table 6, making it the least ideal material for coverings. Although the yield strength, tensile strength, and fracture toughness for epoxy matrix is the highest of all covering materials, plastics were considered more ideal due to their cost effectiveness. Thus, having higher values for the durability properties does not add much value to this material. Additionally, this material has a higher thermal conductivity than the other materials which we are considering. Its thermal conductivity is also the second highest of all the six covering materials that we considered. Although it is translucent, letting in most light, that alone does not make the material a good fit for greenhouse building.

Out of the six greenhouse covering options that were considered, soda lime glass was not a good option as it is most susceptible to cracking and breaking, thus indicating the need for often material replacement. GFRF epoxy matrix was also not a good option for greenhouses, due to the exceedingly high price and poor insulation capabilities. The best materials options for low tunnel coverings were PET and PVC plastic, due to their sufficient values for all material properties, holding in heat well, and having a low price. They are also light weight and flexible, allowing for easy application to rounded structures.

For a cold frame, the plastic polycarbonate sheet is the best material option for the covering, due to it having a high durability and ability to transmit 70% of light into the greenhouse. The most commonly used plastic for this type of greenhouse is a polycarbonate sheet, which is a thick material that does not bend when weight is placed on top of it. As for a low tunnel, the most ideal material is a plastic film which is less than a millimeter in thickness and bends easily, which is commonly made of PET or PVC plastic.

Objective 4: Identification of biogas system for a small-scale greenhouse

We conducted an interview with Alen Amirkhanian, the director of the AUA Acopian Center for the Environment, who provided us with an understanding for the desired complexity of, and direction for, the implementation of a biogas digester in conjunction with our greenhouse design. He explained that the most common biogas digester for research is rudimentary in design and easy to maintain. He also explained how the focus is not on building a biogas digester but directing its emissions into the greenhouse, which is a novel concept. Additionally, he spoke about the fuel types that are utilized in biogas digesters. We learned that each participant would have different types of waste available for use, but in general, cow manure would be the most abundant in the specific areas in which we are working. When we asked about other means of greenhouse heating, such as geothermal, natural gas, and solar power, he explained that these are out of the scope of this project and led us to decide against their implementation. However, he urged us to explore methods that can be used for the biogas digester to combat weather fluctuations that will hamper the speed of biogas production. We did this by looking at ways to keep the biogas digester's tank at a steady temperature year-round through insulation.

A biogas digester is a system where organic materials are broken down and made into biogas. The biogas can then be combusted for use as a renewable energy source. The input for a biogas digester is slurry, which is composed of equal parts of manure and water. The output of a biogas digester is primarily biogas, but also produces fertilizer that is odorless and rich in nitrogen. As the biogas creates pressure in the main tank through the buildup of gas at the top, it pushes the slurry up and out of the opening, creating the fertilizer output. However, not all spent slurry exits as fertilizer and some spent slurry sinks to the bottoms of the digester, where it takes up space and limits the capacity of the digester over time (see Figure 9). These spent solids need to be manually cleaned out periodically. For the sizing of the main chamber, it should be 0.9 m^3 (30 ft^3) for every cow that manure is collected from. This is the most efficient ratio as it gives enough volume to break down the organic materials while remaining compact enough to save on material costs.

Biogas digesters come in two categories of designs, being either above-ground or below-ground. All biogas digesters function by using the same organic waste breakdown mechanism. However, there are slight variations that determine whether an above or below ground system would be the most appropriate depending on the scenario.

The below-ground style digester is commonly a cylindrical tank that is wider than it is tall. This tank is buried fully into the ground, so the soil completely covers the top of digester. This design can also be partially buried, but at the loss of full-weather protection and insulation. There are three openings in the tank, two of which are located on opposite sides. The first is for the input of the slurry, and the second is used to remove the spent slurry. The last opening is located at the top of the tank and releases the biogas, as seen in Figure 9. The benefit of having the digester fully buried is that the digester keeps its internal temperature steady all year long. As stated in Objective 1, we want the trees to receive direct sunlight, and with the below-ground design there is less added shade in the participants' yards. Another drawback is that it requires a lot of digging and depending on the size of the digester it can be buried by the owner with a shovel. A larger digester however will run into the risk of hitting harder stones that need special tools to remove. The need for special tools will increase the cost of labor.

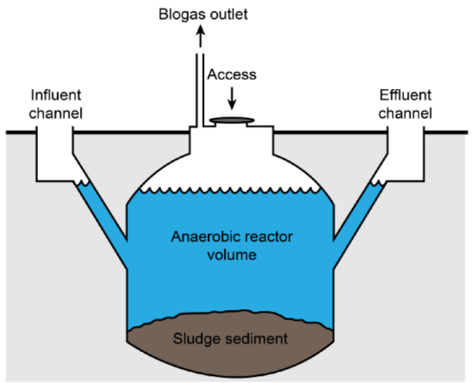

Figure 9: Below-ground Digester Cross Section Diagram (Rennuit & Sommer, 2013)

The other design is an above-ground silo design that is placed on the top of the ground and has a vertical cylinder design, as seen in Figure 10. This design has the same three openings as the underground digester. The benefits of the silo design address the downfalls of the underground design, as it requires no digging and is easy to clean. The drawback with this design is that it protrudes from the ground which may cast shadows and limits sunlight on the seedlings while also not being insulated as well. To counter the drawback of the lack of insulation, a second steel casing can be added with a slight gap from the outer casing of the tank. This gap can be filled with sawdust, which acts as a cheap and effective insulator to keep the heat inside the digester even in the colder months. As for the drawback of creating shade it can be countered by positioning the digester on the northside of the greenhouse as optimal sunlight is received from the south.

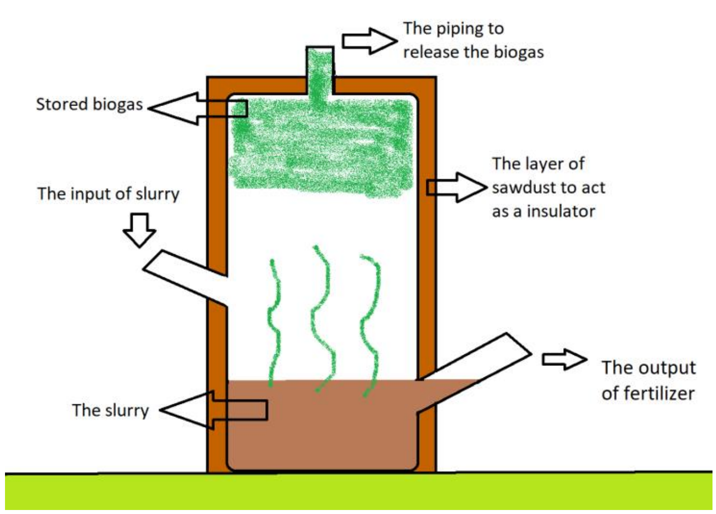

Figure 10: Silo Style Cross Section Digester Diagram.

