Constructing a Passive Solar Greenhouse for Season Extension

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This publication is intended to provide general information about the utilization of a passive solar greenhouse for farmers in the southeastern U.S. Readers are encouraged to follow all state and local building codes, regulations, and safety rules when constructing and utilizing any structures.

Background

Figure 1. Typical High Tunnel Used for Leafy Greens.

In recent years, high tunnels have gained popularity in the United States, with many small to medium-scale farmers looking to capitalize on their season-extending potential. These structures are often passively heated and cooled with no permanent heat source or active ventilation system and are typically constructed with galvanized frames and covered in 4 to 6-mil thick plastic (Lamont, 2009; Figure 1).

While many high tunnels in the United States utilize a similar framing system, other regions have adapted designs to use locally available materials or improve the capacity for season extension (Lamont, 2009). In China, structures utilizing a packed earthen wall, typically on the north side of the tunnel, are widely used (Tong et al., 2009). Depending on the time of the year, a thermal blanket made of a locally sourced material may also be rolled over the plastic cover at night (Figure 2).

Figure 2. A Typical Solar Greenhouse in China. View A features natural grass insulation and View B shows an earthen wall for retaining heat. Photos: John Snyder, professor emeritus, University of Kentucky.

A structure that integrates energy collection and storage into the greenhouse itself is called a passive solar greenhouse (PSG) or deep winter greenhouse (DWG; Hodge et al., 2018). During daylight hours, heat from the air in the structure is absorbed by a thermal mass and is then radiated during the night to heat the enclosed space. The heat collection and storage systems traditionally utilize materials such as rock, soil, or water (Santamouris et al., 1994a, 1994b) and in some rare cases a phase-change material, such as ***chliarolith*** (calcium hexahydrate chloride) or paraffin waxes (Berroug et al., 2011).

The number of PSGs in the United States and Canada is limited compared to high tunnels; however, there are reports of successful year-round production of horticulture crops in the northern latitudes of North America using a PSG/DWG (Hodge et al., 2018). Under conditions where ambient nighttime low temperatures reached -22 °F, air temperatures inside a PSG remained above 32 °F (Beshada et al., 2005). This PSG maintained a nighttime air temperature approximately 36 °F warmer than a traditional unheated high-tunnel structure. It should be noted that other PSG structures, including those described in this publication, did not show such large differences in nighttime temperatures compared to high tunnels.

Other PSG structures utilizing stacked concrete blocks as a thermal mass have been reported to increase nighttime air temperatures inside the PSG by up to 18 °F over ambient air temperatures (Santamouris et al., 1994a). Beshada et al. (2005) tested a structure that consisted of a sand-filled wall on the north-facing side, while other PSGs utilize walls of water-filled barrels as a heat sink (Santamouris et al., 1994a).

To determine the effectiveness of a PSG to produce vegetable crops, a prototype PSG was built using locally available materials. This publication details the building process as well as some of the effects of the PSG on air temperatures inside the structure. This structure was built by the authors Coolong and Jacobsen at a research facility in Lexington, KY.

