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The Feasibility of Rice Bags and Ground Tarp Plastics as Low-Cost and Locally-Available Alternatives to Greenhouse Glazing

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Abstract

Greenhouses can help farmers increase their yields and improve their livelihoods while reducing spoilage and furthering food security. As farms are getting smaller and access to water is getting more difficult, greenhouses are gradually gaining popularity in the agrarian economies of sub-Saharan Africa. Most greenhouses sold in the market are designed for commercial farmers and are beyond the reach of smallholders. The Humanitarian Engineering and Social Entrepreneurship (HESE) program at the Pennsylvania State University has developed and commercialized affordable greenhouses that utilize locally-sourced materials. The only exception is the glazing - the plastic covering on the greenhouse structure - which is imported from abroad. The cost of this glazing is too high, and is subject to foreign exchange fluctuations and supply chain anomalies. In an effort to further decrease the cost of the greenhouse, and thereby increase its accessibility in the market, this article investigates the feasibility of locally-available, inexpensive materials that can be used as substitutes for typical glazing materials. The primary emphasis of this paper is on rice bags and a Polyethylene ground tarp, which are both abundant, inexpensive materials found commonly in developing countries. Two properties of the materials were tested: light transmission and UV resistance, and a third test, water conservation, was performed on the ground tarp material. Results indicated that while rice bags are not an ideal substitute for standard glazing, they may be appropriate as low-cost shade nets, and the ground tarp plastic may prove appropriate as a potential greenhouse glazing replacement.

Keywords: controlled environment farming, environmentally conscious manufacturing, green energy, greenhouse glazing substitutes, greenhouses, food security

1. Introduction

Reflecting the rising global food security challenges, over 60% of the East African population is considered malnourished with many regions in a state of famine (Mati 2006). There is broad agreement on the need to help small-scale farmers move from subsistence to sustainability by boosting their agricultural productivity, reducing spoilage, and providing market linkages (Odulaja and Kiros 1996). One means to boost agricultural productivity is by utilizing greenhouses. Greenhouses allow farmers to grow vegetables and fruits year-round through mechanically-controlled temperature and irrigation systems. Greenhouses can help farmers increase their yields and improve their livelihoods while reducing spoilage and furthering food security. In addition to providing protection from pests and harsh weather, greenhouses reduce water losses in plants by up to 30% by reducing evapotranspiration. Evapotranspiration, or water loss from crops exposed to the environment, is a significant problem resulting in an increase in the total water demand for crop production (Sanchez 2002). This is especially true for many parts of Sub-Saharan Africa, where over 80% of land area is classified as arid or semi-arid. Irrigation systems inside greenhouses have been shown to further reduce water use per unit yield (Fernandez, et al. 2010). This significant reduction in water requirements allows the expansion of cultivable land from high and mid-potential zones to areas previously deemed unsuitable for cultivation.

Despite their many advantages, greenhouses face a major barrier to increased uptake—their high capital cost. Imported greenhouses sold in East Africa are designed for large, commercial farms and cost thousands of US dollars. Greenhouses specifically designed for small-scale farmers are also out-of-reach, costing upwards of one thousand US dollars (Amiran Kenya Limited 2012). The Humanitarian Engineering and Social Entrepreneurship (HESE) program at the Pennsylvania State University, in collaboration with diverse organizations in Kenya, Rwanda, Mozambique, Sierra Leone and Cameroon, has designed, prototyped and field-tested affordable greenhouses created for small agro-enterprises and sustenance farmers. Based on a simple Quonset hut structure, the HESE greenhouse was developed to be easily constructed and maintained. This was accomplished using a modular design along with all local materials for the construction of the greenhouse. The exception is the greenhouse glazing that is currently being purchased from a competing company, which imports it from abroad. Despite the relatively low cost of the "Affordable Greenhouse," when compared to other greenhouses in the region, the price point (~$550 USD) is still unattainable for many small, rural farmers. The current glazing is the most expensive component of the greenhouse design, leading to increased cost and complicating the supply chain needed for the production of the greenhouse kits and their installation on-site. The use of locally-sourced materials would allow for a local ecosystem to evolve around the production, distribution, and maintenance of the glazing. Additionally, this model would make greenhouses affordable to a new demographic that would otherwise not benefit from the technology. In a broader social and economic sense, potential beneficiaries also include agro-entrepreneurs, venture capitalists, and small-scale farmers.

In an effort to further decrease the cost of the greenhouse, and thereby enhance its accessibility in the market, this paper investigates the possibility of using locally-available, inexpensive and recycled materials as substitute greenhouse glazing. The goal is to find a material that displays properties similar to standard greenhouse glazing. These properties include the transmission of visible light through the material, a natural resistance to degradation from harmful UV radiation, and the ability to resist the transfer of water vapor through the material, thus conserving water usage. This study focuses on testing these three criteria for rice bag plastic and generic ground-tarp plastic, both found commonly in markets in developing nations. The study is separated into two phases, each aligning to the two types of materials. Each phase begins by identifying the specific types of plastic through spectrographic analysis, and then begins a series of experiments to test the performance of the materials as compared to a standard greenhouse glazing. This article builds on preliminary data shared through a conference article which found that the initial rice bag testing proved that the material was not appropriate for use as a substitute greenhouse glazing (Bement, Nassar and Mehta 2013).