Both designs use the same piping system to transport the outputted biogas to the greenhouse, as shown in Figure 11. The opening of the tank allows for the release of biogas through the turning of a valve. This allows the gas to then travel through a U-shaped pipe stuffed with steel wool leading to the combustion chamber. Several sets of steel wool can be alternated every 16 weeks to keep the steel wool fresh, allowing it to continue removing sulfur without eroding. When alternating the steel wool, the spent steel wool is often hung up in open air with protection from rain. This allows it to release the sulfur and then it can be reused and function at the same efficiency as it did when new (Villanueva & Magomnang, 2015). Standard household grade steel wool can be purchased for around $10.48 per 2.2 kg (4.85 lbs.) rolls (Alibaba, 2021). In order to remove sulfur from the gas there is a need for 1.9 kg (4.19 lbs.) of steel wool within the piping. The sulfur is caught to avoid corrosion in the pipes and in the combustion chamber (Villanueva & Magomnang, 2015). The U-shape of the pipe, pressure buildup of the biogas, and the biogas' low-density allows the biogas to travel to the combustion chamber.

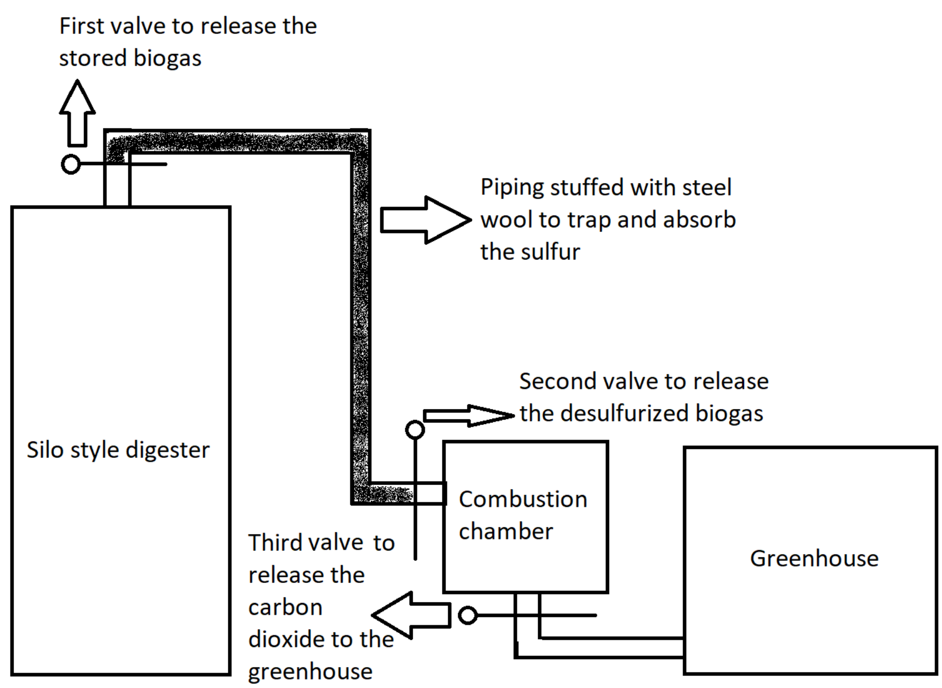

Figure 11: Breakdown of the Transportation of the Biogas

Once the gas has traveled through the piping, it is let into the combustion chamber, which is a heat resistant chamber where the gas can be safely burned and converted into CO_2. The gas is burned using a flint starter located at the bottom of the chamber, which can be activated manually from a switch. A ventilation mechanism is needed on the side of the combustion chamber in the form of a sealable opening. This mechanism can be opened or sealed using valves and provides oxygen into the combustion chamber to ensure the combustion yields CO_2 and not carbon monoxide (CO). CO isn't harmful to the plants as they can just oxidize it to make CO_2, but that is an extra step that would reduce the efficiency of the biogas system. From online tables on combusting various gases, we found that for every kilogram of methane burned 2.75 kg (6.06 lbs.) of CO_2 is released (Engineer's toolbox, 2009). The equation for the combustion of methane is $CH_4 + 2O_2 = CO_2 + 2H_2O$, with the two water molecules at the end being the humidity in the gas. The CO_2 produced in the combustion chamber flows down a pipe, which is attached to the bottom of the combustion chamber. The combustion chamber is located closest to the greenhouse and is slightly higher in elevation to allow for the downward sloping of the piping. The input of biogas is closer to the top of the combustion chamber and the output of CO_2 is at the bottom of the combustion chamber. The output pipe is positioned in this location because CO_2 is denser than oxygen and will sink to the bottom of the chamber when produced.

To connect the biogas digester to the greenhouse, a hole will need to be cut into the greenhouse for the pipe to let the CO_2 flow from the combustion chamber. A biogas digester will be more difficult to implement with the low tunnel design as it is harder to make the walls of the low tunnel be airtight around the piping as they are composed of a thin, flimsy plastic sheet. This plastic sheet would also be unable to support the piping meaning it would have to be laid directly on the ground, which creates a higher chance of corrosion as leftover sulfur may combine with water on the ground. If the piping is raised to avoid the corrosion, then additional materials will be needed to support the raised piping. As for the cold frame designs, the rigid walls make the biogas more feasible to implement. The piping from the combustion chamber can connect through a hole in the bottom by the taller side of the cold frame. The hole will only need to be just slightly bigger than the pipe to allow it to fit in place without losing too much CO_2. An insulating sealant will be put around the hole and piping to form a tighter seal reducing the amount of heat and CO_2 escaping. However, this process still brings up problems such as increasing the wood's chance of splitting when being cut or drilled into for creation of a connection hole for the piping. A thermal bridge is also created in the design, which makes the greenhouse less insulated during the colder months. A thermal bridge is where a material with high thermal conductivity is place in a material with low thermal conductivity reducing the effectiveness of the structure’s ability to keep a steady temperature, which causes heat loss from the greenhouse during the winter months.