The Structure

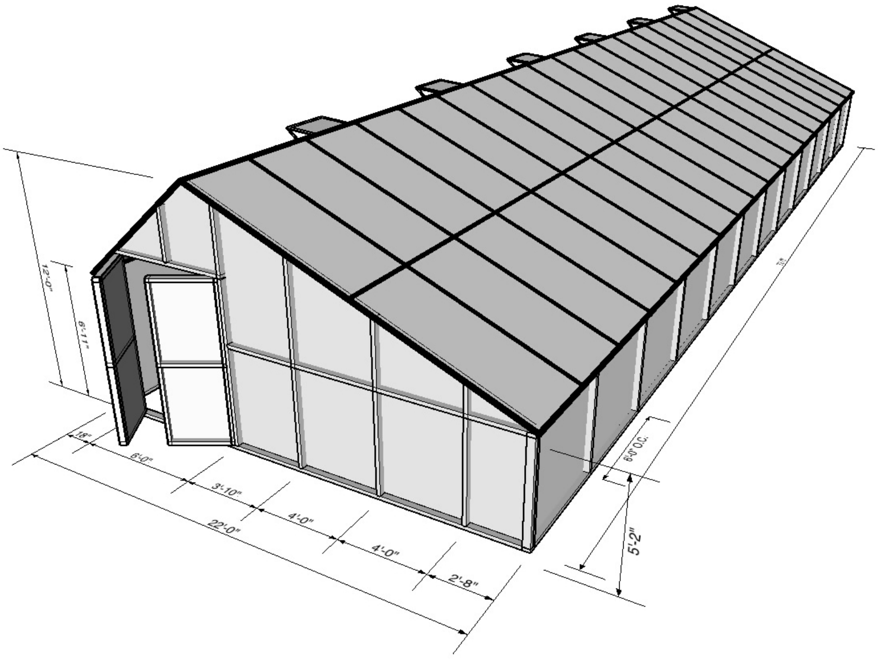

Figure 3. Rendering of the Passive Solar Greenhouse (PSG) Structure Built by the Authors. The primary roof and front wall faced south to absorb the most radiation during the day. Image created by Helen Turner, University of Kentucky College of Design.

We encourage all readers to familiarize themselves with local building codes and regulations. The reader should determine whether their structure would be considered temporary or permanent and ensure that the structure is safe. Please consult a qualified contractor or engineer if you have questions about design. The structure described here was considered a temporary structure when it was erected.

The structure was situated on an east-west orientation (the opposite of how a typical greenhouse would be sited) with the roof facing south. The thermal mass was placed on the north wall to maximize energy capture during the day, which then radiated heat back into the structure at night (Figure 3).

> **Note:** This publication refers to typical lumber sizes, such as “4 x 4,” which do not actually measure 4 in. by 4 in. The actual measurements of these lumber sizes are: 2 x 4: 1.5 in. by 3.5 in.; 4 x 4: 3.5 in. by 3.5 in.; and 2 x 6: 1.5 in. by 5.5 in. Other measurements stated throughout this publication can be assumed to be actual size.

The overall structure was supported by pressure-treated 4 x 4 posts placed every 6 ft on center with approximately 36 in. of the posts below-grade, then backfilled with compacted soil. The interior of the structure was divided into two different thermal mass sections: the western half of the PSG used a sand-filled wall (Figure 4B–C) and the eastern half used water-filled plastic barrels. We used two thermal masses for research purposes, but a farmer would likely choose one type of mass for their entire structure. The surfaces of both thermal masses were painted black to maximize absorption of energy and they were physically separated by a 6-mil polyethylene curtain placed at the midpoint within the interior of the structure. The polyethylene curtain was only utilized in this instance to separate the two sections for research purposes; a grower would not need it.

Figure 4. Construction of the PSG. A. Initial framing layout of treated lumber posts supporting the north wall. B. Posts were initially placed 18 in. apart for the wall, resulting in a thermal mass approximately 12-in. deep/wide after framing was completed—notice the threaded steel rod that goes through the posts on either side of the wall to keep the top of the wall from bowing. C. Finished portion of the sand-filled steel encapsulated wall on one side of the solar greenhouse. D and E. Two layers of foam insulation (3 in. total thickness) were placed on the outside of the north wall.

The north wall of the western section consisted of a sand thermal mass, 1 ft wide by 6 ft tall, contained within galvanized corrugated steel paneling. The paneling was supported and framed using pressure-treated 2 x 4 lumber in a horizontal orientation at ground level, and 24, 60, and 84 in. above grade (Figure 4C). The exterior side of the north-facing wall also was covered with two layers of 1.5-in. rigid foam insulation (R-10 UtilityFit insulation from Dow®; Figure 4D–E), which was sheathed with 6-mil black plastic for additional protection.

The eastern side of the PSG contained a thermal mass constructed of 55-gallon plastic barrels, stacked two barrels high and filled with water. Though not visible in the picture (Figure 5B), two high-strength cables (one for each row of barrels) were strung below the upper lip of adjacent barrels and attached to the 4 x 4 framing posts for support to keep the barrels stable (Figure 5).

Figure 5. Two Options for Thermal Mass. A. The completed interior with the sand-filled thermal mass on the west side of the structure. B. The east side of the PSG contained stacked barrels filled with water. It may not be visible in the picture, but the barrels are secured in place with high-strength cables that are anchored to each post to prevent shifting or falling. Each barrel weighs more than 450 lb when full.

Walls on the east and west ends of the PSG were framed using pressure-treated 2 x 4 lumber (Figure 3). Polycarbonate panels 6 mm thick with a thermal resistance (R-value) of 1.6 were attached to the exterior of the wood framing. The south-facing wall of the structure was a roll-up wall similar to those found on most high tunnel structures; it was made of a 10-mil semi-opaque woven polyethylene plastic film. A gearbox assembly (15:1 roll-up gear box from FarmTek) was installed to assist with manually adjusting the curtain height; a curtain stabilizer bar also was installed to hold the bottom of the curtain firmly against the bows (Figure 6). The roof and end walls were covered with 6 mm twin-wall polycarbonate sheeting attached to bows using aluminum “H” and “U” channels that secured the sheeting to the frame and sealed the seams between polycarbonate sheets. The roof framing of the PSG consisted of 2-in. x 2-in. square steel tubing welded together to form bows (Figure 6).