1.1 Review of Greenhouse Basics

1.1.1 Controlling Temperature

In traditional greenhouses, the internal temperature rises above the outside ambient temperature by allowing sunlight through the glazing and trapping the thermal energy produced from the light inside the greenhouse. This occurs because the sunlight (UV and visible radiation) that enters the greenhouse has a short wavelength, relative to the wavelength of thermal (infrared) radiation. Once sunlight is transmitted through the glazing, it strikes vegetation and soil, producing thermal energy, some of which is radiated along infrared wavelengths. In general, greenhouse plastics allow higher transmission of visible radiation than infrared radiation. Thus, the thermal energy is effectively trapped inside the greenhouse. This phenomenon, in conjunction with a ventilation system, allows control over the temperature inside the greenhouse and enables farmers to extend growing seasons by maintaining a warm microclimate in colder months (Pack and Mehta 2012).

1.1.2 Conserving Water

Greenhouses can conserve water by up to 30%, depending on outside conditions, via control of evapotranspiration (Fernandes, Cora and Campos de Aruajo 2003). Evapotranspiration is the sum of evaporation from the soil and transpiration from plant processes that result in water being lost to the local atmosphere in the form of water vapor. Greenhouses interrupt this process and trap the moisture in a micro-environment. They also help reduce the rate of evaporation by decreasing wind speeds in the greenhouse, increasing the relative humidity and lowering the intensity of direct sunlight upon the plant or soil (Fernandez, et al. 2010). These factors result in more efficient use of the water, essentially getting more plant growth per drop of water than outdoor growing (Brown 2000).

1.1.3 Greenhouse Structure

The framework of the greenhouse can be constructed using a variety of materials, including woods, plastics or metals. Steel and other metal frames are durable and, due to their high strength, the volume of material can be minimized in most designs. Metal is however expensive and difficult to install because of its machining requirements. Wooden frames are relatively inexpensive and very easy to construct but degrade over time in moist environments (Pack and Mehta 2012). Plastic piping can also be used to construct the framework of the greenhouse because it is light-weight and inexpensive, though access to quality piping can be difficult in some developing countries. Plastics also have a tendency to creep after consistent exposure to sunlight and wind loadings. In addition to material options, greenhouse frames can also be arranged in a variety of ways and with varying layers of glazing. These include A-frames, rigid frames, panel frames, and Quonset or hoop houses. The selection of the frame depends on the type of glazing and structural material being used, as well as the climate where the greenhouse is being constructed. Typical examples include glass panels being used in conjunction with rigid frames and non-rigid plastics being draped over hoop house frames. Other components of greenhouses can include irrigation systems, beds to plant in, supplemental lighting, benches to raise the plants off the ground, and ventilation systems (Grimstad 1987). Often times, a greenhouse can also include automated systems that optimize crop growth. High tunnels are a similar technological design that is much simpler than greenhouses as they utilize only one layer of glazing and often rely on manually-controlled ventilation. Due to their similarities, high tunnels are often referred to as greenhouses, a convention that is used throughout most of this paper. It is important to note that the "Affordable Greenhouse Design" is actually a high tunnel by classification.

1.1.4 Greenhouse Glazing

The glazing covering the greenhouse is vital to the success of the system. There are five basic tenets that every glazing material should accomplish. It is important that the material allow the maximum amount of Photosynthetically-Active Radiation (PAR) possible into the greenhouse, both in terms of intensity and diffusion of incident radiation. In addition, the glazing should prevent pests and disease from harming crop growth while simultaneously reducing water and heat loss to the outside environment, when necessary.

Photosynthetically-active radiation (PAR) is composed of wavelengths of light that encourage the process of photosynthesis to occur in plants. This optimal spectrum ranges from radiation with wavelengths of 400 to 700 nm (visible light). This range lies above the ultraviolet range (UVA and UVB) and below the long wave infrared range (LWIR). When choosing glazing options it is important to have a metric of comparison that depicts clearly the ability of light to transmit through the materials. This metric is referred to as the spectral transmissivity, $\tau(\lambda)$, and is defined as the fraction of the incident energy radiation flux that is transmitted through the glazing at a certain wavelength, λ. The spectral transmittance coefficient is defined as a coefficient determined by averaging the different wavelength intervals: UVA/UVB, PAR, and LWIR. Because of its importance in relation to greenhouses, the coefficient corresponding to the PAR range is essential when choosing a glazing material (Scarascia-Mugnozza, Schettini and Vox 2004). The coefficient for each of the intervals is calculated using weighted average values of $\tau(\lambda)$ over their respective wavelength intervals. For example, the coefficient for the PAR range would be found by averaging the weighted values of the spectral transmission for each wavelength in the PAR range, 400 to 700nm (McCree 1972). In addition to the type of radiation being transmitted through the glazing, the intensity and diffusion of the light is also important. Diffusion (or scattering) of incoming light allows broader light coverage, and consequently, deeper penetration into the leafy canopy of the crops. This results in greater surface area for photosynthesis to occur. Light diffusion, however, results in decreased intensity reaching the plants. It has been shown that a decrease in light intensity has an immediate effect on the rate of photosynthesis present in the plant, and subsequently a drop in the overall growth of the crop (Both n.d.). It is thus essential to balance the intensity of the incident light and the amount of light that is diffused throughout the greenhouse.