In order to operate this system, it is suggested that a series of three valves be installed in order to control each step of the carbon dioxide delivery to the greenhouse. During clear days when the sun is out and there is only a small presence of clouds, CO_2 needs to be added to the greenhouse, in which case the first valve should be turned, releasing the required amount of biogas. The amount of biogas required will depend on the amount of direct sunlight the plants are getting and whether the greenhouse is being ventilated as stated in Objective 1, as these factors will reduce the amount of CO_2 supplementation needed. During ventilation, the required amount of CO_2 is less because there is a direct air exchange with the outside environment, which has adequate CO_2 concentration to support plant growth as mentioned in Objective 1. While the first valve is opened biogas will be flowing through the piping with the steel wool inside taking the sulfur out. After the desired amount of biogas is released, the first valve should be closed to prevent more gas from coming through.

Then the second valve should be opened, letting the biogas into the combustion chamber. After a few seconds, which should give enough time for biogas to enter the chamber, the igniting switch for the flint starter should be activated. This ultimately combusts the stored gas. The valve at the bottom of the chamber should then be turned to let the CO_2 into the pipe which leads directly to the greenhouse. After a few seconds the combustion chamber door should be opened to let oxygen back into the chamber as well as assist in moving out the last of the CO_2 into the greenhouse. Lastly the valve leading into the greenhouse should be turned off and the combustion chamber door should be closed. This will bring the system back to its initial state with all valves closed. The valves must be operated in this individual sequence to minimize the risk of the digester exploding. The timing that each valve remains open for will be discussed in the future work section of the recommendations. The biogas digester is full of flammable gas that needs to be released in a controlled way to avoid the chance of a stray flame traveling through the piping igniting all the stored biogas.

Steel is the most used material for the construction of both types of biogas digesters since it is durable and has a high resistance to corrosion. While steel is the most common material used, any material with similar corrosion resistance when exposed to high sulfur levels and water can be used as a substitute. Corrosion can eat away the metal piping and form leaks in the system, so a material with high corrosion resistance is needed.

Slurry is the first thing added to the biogas digester, and due to its abundance, cow manure is the base we have chosen for the slurry. The first time a digester is used, extra bacteria are added into the tank to assist the breakdown of inserted organic materials. The bacteria added can be found in cheese or yogurt. The bacteria only need to be added one time as they are self-reproducing and continue to work so long as there is a steady input of slurry being added to the digester. As the bacteria replicate on their own, there is no specified starting amount. However, it is recommended to start with a small quantity, such as several grams, to avoid bacteria competing against one another for "food". The biogas from the volatile solids created by bacteria breaking down the organic compounds is composed of 60 % – 75% methane (EPA, 2021). The gas rises to the top of the tank as the digestion process goes on and builds up pressure. From here the gas will travel through the sequence described previously (See Figure 11). The retention time, which is the time period slurry remains in the chamber before being used up, is roughly 14 days, depending on digester size. Once the initial 14 days pass and as long as new slurry is added each day then biogas can be drawn from and used each day.

The most common type of cattle in Armenia are dairy cattle (Ministry of Economy of the Republic of Amenia, 2020). We found that the average dairy cow weighs 680 kg (1,500 lbs.) and produces roughly 57 kg (125 lbs.) of manure a day (Nicky Ellis, 2020). Dairy cow manure is made up of about 15 % solid material with the rest being liquid, and about 91 % of these solids are volatile. Volatile solids are the usable parts of a material that can be broken down into biogas. Thus, only 7.78 kg (17.15 lbs.) of manure per day are usable as fuel for biogas. From the volatile material, 20 % to 30 % turns into biogas. Over the course of the two-week retention time, 1.945 kg (4.29 lbs.) of CO_2 are produced after combustion for every cow's manure collected a day (See equation below for the breakdown).

$$57\text{ kg} \times 0.15 = 8.55\text{ kg}$$

$$8.55\text{ kg} \times 0.91 = 7.78\text{ kg}$$

$$7.78\text{ kg} \times 0.25 = 1.945\text{ kg}$$

The targeted concentration of CO_2 as stated in Objective 1 during a clear day is 1,000 ppm. In order to determine the mass of CO_2 needed in grams to achieve this level. The following equation can be used for the specified greenhouse according to its volume. Generally, for every 1 m^3 (35.3 ft^3) in volume of the greenhouse, you need to add 1 kg (35.27 oz) of CO_2. In these equations volume (V) of the greenhouse is in milliliters (ml), and the mass (M) of CO_2 is in grams (g).

$$PPM = (M/V) \times 10^6$$

$$1000 = (M/V) \times 10^6$$

$$0.001 \times V = M$$

Objective 1 also stated that the ideal CO_2 levels in the greenhouse will change from 340 ppm, the level of CO_2 outside, to 500 ppm during ventilation. This results in a variation in the equation from above, which is shown below. Generally, for every 1 m^3 (35.3 ft^3) of volume 0.2 kg (7.05 oz) of CO_2 are needed to be added.

$$PPM = ((M/V) \times 10^6) - PPM_{outside}$$

$$500 = ((M/V) \times 10^6) - 340$$

$$160 = (M/V) \times 10^6$$

$$0.00016 \times V = M$$

Lastly, at night or when the greenhouse is not in sunlight, there will be no need to add CO_2 since there will be no light available for the plant to use in order to go through photosynthesis. These calculations are just a rough guideline for how much CO_2 to add into the greenhouse at a time. This is because we do not yet have a way to measure the amount of CO_2 being added into the greenhouse at a time.

Recommendations

We examined the growing needs of tree seedlings, appropriate structures and materials for greenhouse construction, and a method by which plant growth can be stimulated with carbon dioxide supplementation. Here, we introduce several recommendations for our sponsors. By making these recommendations we hope that it will provide ATP and AUA Acopian Center for the Environment the foundational knowledge for expansion and the implementation of a greenhouse with an external biogas digester system.

Based on our research, we are recommending a single-winged cold frame over a double-winged cold frame because it requires less material, which makes it more cost effective. If the resources needed for a single-winged cold fame are not available, then the structure can be substituted with a low tunnel greenhouse structure. A single-winged cold frame is also beneficial as it exposes the seedlings to varying degrees of light intensity throughout the day. As described in Objective 1, we are growing shade-tolerant tree species and varying light intensities will still promote growth while also preparing them for sunlight condition in the forest.