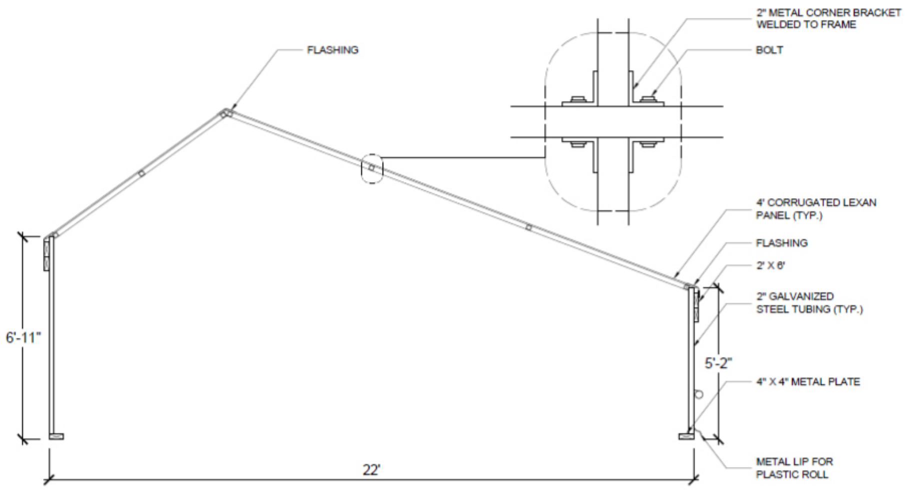

Figure 6. Schematic of the Bows With a Side View of the Structure. Image created by Helen Turner, University of Kentucky, College of Design.

The bows were attached to the north wall of the structure with a pressure-treated 2 x 6 sill plate secured to the top of the thermal-mass wall framing. Bows were welded to a 4-in. x 4-in. square plate that was connected to the sill plate’s lag bolts. The southern-facing sides of the bows were attached to a sill plate consisting of two 2 x 6 pressure-treated boards fastened perpendicular to each other. The sill plates were attached to 8-in. diameter concrete piers (made using a SonoTube® concrete form from Sonoco®) with approximately 24 in. of the pier buried below grade and approximately 6 to 8 in. above grade. Sill plates were attached to the piers using lag bolts set into the concrete before it cured. Bows were spaced every 6 ft on center along the length of the PSG. Six 17-in. x 32-in. heat-sensitive automatic greenhouse vents were installed into the center of polycarbonate roof panels after every third bow so that each section of the solar greenhouse had three vent panels that would raise when air temperatures exceeded 85 °F (Figure 3). The finished structure is shown in Figure 7.

Figure 7. The South Face of the Completed Structure. A gutter was added for rainwater collection. Plastic sheeting was added to the bows on either end of the structure, similar to a high tunnel, to prevent air loss during cold periods.

Future Suggestions

This project was developed as a proof of concept to determine if a PSG would be more efficient in trapping heat in the winter compared to a high tunnel and to optimize materials for building the heat sink on the northern wall. The custom-fabricated bows were the biggest expense associated with this project, followed by the polycarbonate panels for covering the walls and roof.

Figure 8. A Typical Sidewall From a High Tunnel Structure (with ground posts for anchoring). This type of sidewall could be

utilized for the south-facing wall of a PSG.

Growers would be encouraged to use prefabricated greenhouse or high-tunnel bows in place of custom-made bows and rolls of clear greenhouse plastic (6 mil) instead of polycarbonate sheets to make this project more economical. Polycarbonate sheets were chosen to maximize the structure's insulation, but they were expensive. The bow spacing also had to be exact to fit the panels within the channels that anchored them to the bows.

The structure's peaked roof was developed to shed snow and allow hot air to escape through automatic roof vents, but a rounded Quonset-style bow modified to fit the needs of a PSG may be more cost-effective, particularly for growers in the deep south. While we utilized concrete piers for the base of the southern-facing wall, a standard high-tunnel wall with ground posts would have been far easier and more economical to construct (Figure 8). Further, if in a mountainous or sloped area, the thermal mass could be fully or partially dug into the side of a hill or bank. Measures to prevent the collapse of the earth would need to be considered if a partially buried structure was desired.