In addition to transmission characteristics, glazing material selection also depends on cost and availability. Standard, expensive glazing options produce the best greenhouses, but design restraints sometimes require a need for low-cost glazing substitutes. Due to their wide spread availability and low cost, rice bags show promise as a potential replacement for standard greenhouse glazing. Rice Bags come in various forms including paper, plastic, and cloth. In the first part of this study, plastic rice bags were chosen as the test material and purchased from a marketplace in Nyeri, Kenya. Due to the large variability and unknown origin of most rice bags, choosing standard bags can be difficult. For the purposes of this test, only white, highly translucent rice bags were chosen. The second phase of testing was focused on generic samples of Polyethylene plastic purchased at markets in Nyeri, Kenya and Bamenda, Cameroon. This PE plastic is generally used as a ground tarp to protect crops and other items from weather damage and is advertised as lasting at least a year when exposed to the elements. After a potential plastic substitute is chosen, in many cases it is still necessary to coat the plastic with a substance that will make it withstand the consistent exposure to UV radiation that naturally breaks down polymers in plastic and ultimately causes those plastics to degrade (Chemisana and Lamnatou 2013). Some of the most commonly used coatings work by applying a UV protective varnish. This type of coating works by layering the plastic with additives that are called hindered-amine light stabilizers. These additives absorb the UV light directly, protecting the physical properties of the plastic (Booma, Selke and Giacin 1994). Three types of additives are made of nanoparticles including titanium dioxide, silicon oxide, and zinc oxide. The particles compose 2% of the resulting weight of the coating, which uses a polyethylene base as its matrix (Espejo, et al. 2012). Altogether the substances form a coating about 200 microns thick. When compared to the original material, the physical properties of the coated materials are similar, though the optical and radio-thermal properties change drastically. Titanium based films are much less transparent, but excel at protecting the greenhouse from UV damage. The zinc based film preserves the transparency of the original material, while still blocking a significant amount of UV decay, making them optimal for use with greenhouse glazing (Espejo, et al. 2012). Another coating that can be applied to glazing materials is an anti-drip layer. This coating prevents water from condensing and dropping down to the crops below which is beneficial because it lowers the chance of moisture dependent diseases that occur in plants. In some circumstances this can lead to the development of crop-killing blights or mold (Business & Agriculture Editors Agritech 99 1999). Anti-drip coatings can also help increase the amount of light that enters the greenhouse in the morning hours when condensation would naturally form on the glazing, effectively making it less translucent.

2. Experimental Methodology

2.1 Part One: Rice bags

2.1.1 Test Phase 1 – Transmittance

The first phase of tests determined the transmittance of the rice bags for wavelengths between 300 nm (UV) and 1000 nm (NIR).

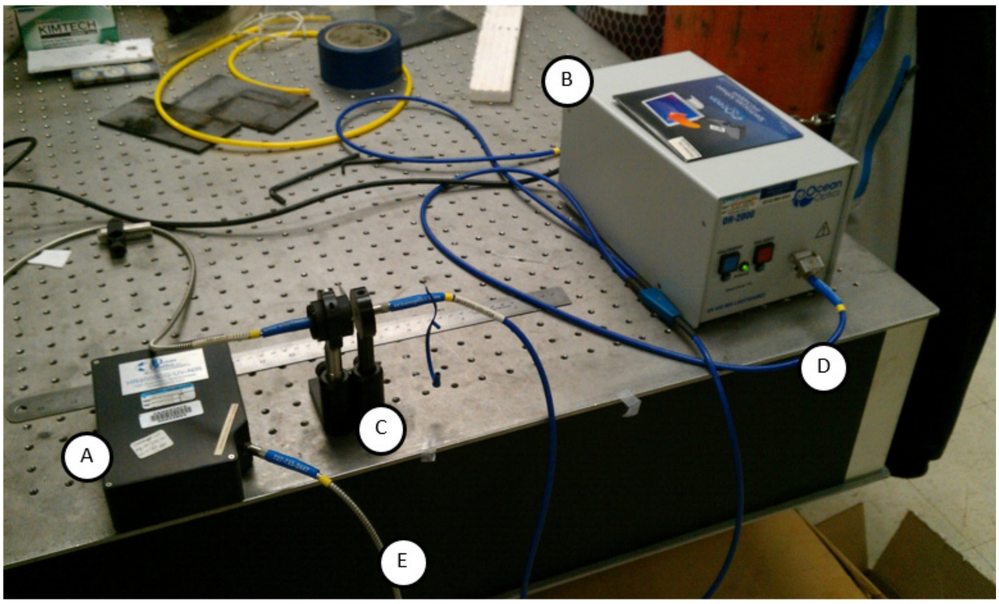

Figure 1. Transmittance Test Layout; A. OceanOptics HR4000 CG Spectrometer, B. DH-2000-CAL Tungsten/Halogen Lightsource; C. Clamping Fixture; D. 200 micron optical fiber; E. 200 micron optical fiber

An ultraviolet to near-infrared (UV-NIR) OceanOptics HR4000 CG spectrometer with a spectral range from 200 to 1100 nm and an optical resolution of 0.50 nm was used to study the fraction of light transmitted through various plastics. A DH-2000-CAL Deuterium Tungsten Halogen Calibration Standard was used to generate the light incident on the plastics. The DH-2000 light source, with both Halogen and Deuterium bulbs activated, was coupled to a 200 micron diameter optical fiber which was attached to the fixture indicated in Figure 1. Directly opposite and parallel from the termination point of the first optical fiber was another 200 micron optical fiber which was coupled to the Ocean Optics HR4000CG spectrometer. This fiber will henceforth be referred to as the spectrometer fiber. The gap between the two fibers was maintained at a constant distance of 5 mm. To measure transmittance, 4 cm x 4 cm square samples were held in place perpendicular to and directly before the spectrometer fiber. Spectral data was recorded using Ocean Optics Spectra Suite software (version 1.6.0_03). Transmission was measured by capturing three spectra: an attenuated transmission spectrum; a dark, 0% transmittance, spectra; and the spectra transmitted though each sample. The transmittance of each sample was determined by the ratio of the total light transmitted though each sample to the attenuated spectra, after the dark spectra was subtracted from each. Each spectrum was integrated over a 500 millisecond collection period. A boxcar average over 5 pixels was used to reduce noise. For each sample, data was captured twice and then averaged together.