For the framing of the cold frame structure, it is recommended that it be composed of wood. The main deciding factor for using wood was the price, as this was the cheapest framing material option according to Objective 3. Since wood is abundant in our project locations, it is easily obtainable for construction. We do recommend that if the wood being used is not redwood cedar, a protective paint coat should be applied before utilization. This makes the wood rot-resistant and increases its longevity. We recommend that this greenhouse be constructed in accordance with the structural aspects outlined in Objective 2. The structure will require two long and two short framing pieces, with an angled top. As this is the usual process for creating the slope for the covering, we recommend that the angle for the top be created with a decreasing height from the wall that contains the hinges for the roof and the one opposite. The height difference should be determined based on the width of the greenhouse; a 2.5 cm (1 inch) drop in height corresponds to a 30 cm (1 foot) width (DIY Network, 2021).

For the covering material of the angled roof, we recommend a polycarbonate sheet or any other transparent plastic sheet that allows at least 70 % of light to pass through. Polycarbonate is the desired material as it has a low price, is very durable, and has a low probability of bending or breaking if there is additional stress placed on it. It is also a good insulator and allows heat to be retained inside the structure minimizing heat loss, making it very beneficial for the colder months spanning from November to late April in the potential project sites.

In addition to the framing and covering materials, we suggest using four furring strips, which are small wood pieces, in order to create the window frame. This window frame is the connecting piece for the cover to the rest of the frame. For the hinges and screws that will be required to connect the window frame and base frame, we recommend using any type of metal, as it is commonly used for this structural component. These hinges and screws should have a paint or powder protective coat added to them, which will reduce corrosion and increase longevity. Most metals are durable enough for cold frames and can withstand additional stress created from the weight of holding together a furring strip and plastic cover to a wooden frame. These metals can also handle more cycles of stress than other materials, meaning that regardless of how many times this material is used to open and close the cover, it will remain fully functional. All these components can be visualized in Figures 12.

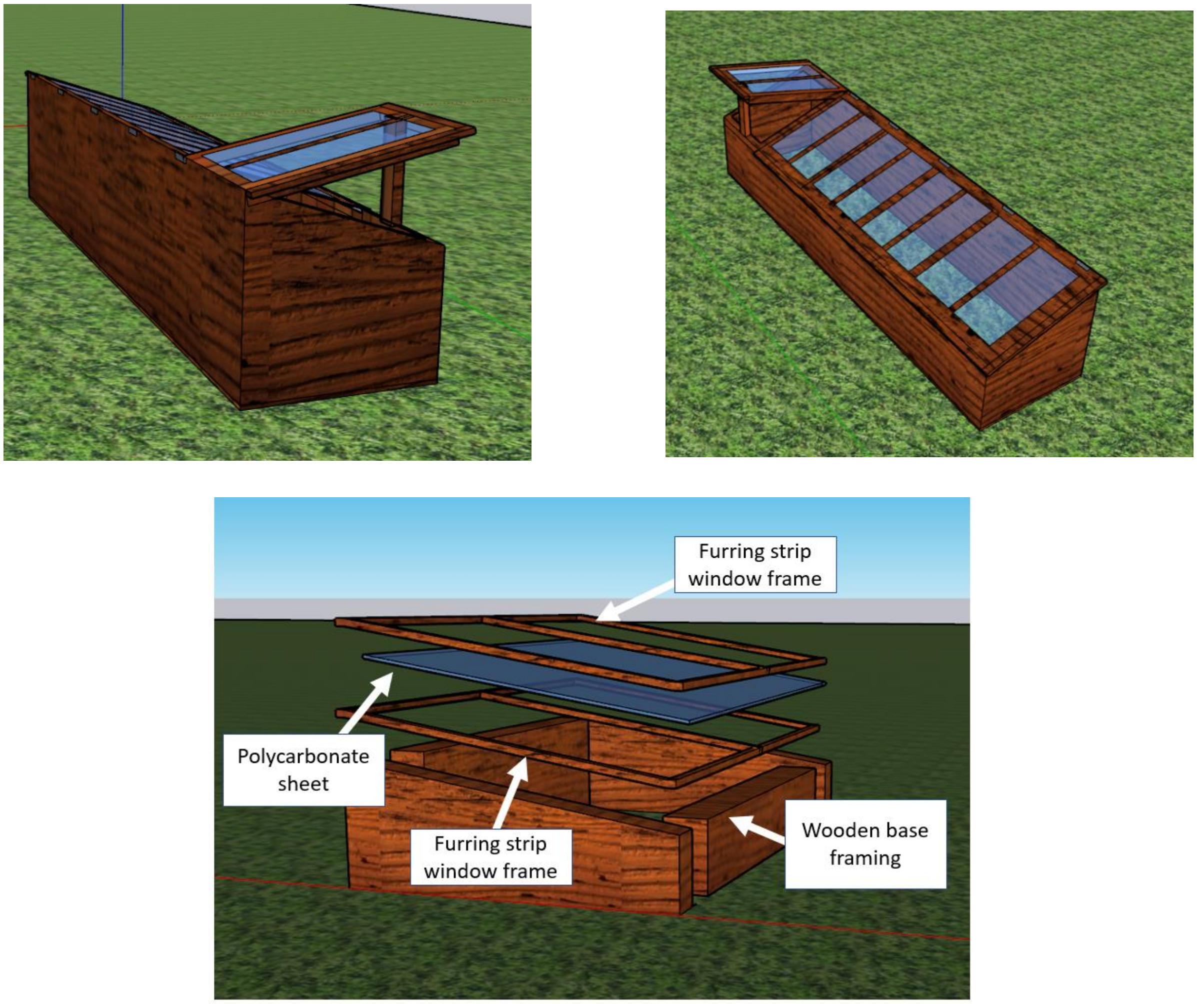

Figure 12: Isometric Views and Layering of Single-Winged Cold Frame

For the low tunnel greenhouse design, the structural composition is slightly different than the cold frames. The first structural component is a frame made of semicircular metal wires spaced evenly apart. This wire is not only cheap, but easily bendable. This brings down the labor cost, as there is no machinery required to achieve the desirable semi-circular shape and can be purchased in rolls. We also recommend that a powder or paint coat is added to the metal just like the one needed for hinges and screws, as it will increase its corrosion resistance. This is especially important for this structure as the metal makes contact with the ground which at times has a higher rate of moisture from rain or snow, increasing the probability of corrosion.

The second structural element of the low tunnel is a covering that is placed and secured on top of this frame, forming a tunnel-like enclosure. We recommend using a material that is either polyethylene terephthalate (PET) or polyvinyl chloride (PVC) film. The price was one of the main deciding factors for the material choice, as these were the two cheapest covering material options. The thickness of the material is also a benefit, as it makes it more durable and decreases its probability of being damaged or ripped if anything falls on the greenhouse. This flexible transparent film not only exceeds the transparency requirements previously mentioned, but also retains heat well. The flexibility of the material is also crucial for this structure, as the material must fit snugly around the wire framing to prevent gaps between the cover and the ground. This makes it highly effective at keeping heat in during the day, night, and colder months. The complete low tunnel structure can be visualized in Figure 13.