Heat and Crop Growth

As was expected, air temperatures during the winter months in the PSG were greater than in nearby high tunnels (which were covered with two layers of inflated 6-mil plastic). Using a base of 50 °F, there was no difference between the sand and water sections of the PSG for accumulating growing degree days. However, they accumulated significantly more growing degree day units than nearby high tunnels or fields (Figure 9). The roof vents installed did not exhaust enough hot air to cool the PSG during summer months as the average maximum daily temperature inside during June, July, and August was nearly 20 °F higher than in the open field (data not shown). An alternative ventilation system combined with a shade covering likely would be required to utilize this structure during the summer months in Georgia.

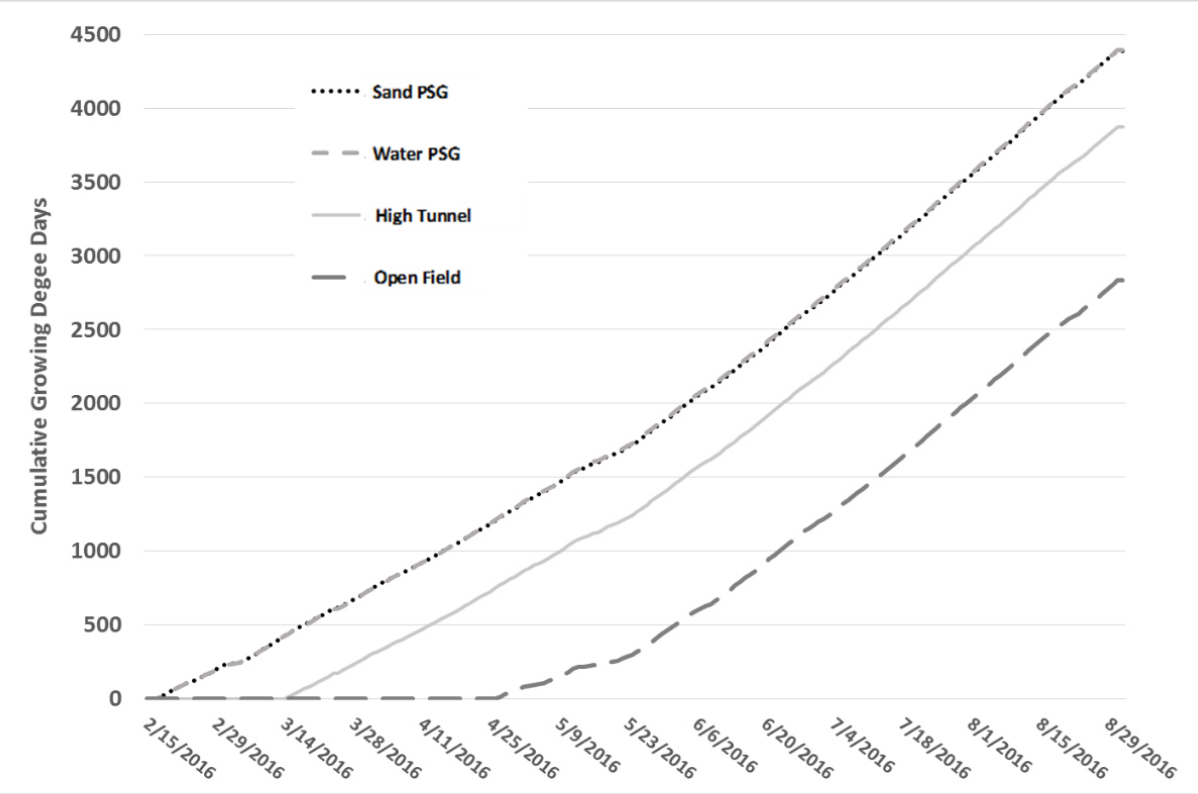

Figure 9. Comparison of Cumulative Growing Degree Days Among Different Growing Options. There is no noticeable difference between passive solar greenhouses with either water- or sand-filled thermal masses, but both PSG options show 1 month of season extension over a high tunnel structure, and all three man-made structures provide weeks of season extension compared to an open field.

Results of this study demonstrate that PSG structures have the potential to lengthen the season for warm-season crops at least 1 month earlier than a traditional high tunnel. Season-extending potential may be further increased with the use of row covers or other frost protection. Further, low-cost thermal-mass materials that do not require earth moving and are locally available were successful in extending frost protection.

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