Transmittance measurements were made for three types of rice bags, each labeled as rice bag 1 through 3, commercial bubble wrap and a sample of Dura-Film Super 4 greenhouse grade plastic. Each rice bag sample was cut from the larger rice bag material.

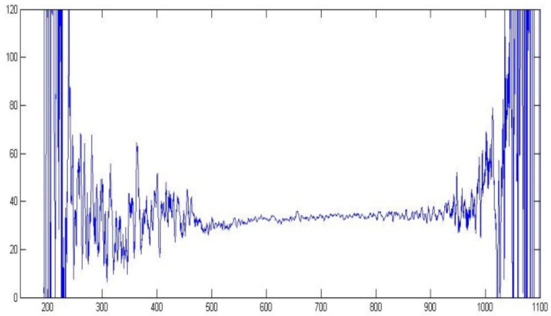

Figure 2. Graph of transmittance of sample rice bag 1

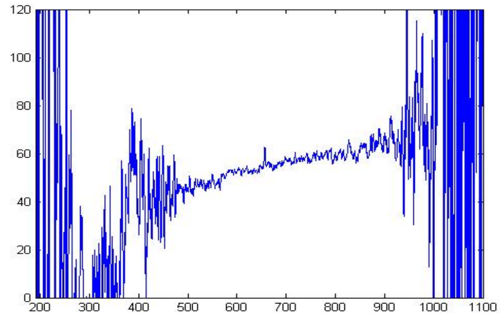

Figure 3. Graph of transmittance of Greenhouse-Grade Dura-Film Plastic

Figure 2 shows a sample transmittance spectrum for the rice bag 1 sample. From this graph it can be interpreted that the average transmittance, in the visible range of the spectrum, is approximately 30%. Figure 3 shows the spectrum for the standard Dura-Film Plastic. As can be observed in Figure 3, the transmission of the standard Dura-Film Plastic rapidly falls to zero near the UV portions of the spectrum, owing to its UV-protective coating. Table 1 shows transmittance results for all the samples.

Table 1. Transmittance percentages for the test specimens

Test Specimen	% Transmittance		
	Sample 1	Sample 2	Avg. Transmittance
Control	100	100	100
Rice Bag 1	40	30	35
Rice Bag 2	20	20	20
Rice Bag 3	15	10	12.5
Bubble Wrap	78	54	66
ND 0.6 Filter	25	30	27.5
Dura-Film Plastic	60	65	62.5

Among the rice bag samples, rice bag 1 had the highest transmittance within the visible range of the spectrum. This is most likely caused by the fact that the other two bags were woven strands of Polypropylene, whereas the sample rice bag 1 was a translucent solid sheet of Polypropylene. The Bubble Wrap displayed the best transmittance value of all the specimens. This has very positive implications for its use as an alternative greenhouse glazing material. Further testing is under way to determine its durability and availability in the desired regions.

The control measurement was performed with no specimen in the test stand. As expected the transmitted value for this experiment was 100% for both runs. Similarly the neutral-density (ND) filter with an optical density of 0.6 was used to determine the accuracy of the measurements. This type of filter is designed to allow 25% of light to pass through it. Based on the measured average value of 27.5%, an error around 10% can be assumed for the experiment. The greenhouse-grade plastic that was tested was documented from the manufacturer as having 92% transmission. The discrepancy between our tested results and the documented value may be present because our experiment tested only for direct transmission through the material, where the Dura-film plastic was designed to create diffuse radiation upon transmission through the material. Some of this radiation could have been lost and not detected by our spectrometer.

2.1.2 Test Phase 2 – UV Resistance

The second phase of testing simulates the rice bags exposure to consistent direct sunlight. This is accomplished using long-term exposure to UV radiation via a QUV machine equipped with four UVA-340 bulbs. This exposure testing was conducted with the collaboration of The Pennsylvania State University Behrend College's Plastic's Engineering program. The specimens were tested through a simulation process that replicated a year's worth of exposure to sunlight. Upon completion of this simulation, the specimens were tested to determine the degradation of their physical properties including tensile deformation and yield stress. Unlike standard greenhouse plastic, the materials that have been selected as possible glazing alternatives have not been coated with a protective UV absorption layer. This resulted in a more rapid degradation to the materials appearance and strength, when compared to standard greenhouse plastics. To combat this, we have coated several specimens with materials commonly used as UV absorbers. The first of these coatings is a titanium-sulfate based paint. Unfortunately, this paint coats on to form a white opaque surface on the material, thereby rendering it ineffective as a greenhouse glazing. Despite this, we chose to use it to obtain an understanding of how titanium-sulfate based products will protect the rice bags. The second material is a clear spray-on protective coating commonly applied on camping tents. Both coatings work by absorbing UV radiation before it is able to reach the glazing material, preventing potential break down of the glazing. Figure 4 shows the before and after for each of the four materials tested. It can be seen that the DuraFilm plastic and the Behr coated sample remain relatively the same, while the uncoated rice bag sample and the Nikwax coated rice bag sample show definite signs of degradation.