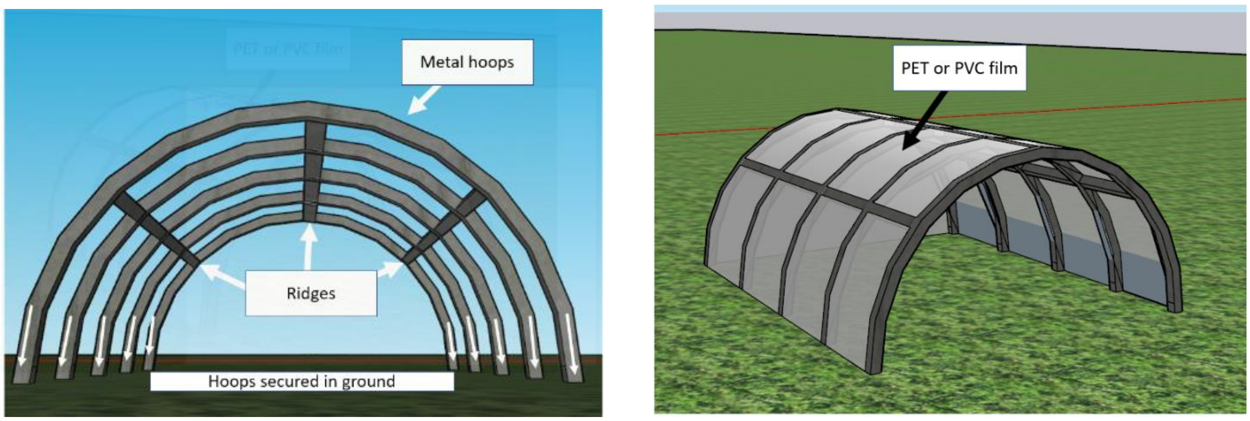

Figure 13: Isometric Views of Low Tunnel

In order to ensure that the greenhouse will receive optimal sunlight throughout the year, it is suggested that a sun path chart be used before installation of the greenhouse onto each site. This chart can provide analysis of the elevation of the sun everyday throughout the year (UNH, 2019). This elevation is used to analyze the shadows that are cast by any buildings, structures, or obstructions that are in the vicinity of the greenhouse. The greenhouse should be established in an area of the property that minimizes overlap with large shadows that will occur throughout the year. This will optimize the sunlight received by the seedlings within the greenhouse.

Once the proper location within the property has been determined, then the orientation of the greenhouse should be considered. In the case of a single-winged cold frame it will not have uniform sunlight on all sides therefore allowing the sloped covering of the cold frame to let more sunlight in. This sloped covering should be facing south in order to reach an optimal amount of sunlight. In the case that a low tunnel structure is utilized; then the longer sides should be facing north and south due to its even distribution of light (Giacomelli, n.d.).

We recommend that a ventilation cycle be implemented for the greenhouse to mitigate the trapping of humidity and aid in air flow. Since the seedlings grow at an ideal temperature of 12 – 20 °C (53.6 – 68 °F), according to Objective 1, it is important that the ventilation process be in accordance with these temperatures. It is recommended that a thermometer be placed in a section of the greenhouse where there is no direct sunlight. This thermometer would be suspended above ground and would be used to measure the air temperature. It is suggested that the thermometer be checked during the hottest hours of the day in order to ensure that the trees are not overheated. Once the temperature reaches 12 – 20 °C (53.6 – 68 °F), it is assumed that the rest of the cold frame is above this temperature threshold since the thermometer is placed in a shaded area. At this point, the window should be opened and held up by a vertical post within the cold frame (Rocburn Limited, 2020). We recommend that calculations for length of time that ventilation needs to occur be carried out as it is dependent on the size of the greenhouse that is being implemented. In order to minimize humidity within the greenhouse we recommend research also be completed on tools that can be used to determine the percentage of relative humidity within the greenhouse as it should not exceed 91 % (University of Massachusetts Amherst, 2015). This ensures that there is a healthy air flow for the seedlings in the greenhouse.

A risk of opening the greenhouse to the outside environment for ventilation is the attraction of pests. These pests feed off the seedlings and damage their overall health. In terms of tree growth for forestation, the most common method for pest removal is introducing a natural enemy of the pest into the greenhouse environment (Bessen et al., n.d.). However, it is recommended that research be done on the use of natural pesticide and other pest prevention methods as there may be a more cost-effective method.

It is also recommended that the plants grow within the soil itself rather than in individual pots. It should be recognized that this could result in difficulty when trying to transplant the trees as the roots tend to grow two to three times larger in size than the height of the tree itself. The trees will be growing for around two-to-three years and therefore digging them out of the ground may cause some damage to the roots. The trees will therefore require a spacing of approximately 105 cm (3.45 ft) for the height they will reach of 35 cm (1.15 ft), which ultimately puts a limitation on the greenhouse's capacity. However, the size of the greenhouse and desired trees per acre will ultimately dictate spacing and should be determined for each greenhouse. However, growing trees in pots also results in a difficult transplantation process along with the downfalls that were mentioned in Objective 1. Since the transplantation process for the trees was not explored in this project it is recommended that the effects of the greenhouse on the transplantation process for forestation be studied further.

The recommended soil growing method may not guarantee optimal soil conditions, so it is recommended that the soil pH be tested for each plot of land that is to implement the greenhouse. It is recommended that a simple handheld reusable pH tester be purchased at the discretion of the ATP team or the backyard nursery growers. The reading on the meter should fall within the optimal pH range that was discussed within Objective 1. If this is not the case, then soil should be supplemented with materials that can adjust soil characteristics. In the case that the soil is too acidic and needs to be made more basic, either lime or wood ashes can be added into it (Clemson University, 2012). Ground limestone products can be commercially obtained and come in many forms, but the more finely ground the limestone is, the faster it will affect the soil pH. The lime should be incorporated into the soil two to three months before planting to allow the soil time to become less acidic. If wood ashes are easier to obtain, they should be spread over the plants in small amounts as they can damage or strip the soil of nutrients if used extensively. Soils that need to become more acidic should be supplemented with aluminum sulfate or sulfur (Clemson University, 2012). Aluminum sulfate will work more quickly as it changes the soil pH upon dissolving into the soil, but sulfur additions tend to have a slower reaction. The conclusion of the appropriate amounts of each material to add to the soil is dependent on the gap in pH values and the texture of the soil, which should be determined for each individual greenhouse. Therefore, it is recommended that ATP consult the various research centers that exist for agricultural practices or agricultural experts on the specific amount of material and method for application.

The system of delivering CO_2 into the greenhouse using biogas is viable but will need to have a pilot program to test it as discussed later. Biogas would be better applicable to the cold frame design as the rigid wall will provide better support and make a better seal around the pipe. The biogas digester is cheap to maintain and is a renewable form of CO_2 for the greenhouse. Further testing with a pilot program will be needed to see if this novel idea is viable in practice. A biogas system can be used in conjunction with the greenhouse in order to supply carbon dioxide for the stimulation of seedling growth solely with the cold frame designs. We suggest that a silo-style biogas digester be utilized over the below-ground design. This design is the easier and cheaper option to construct. The average cost of current biogas digesters, including labor costs for digging, is \$50 to \$60 per 0.9 m^3 (30 ft^3) of volume (Energypedia, 2015). The ability to easily clean out the digester will avoid participants having to dig up the digester every few years for maintenance of the tank. It is recommended that sawdust be used as insulation to offset the drawback of not being insulated by the ground. As this sawdust retains heat well, we recommend that it be placed in between the two outer walls of the digester. Although if another material that has low thermal conductivity is more available that material can be used instead.

Since the greenhouse will need to maintain a higher internal temperature than external temperature, it is recommended that additional heating sources outside of the potential heat benefits of biogas be utilized to help stabilize heat in the colder months. This is especially needed in the winter months as biogas can't be used at its full capacity without sunlight. Also, heating is needed during ventilation and as stated previously the CO_2 supplementation during ventilation is at a lower level signifying the decreased use of the biogas digester system during those times.

Additional heating sources should be created through the use of thermal massing and a raised hotbed for the greenhouse. A hotbed is a foundation for plants to grow that is raised above ground and decomposes organic waste to create heat. The most used organic waste is straw, manure, and compost. A raised hotbed helps the temperature stay around 23.9 °C (75 °F). "The ratio of heat-producing material to growing medium should be 3:1. Therefore, the growing medium of soil and compost should be around 20 – 30 cm, or 7.9 – 11.8 in deep." (Waddington, 2020). In total, this hotbed should be 80 – 120 cm (31.5 – 47.2 in) deep. One of the primary benefits is the repurposing of organic waste that would otherwise be thrown away, as the compost it requires is best if it is homemade and fresh. The easiest way to measure the depth of the hotbed is adding the thin layers of material after building the cold frame. This way, the framing can be used to measure out 20 – 30 cm (7.9 – 11.8 in) deep and can be used to keep the mixture in. It is recommended that the first part of the mixture added is the heat producing material, which would be layers of fresh animal manure and straw in a 1:1 ratio (Waddington, 2020). This will be 60 – 90 cm (23.6 – 35.4 in) deep. On top of this, the mixture of compost and soil should be added, also in a 1:1 ratio.

Thermal mass helps raise the internal temperature of the greenhouse by a few degrees, which in the winter has a significant impact. Since we proposed small-scale greenhouses, it is recommended that closed plastic gallon jugs or buckets be filled three-quarters full of water and placed alongside the plants in empty patches of soil. These should be painted black or black food coloring should be added to the water so that the heat absorbed is the highest level possible (Odom, 2017). Another important aspect of this system is that the containers being used are closed so that they don't increase humidity in the greenhouse.

Insulation is also another mechanism by which warmer temperatures can be maintained within the greenhouse. It is recommended that either the greenhouse be insulated with bubble wrap or root coverings be placed over the soil. The best insulation option for cold frames is using bubble wrap, as it helps keep heat in while adding a second layer of protection against cold temperatures and drafts. This should be lining the interior of the greenhouse walls, and anything made of wood framing. Horticultural bubble wrap should be used, as it lasts longer due to higher durability than other types and can be easily obtained at most garden centers. It also includes UV stabilization, which is a layer of protection added to the bubble wrap, so the material doesn't degrade at a fast rate when exposed to direct sunlight (Odom, 2017). Other bubble wrap can be used, but it will need to be replaced more often (Volente, 2021). This recommendation only applies to colder months, and the bubble wrap should be removed during the warmer months as it can keep too much heat in and can make the plants overheat. In order to make the bubble wrap stay in place an adhesive should be used. When applying the wrap, there needs to be an air gap in between the framing and bubble wrap for heat retention.

Different coverings which help keep the saplings and their roots warm during the winter can also be used for insulation. Plants should be covered if the temperature goes below 0 °C (32 °F) (Volente, 2021) within the greenhouse, which is especially important in the winter when temperatures can get too cold and can affect healthy seedling growth as mentioned in Objective 1. There are different options for coverings that can be applied to both cold frame and low tunnel greenhouse structures. Plants can also be wrapped in horticultural fleece or clothing and textiles that can be found in a household to help keep heat in (Waddington 2020). The material should be gently wrapped around the base of the plant and extended out over the roots. This can be done for individual or rows of plants. There are also some materials that can be layered on the ground around the plants and plant roots to provide extra heat. These materials include thick layers of mulch, straw, sheep's wool, and bracken which is a coarse type of fern (Waddington, 2020). For the cold frames, it is recommended that a thick layer of mulch is added on top of the plants, as it keeps in heat well. For the low tunnel structure, there should be a layer of straw and mulch, since it cannot utilize the bubble wrap insulation.

In order to maintain the optimal water levels for the plants, we recommend that an irrigation system be used. The plants will grow best in moist soil conditions as described in Objective 1. Therefore, manually watering the plants to maintain this level of moisture would require an unnecessary amount of labor for the caretakers. We did not have access to resources to determine the exact value of water supply each individual tree species requires, and we recommend that it be determined so that each species can receive ideal water supplementation. The greenhouse should be divided into sections if there is more than one species growing within and use a separate irrigation system to accommodate each optimal water level. We recommend that the system be able to support approximately 25.4 mm (1 in) of water a week as this is a general water requirement for seedling health (Chicago Botanical Garden, 2021).