(a) DuraFilm Greenhouse Plastic	(b) Uncoated Rice Bag Sample 2	(c) NIKWAX Coated Rice Bag Sample 2	(d) BEHR Coated Rice Bag Sample 2

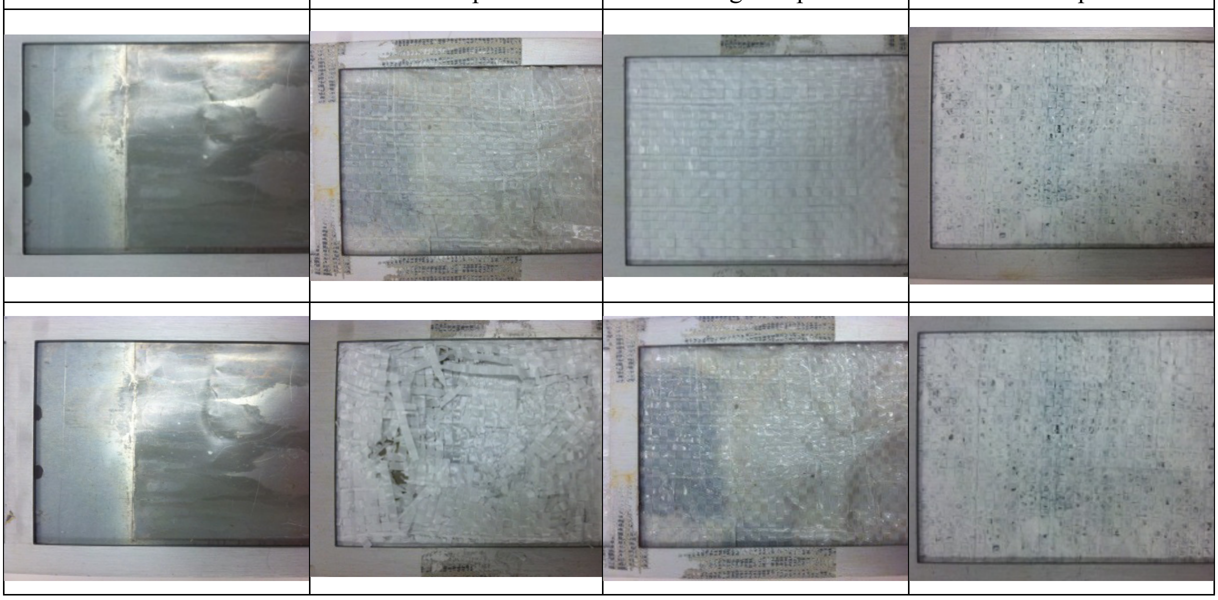

Figure 4. Samples on top are before simulation and samples on the bottom are after simulation a) Dura-film Super 4 Greenhouse Plastic b) Uncoated Rice Bag Sample 2 c) NIKWAX coated Rice Bag Sample 2 d) BEHR coated Rice Bag Sample 2

2.2 Part II Market Polyethylene Plastic

2.2.1 Test Phase 1 – Transmittance

An initial transmission spectrum for the PE market plastic and the Dura-Film standard greenhouse plastic was acquired using a Perkin-Elmer Lambda 950 UV-Vis-NIR Spectrophotometer. The initial graphs from both materials were compared to assure that the market plastic specimen allowed a similar amount of Photosynthetically Active Radiation through the material. The samples were each cleaned with distilled water and a dry cloth to remove dust and other particulates from the material.

The percentage of light passing through the DuraFilm Standard Greenhouse plastic is shown in Figure 5 and the Cameroonian Market plastic is shown is Figure 6. Figure 5 shows that some of the UV radiation impacting the DuraFilm glazing is being absorbed by the material, while Figure 6 shows that the UV portion of the spectrum is fully passing through the material. These results align with what was expected because the DuraFilm plastic is advertised as being protected against exposure to UV radiation, so the coating is absorbing the UV rays before they can pass through the material. Similarly, the Cameroonian market plastic was expected to have no coatings, so at the initial test there is nothing preventing the UV radiation from penetrating into, and through, the material.

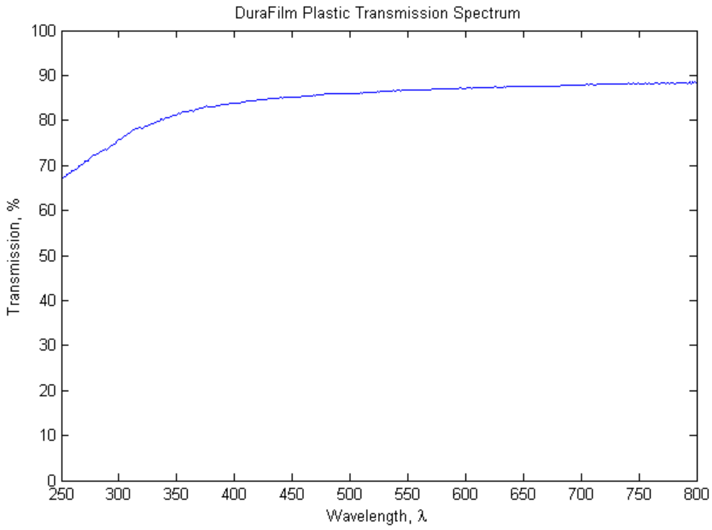

Figure 5. Percentage of light transmitted through DuraFilm Greenhouse Grade Plastic

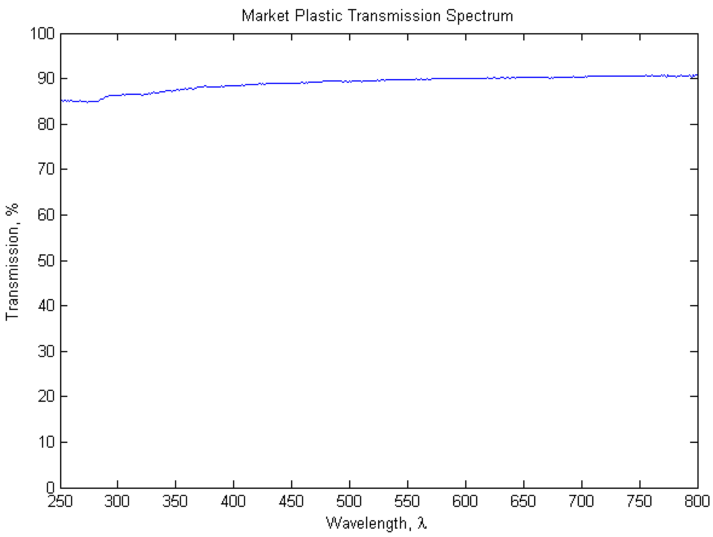

Figure 6. Percentage of light transmitted through the Cameroonian Market Plastic

2.2.2 Test Phase 2 – UV Resistance

A Q-LAB QUV model SE Accelerated UV-Temp-Humidity weathering machine was used to simulate the materials response to consistent solar radiation exposure. The exposure followed the ASTM G154 cycle 1 standard using UVA-340 bulbs in the machine with an average irradiance of 0.89W/m^2/nm and day-night fluctuations of 8hr at 60C and 4hr at 50C. Sixteen 6.0 cm^2 samples from each material were placed in the machine at the start of the experiment and samples were pulled at time intervals according to recommendations made by cycle 1. These intervals and their corresponding simulated exposure times are shown in Table 2.

Table 2. Correlation of laboratory exposure times to simulated sunlight exposure

Actual Exposure	0hr	24hr 45min	72hr	168hr	288hr	400hr
Simulated Exposure	0hr	37.6 days	109.5 days	255.5 days	438.0 days	608.3 days

When each sample was pulled from the machine it was once again tested for PAR transmission in the Perkin-Elmer Lambda 950 UV-Vis-NIR Spectrophotometer. When all the samples were pulled their spectral graphs were compared to determine the effects of the exposure. Particular attention was given to the UV portion of the spectrum because this is what effected the integrity of the material the most.

Although initially coated to prevent ultraviolet radiation from affecting the material, the DuraFilm plastic begins to weaken after prolonged exposure to the ultraviolet radiation as shown in Figure 7. Similarly, in Figure 8 the Cameroonian market plastic also shows signs of degradation after being exposed to the simulated sunlight. The DuraFilm plastic allows, on average, 30% less of the UV portion of the spectrum through the material at all data points, presumably due to its initial protective coating. The amount of radiation that is not passing through the material is instead being absorbed by either a protective coating (in the case of the DuraFilm) or being absorbed by the material itself (in the case of the unprotected market plastic). This is causing the polymers in the plastic to dissolve and consequently the material to disintegrate.