The recommended irrigation design consists of tubing that extends across the length of the greenhouse. Generally, tubing systems used for irrigation can be found above or below the soil, but in order to avoid the labor cost of digging, the recommendation is that the tubing system be placed above ground and covered with soil. The tubing should have openings at each seedling's position and should only support one way flow, as water flowing back and forth could result in uncontrolled watering. The water leaving the tubing should avoid hitting the stem of the seedlings, which results in increased humidity within the greenhouse. The water should be fed directly into and be absorbed by the soil itself, since water enters a plant through its roots and not its stem or leaves. It is recommended that this tubing system be hooked up to a water supply that can be adjusted according to the soil's moisture. Moisture sensors and automatic timers can get quite expensive and may not be feasible, so it is recommended that a simple daily watering schedule or method for determined soil moisture be studied further.

We also recommend exploring the use of a stand-alone rainwater collection mechanism or one used in conjunction with the greenhouse. The greenhouse enclosure prevents the rainfall from reaching the seedlings by covering them on all sides. Since specific regions within Armenia lacks adequate rainfall year-round the rainwater collection system will need to be used in conjunction with additional water sources. These can be obtained commercially, from household water supplies, or from water towers. However, the rainwater collector is a cost-effective method as it recycles the water that is prevented from entering into the greenhouse. For a rainwater collection mechanism that is used in conjunction with a greenhouse, a gutter would be attached at the bottom of the sloped roof and would feed into a large water container that contains a water-permeable covering. A water-permeable covering is important for the filtration of water, so that it does not clog the irrigation tubing when delivered to the seedlings. A simple standalone water collector would also consist of the same container but could be placed anywhere outside or under the release of a household's gutter system.

We recommend that continued progress be made towards determining the appropriate methods for implementation of the greenhouse within the backyards of ATP's program participants. We also recommend that interviews and focus groups be carried out with the target participants. Although we did not have the capabilities to carry out this communication within this project, client feedback is a very important aspect of product development. In the case that the greenhouse is not appealing to the audience for which it is being designed for, it will most likely fall short of the intended impact, as it will not be used. Feedback will allow for analysis of the feasibility of greenhouse and seedling care taking. An overly complex greenhouse may require too much labor and more costs, outweighing the overall benefit it provides. It is suggested that this project's proposed greenhouse design be pitched to the audience and the initial reactions be obtained. The greenhouse design should be adjusted based on feedback and piloted as described below. Another round of feedback should be obtained and during initial adoption of the greenhouse the participants should be polled regularly. This will be used to determine their opinions on the level of maintenance that they must carry out on the greenhouse as well as the demands of caretaking for the seedlings. It should be determined whether they believe the benefits of the greenhouse outweigh the work they must put into it.

We suggest that the construction of a single-winged cold frame and a low tunnel greenhouse design be carried out by ATP in order to determine the appropriate steps and whether the structures are as sturdy and effective as they are currently assumed to be. Identification of the construction steps and confirmation of the materials that are necessary for the proper assembly of the greenhouse could be used to create an instructional pamphlet. This will increase the audience that can participate in building greenhouses as it will walk the reader of the pamphlet through the process step by step. A pamphlet can easily be distributed and consulted when working on building a structure outside and it will also allow the builder to have all tools and materials ready before starting the process. Compared to the pamphlet, an even more effective way to relay the information would be an instructional video on each step of the process. Often times, pamphlets can be difficult to understand completely, and an instruction video can walk through the smaller steps that may not appear in an overview pamphlet. An example of an instructional video that can provide an understanding of what the greenhouse video should be like is provided on the

AUA Acopian Center for the Environment website for the Kalavan Schoolhouse (AUA Acopian Center for the Environment, 2021, *Kalavan schoolhouse thermal insulation project*).

It is also recommended that the greenhouses be piloted for at least one year so that weather fluctuations and seedling needs can be observed throughout all seasons. A pilot of the greenhouse will expose any downfalls in the design or any additional maintenance needs that were not determined for this initial greenhouse proposal. Since environmental conditions can fluctuate, a research-based approach may not be sufficient and therefore a full analysis of the greenhouse's behavior in the actual environment is required.

There should also be a pilot program for the implementation of biogas within the greenhouse. The pilot of a greenhouse with biogas and another one without biogas, will give a basic understanding of the benefits that biogas can provide. As biogas digesters in conjunction with greenhouses have not generally been implemented, the maintenance requirements of the system may exceed the overall benefits, making it less appealing and appropriate for use. The current lack of implementation of biogas digester utilization with greenhouses can signify that it either will be widely successful and more people will continue to expand on the idea, or it may have great downfalls that make it less of an unideal option than was proposed in this project.

We also recommend that with this biogas digester piloting, further research and studies be conducted to determine the exact heat and CO_2 levels generated by the combustion chamber. The heating aspect is important because if too much heat is produced within the combustion chamber, then it will slow down the flow of CO_2 into the greenhouse delaying delivery of optimal levels of CO_2 to the seedlings. Determining the exact levels of CO_2 produced is also important as improper levels can kill off or severely slow down the growth of the seedling within the greenhouse. Specifically, we suggest a focus on the amount of biogas release when the first valve of the system in turned to an open position. Lastly, how these valves will be installed and operated will need future research and testing. We do not have a way to measure the amount of biogas being released when the valves are opened as the pressure build up is depending on the biogas digester that will be implemented. However, it is recommended that the biogas digester work in conjunction with the ventilation times as this is where the change in recommended CO_2 levels take place.

Conclusion

The goal of this project was to assist in increasing the yield of healthy seedlings for transplantation into the forests of Armenia through greenhouse use. Our recommendations on greenhouse designs and methods for maintenance of an ideal internal environment will enable ATP to implement a greenhouse initiative within their backyard nursery program. This greenhouse will provide a controlled growing environment, increasing the probability of successful trees. Since the participants earn a profit for each high-quality seedling, the overall yearly income for participants will be increased, in turn increasing motivation to participate in ATP's program which expands its influence and forestation impact. A successful piloting of the greenhouse will allow participants to quickly grasp all the skills needed for greenhouse use and seedling growth. This will take stress off ATP staff, as the necessity for oversight of individual nurseries will be decreased and will ultimately allow for the increase in the amount of backyard nurseries.

Beyond the scope of ATP's work, these individualized greenhouses will assist in reaching the country's goal of doubling the number of trees by the year 2050. The increased rates at which high-quality seedlings are being raised will positively impact the presence of healthy trees for the rejuvenation of Armenia's forested regions. These trees provide increased air quality and mitigate the risk of insect transmitted diseases, positively impacting the health of those living in the country. These efforts have positive impacts not only for the environment, but for the people as a whole.