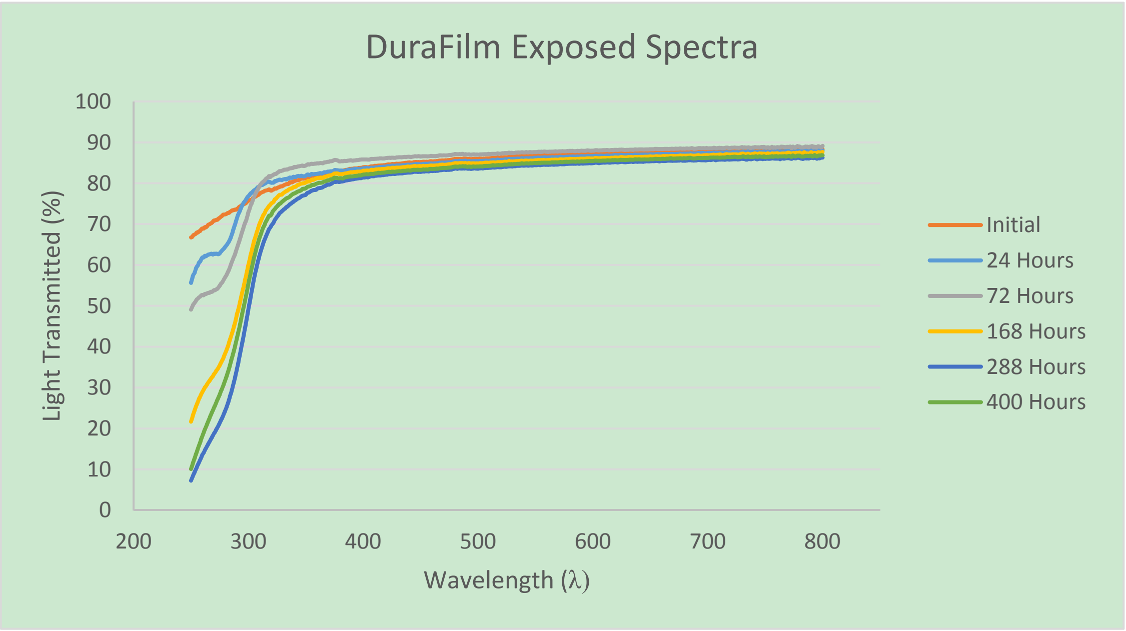

Figure 7. DuraFilm plastic spectra after 400 hours of simulated exposure

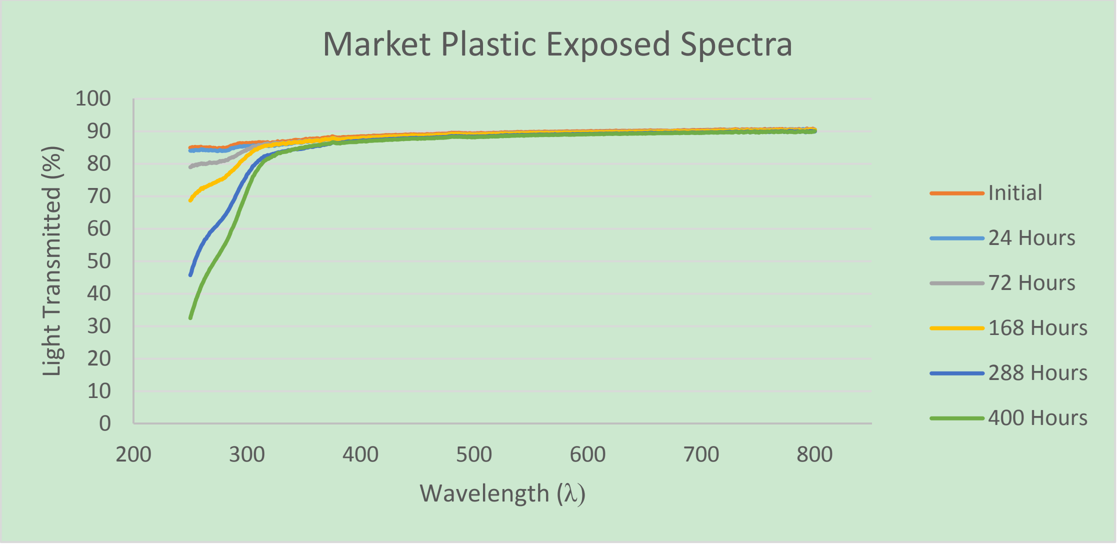

Figure 8. Cameroonian Market plastic spectra after 400 hours of simulated exposure

A qualitative analysis of the materials is shown in Figure 9. As can be seen, the market plastic was fully brittle by the end of the test. The material began showing signs of disintegrating around the 168hr (255.5 days) mark. As expected the DuraFilm greenhouse glazing remained intact through-out the entire test process, although at the last benchmark it showed a foggy discoloring. This is an interesting result because, while it would still be physically intact as a glazing, the opaque discoloring would prevent PAR from entering the greenhouse and consequentially cause severe harm to crop growth.

Figure 9(a)

Figure 9(b)

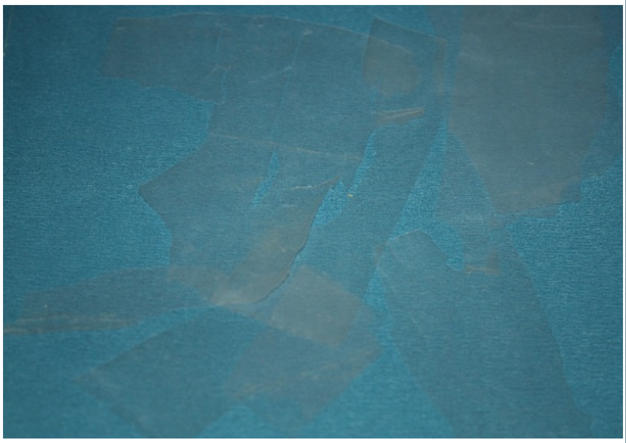

Figure 9(c)

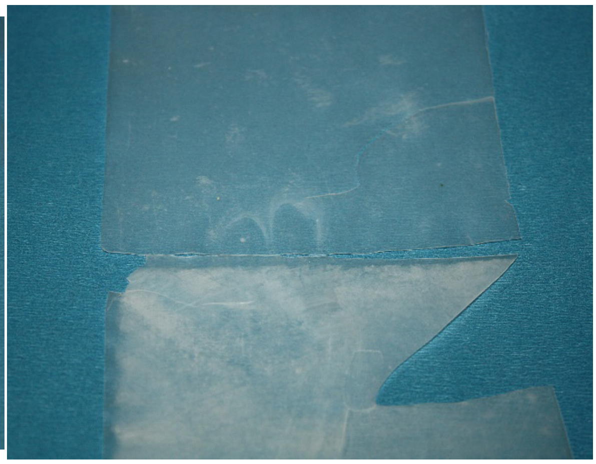

Figure 9(d)

Figure 9. Market plastic and DuraFilm glazing before and after experiencing 600 days of simulated exposure to sunlight. (a) Market plastic at 0 hours, (b) DuraFilm plastic after 0hrs, (c) Market plastic after 400 hours, (d) DuraFilm plastic after 400 hours

2.2.3 Test Phase 3 – Water Conservation

The ratio of water transmitted through the Polyethylene plastic to the standard greenhouse glazing was determined using a modified ASTM E96 cup method (ASTM Standard E96-95, 1995e1 n.d.). Two identical buckets were obtained and samples of the Polyethylene market plastic as well as the standard greenhouse glazing were cut slightly larger than the opening of the buckets. The buckets were filled with six liters of water and then the PE sample was securely attached over the opening of the first bucket and the greenhouse plastic was similarly attached to the other bucket. The buckets were then weighed on a Camry EK9150 kitchen scale to establish an initial data point. The buckets were then placed outside in State College, PA at an open location that received direct sunlight for approximately 10 hours a day. The buckets were weighed weekly from 21 May 2014 to 20 August 2014 and were only moved inside when weather conditions (strong wind, heavy rain, etc) threatened the integrity of the experiment.

Both buckets were filled with water and the initial weight measurement for the DuraFilm bucket was 3.57 kg and the market plastic bucket was 3.66 kg, as can be seen in Figure 10. Because of the initial discrepancy of 0.08 kg between the two bucket weights a third data set was created which represents the weights of the DuraFilm Plastic shifted up the 0.08 kg difference. It can be seen that the DuraFilm plastic allows more water vapor to pass through the material over time. The difference between the water transmitted through both materials is never greater than 0.11 kg however, so both plastics were determined to be comparable when considering water transmission.

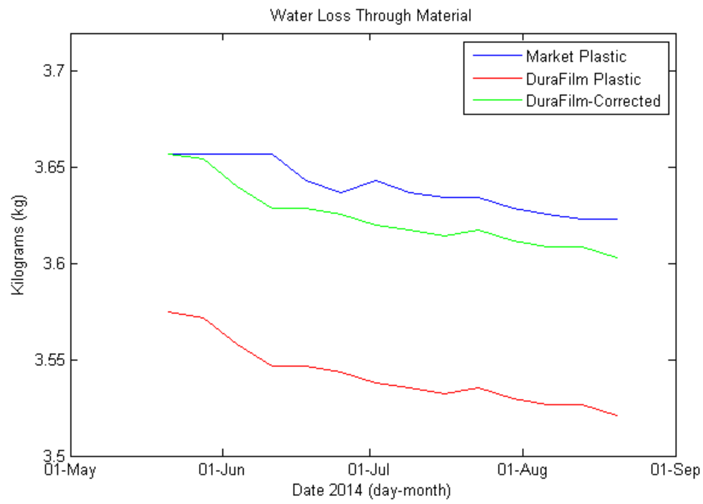

Figure 10. Comparison of water transmitted through the DuraFilm glazing and the Market Plastic

3. Discussion

The results of the rice bag testing shows that rice bags may not serve as perfect replacements for standard greenhouse glazing however; they are still an affordable way to protect crops from harsh weather and pests and could serve instead as shade nets for the plants. Shade nets are a valuable tool that allows farmers to protect certain crops from potentially harsh sunlight. Seedlings are often grown under such nets, and then transferred to other locations to grow until full yield. Like a greenhouse, shade-houses will still be constructed so that water will be conserved within the system. Also, they can be used to create a separate micro-climate inside the growing structure which enables increased growth rates in crops, as well as the ability to grow plants not typically seen in that region. This can be advantageous for farmers because it will allow them to bring a different variety of crops to the market, increasing the potential for profit (Pack and Mehta 2012). The data also reveals that bubble wrap may be a good choice for an inexpensive alternative to typical greenhouse plastic. It can also be purchased locally, mostly as waste from other imported goods in East Africa and in many places around the world, ensuring that the carbon cost of creating our greenhouses remains at a minimum. The rapid degradation of the rice bag material will result in the need to frequently replace the shade net structures. While a coating substance could be applied to extend the life of the material, it is more economical to simply replace the very inexpensive rice bags as needed.

The second set of testing revealed that ground tarp plastic, readily available in a diverse set of regions, could be a potential replacement for the greenhouse glazing. It allows a very similar array of PAR into the greenhouse, though it is not as strong at resisting ultraviolet radiation as typical greenhouse plastics. This can be overcome by developing a coating solution for the material, but due to manufacturing difficulties, as well as cost, this may not be the best option. Instead, creating a business model for the Affordable Greenhouse that incorporates replacing the glazing every 2 or 3 years may prove to be more worthwhile. While this is not an optimal solution, it lowers the risk of purchasing a high-cost glazing designed to last 5 years, only to have it tear after a couple months. Further research on this topic could include determining the effectiveness of the rice bag material as a shade net as well as the need for such a system. Farmers in Kenya and Cameroon have been observed using plantain or banana leaves as makeshift shade netting so the demand is very likely present. Additionally determining the cost and effectiveness of a coating material for the Polyethylene market plastic would be beneficial in taking the next step towards introducing the plastic into the standard Affordable Greenhouse design.

4. Conclusion

Higher crop yields, decreased fertilizer use, and decreased water use contribute to an overall increase in resource productivity. Two of the UN Millennium Development Goals in particular are directly addressed by this increase in productivity: the eradication of hunger and poverty, as well as ensuring environmental sustainability. Hunger and poverty are reduced through higher crop yields, a result of both extended growing seasons and climate control within greenhouses. This serves to empower not only farmers, but also the transporters and retailers along the food supply chain. Farmers reap the benefits of more consistent income and more stable outputs since they are able to mitigate impact of weather, both on a day-to-day and seasonal basis. They are able to maximize profit by growing plants when they are not typically available in local markets. In addition, some fruits, such as tomatoes, are particularly sensitive to sudden changes in rainfall, especially during their latter stages of growth. They tend to bruise and become tender, making transport without ruin difficult, especially when coupled with the questionable road conditions that may arise in rural areas and developing countries. For retailers, greenhouses act as a constant source of supply, contributing to less seasonal volatility in prices. Retailers in open-air markets, particularly in developing countries, tend to rely on smaller farm operations and therefore are subject to sudden price changes due to regional weather changes or pest outbreaks.

While these qualitative measurements of the impact of greenhouses on rural agriculture in developing communities are readily apparent, quantitative measurements are more difficult, though not impossible to make. For example, due to construction, some global warming impacts are larger with the greenhouse mostly due to the un-recycled plastic glazing; however, the decreased water use, pesticide use and increased land productivity that they allow have other important socio-ecological benefits. Use of alternative, recycled glazing materials versus virgin material, most likely shipped from China, reduces the total amount of carbon dioxide (CO_2) produced by the construction process. Assuming the virgin material is made of high density polyethlyne resin with a weight of 20.3 kg (conservatively, one greenhouse), this results in a net reduction of 62.2 kg CO2 equivalent. A Life Cycle Analysis of both greenhouse and open-air tomato production in the Mediterranean (Muñoz, et al. 2008) showcases both the benefits of greenhouses in general and ultimately leads to the need for alternative glazing materials. The study looked at several different impact categories, including eutrophication, ozone depletion, greenhouse gas emission, and ecotoxicity. They found that due largely to the difference in yields, greenhouse farming was far superior, and thus an essential part of sustainable development. By continuing to discover methods to reduce the negative impacts of greenhouse construction, most importantly the glazing material, it is possible to further increase the sustainability of greenhouse farming and improve the lives and livelihoods of all actors along food value chains in developing countries.

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