The success of Armenia's reforestation initiative can potentially have a global positive impact. Our analysis of biogas use as a plant growth stimulant in a greenhouse is a novel concept that can potentially change the course of greenhouse carbon supplementation. The use of biogas is one of the least expensive options that provides the amount of CO_2 that plants need in order to thrive. An effective and affordable method for reforestation efforts that can be carried out in an individual manner can spark worldwide interest and adoption. Reforestation can often seem like a daunting task for an individual to undertake by themselves, but every small effort makes a difference in the grand scheme of things. With this backyard greenhouse, individuals worldwide will have the ability to nurture the forests of the world back to their healthy states.

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Appendix

Table A: Materials and their Properties for Greenhouse Framing

Framing Material Properties								
Column1	**Soft Wood Cedar**	**Stainless Steel**	**Low Carbon Steel**	**Aluminum (High Strength)**	**Aluminum (Light Alloy)**	**PVC (tpPVC)**	**Polyetheline Pipe**	**Cellulose Acetate (Resin)**
Density (lb/in^3)	0.017-0.021*	0.275-0.284	0.282-0.283	0.0965-0.103	0.095-0.0975	0.0466-0.0527	0.0339-0.0347	0.0354-0.0361
Yield Strength (KSI)	5.73-7.01*	37.3-165	37-51.5	35-75.4	9.44-36.5	5.45-6.6*	2.6-4.21*	3.63-4.06*
Tensile Strength (KSI)	7.37-9.01*	74.7-189^	55-77.2	41.8-82.8	21.9-46.8	5.51-6.67	3-6.5	4.06-4.5*
Fatigue Strength (KSI)	2.38-2.9*	37.1-78.6^	29.4-40.3	14.5-31.8	8.95-21.8	2.41-3.06	3.05-3.34	1.22-1.8*
Fracture Toughness (KSI.in^0.5)	3.37-4.19*	51.9-125^	37.9-71.9	23.4-37.3	24.6-33.7	3.3-3.5	1.31-1.57*	1.37-1.64*
Thermal Conductior / Insulator		Poor Conductor	Good Conductor	Good Conductor	Good Conductor	Good Insulator	Good Insulator	Good Insulator
Thermal Condictivity (BTU/hr.ft.degrees F)	0.133-0.162*	8.09-14.4	28.8-31.3	78-107^	72.2-109^	0.0849-0.121*	0.233-0.251*	0.0751-0.0867*
Specific Heat Capacity (BTU/hr.ft.degree F)	0.396-0.408	0.107-0.122*	0.11-0.121*	0.21-0.239	0.211-0.233	0.239-0.263	0.432-0.449^	0.332-0.337
Transparency	Opaque	Opaque	Opaque	Opaque	Opaque	Transparent	Transluscent	Transparent
Fresh Water Durability	Limited Use*	Excellent	Acceptable	Excellent	Excellent	Excellent	Excellent	Excellent
Salt Water Durability	Limited Use	Excellent	Limited Use	Acceptable	Acceptable	Excellent	Excellent	Excellent
Soil Acidic (Peat) Durability		Excellent	Acceptable	Unacceptable*	Unacceptable*	Excellent	Excellent	Unacceptable*
Soil Alkaline (Clay) Duriability		Excellent	Acceptable	Excellent	Excellent	Excellent	Excellent	Unacceptable*
Rural Atmosphere Durability		Excellent	Acceptable	Excellent	Excellent	Excellent	Excellent	Acceptable
UV Radiation Durability	Good	Excellent	Excellent	Excellent	Excellent	Fair	Fair	Fair
Flammability	Highly Flammable*	Non-flammable	Non-flammable	Non-flammable	Non-flammable	Self Extinguishing	Highly flammable*	Highly flammable*
Source:		GRANTA Edu Pack 2020						
KEY 1:	* = Low Value	^ = High Value						
Key 2: Thermal Conductor/Insulator	Good Insulator	Poor Insulator	Poor Conductor	Good Conductor				
Key 3: Electrical Conductor/ Insulator	Good Insulator	Poor Insulator	Poor Conductor	Good Conductor				
Key 4: Transparency	Opaque	Transluscent	Transparent	Optical Quality				
Key 5: Flammability	Highly Flammable	Slow Burning	Self Extinguishing	Non-Flammable				

Note: This information was taken from GRANTA EduPack, Databases. Ansys & Worcester Polytechnic Institute.

Table B: Materials and their Properties for Greenhouse Coverings

Coverings Material Properties						
Column1	Soda Lime Glass	Poly Carbonate	Polyethelyne Terephthalate (PET)	GFRF Epoxy Matrix (Isotrophic)	Polymethyl Methacrylate (Acrilic PMMA)	Polyvinylchloride (PVC)
Density (lb/in^3)	0.0882-0.09	0.043-0.0437	0.0466-0.0502	0.0632-0.0712	0.0423-0.0434	0.0466-0.0527
Yield Strength (KSI)	4.5-4.96*	8.57-9.46	7.25-7.98	30-44.1^	7.83-10.4	5.45-6.6
Tensile Strength (KSI)	4.5-4.96	9.09-10.5	7.98-8.7	30-44.1^	7.83-10.4	5.51-6.67
Fatigue Strength (KSI)	4.26-4.71	3.44-4.47	2.8-4.21*	5.99-13.2	2.2-2.44*	2.41-3.06*
Fracture Toughness (KSI.in^0.5)	0.582-0.592*	1.91-2.09*	4.32-4.78	17.6-28.2	0.637-1.46	3.3-3.5
Thermal Conductior / Insulator	Poor Insulator	Good Insulator	Good Insulator	Poor Insulator	Good Insulator	Good Insulator
Thermal Condictivity (BTU/hr.ft.degrees F)	0.404-0.751	0.112-0.126	0.0797-0.139	0.243-0.295	0.0965-0.145	0.0849-0.121
Specific Heat Capacity (BTU/hr.ft.degree F)	0.203-0.227	0.275-0.299	0.275-0.299	0.244-0.268	0.334-0.363	0.239-0.263
Transparency	Transparent	Optical Quality	Opaque*	Transluscent	Optical Quality	Transparent
Source:	GRANTA Edu Pack 2020					
Key 1:	* = Low Value	^ = High Value				
Key 2: Thermal Conductor / Insulator	Good Insulator	Poor Insulator	Poor Conductor	Good Conductor		
Key 3: Electrical Conductor/ Insulator	Good Insulator	Poor Insulator	Poor Conductor	Good Conductor		
Key 4: Transparency	Opaque	Transluscent	Transparent	Optical Quality		

Note: This information was taken from GRANTA EduPack, Databases. Ansys & Worcester Polytechnic Institute.