*sustainability*

*Review*

# Environmental Sustainability of Greenhouse Covering Materials

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**Abstract:** The fundamental objective of the review article was to explore the ecological sustainability of greenhouse covering material based on the following themes; considerations for greenhouse materials, properties of polymers and glass, additives, fillers, stabilizers and reinforcements, performance, Ultraviolet (UV) transmittance, phase change materials (PCMs), and environmental sustainability. A comparison of various polymers (polyvinyl chloride (PVC), acrylic, D-polymer, Linear low-density polyethylene (LLDPE), polyolefins), and silica glasses illustrated that each type of greenhouse cladding material has its unique merits and limitations. The performance of silica glasses, PVC, polyolefins was influenced by weather, greenhouse design, plant under cultivation, percentage UV transmittance, incorporation of additives and stabilizers, reinforcements, and integration of photovoltaic panels into the greenhouse roof among other factors. Polymers can be customized to achieve 0%UV transmittance, slow-insecticide release, and anti-microbial properties. In contrast, glass materials are preferred based on suitable photosynthetically active radiation (PAR) transmittance and near-infrared (NIR) reflection and less risk of photo-oxidation. From an ecological perspective, polymers can be recycled via mechanical and chemical recycling, closed-loop cycling, and polymerization of bio-based feedstock. However, post-consumer plastic films do not possess the same optical and energy properties as virgin polymers. The combined benefits of different polymers suggest that these materials could be adopted on a large scale over the long-term.

**Keywords:** cladding materials; greenhouse; environmental sustainability; plastics; glass; semi-transparent solar panels; ultra-violet radiation

## 1. Introduction

Greenhouse structures are central to the sustainability of modern civilizations considering the unreliability of traditional methods of farming, global population increase, and a projected increase in food and energy demand. Hassanien and co-researchers estimate that global food demand would increase exponentially by 2050 [1]. Industrialization and post-industrial growth have induced anthropogenic degradation of the environment [2], leading to global warming and climate change and unpredictable weather patterns, which diminish the reliability of rain-fed agriculture, especially in arid and semi-arid areas. These factors underscore the need for commercial farming in controlled environments such as greenhouses [3]. The ecological sustainability of greenhouse covering materials is considered in the context of energy sustainability [4,5], global production of PET [6], energy-efficient materials [7–11] and customized optical properties [12], and synthesis techniques [13].

This research article explores the ecological sustainability of the materials utilized in the cladding/covering of greenhouses. The primary emphasis is placed on radiometric and physical properties such as the heat transfer coefficient, absorptivity, UV and IR reflectivity, and transmissivity [14]. The properties determine photo selectivity and ability of the material to filter ultraviolet radiation (UV) and infra-red (IR) radiation and achieve the desired cooling effect [14]. The protection against UV-B is critical, given radiation levels between 280 nm and 315 nm damage plants and inhibit photosynthesis by triggering stress and photomorphogenic responses [15]. In contrast, UV-A radiation does not have significant adverse effects on plants and is of minimal importance in the selection of cladding materials for greenhouses [15]. The selection of greenhouse materials is also informed by seasons; this is because seasons determine the variations in energy and heat requirements in summer (in the south) and winter (in the north) [16]. In particular, materials with a high transmittance coefficient are suitable for constructing greenhouse materials during winter because they do not filter out photosynthetically active radiation (PAR) [17]. In contrast, materials possessing high PAR coefficients are unsuitable during summer due to the risk of overheating and the need for alternative cooling such as evaporation cooling.

Standard greenhouse covering materials are glass [18], plastic sheets, and films, double or single glazing, and the material characteristics of interest for greenhouse cladding are thermal efficiency and optical properties because they determine radiation control, heat transfer, UV, soil [19], and IR absorbance or transmittance [20,21]. The values listed in Table 1 confirm the variations in energy and optical properties depending on the composition and cross-linking of the polymers; the least energy transmittance was reported in VPVC-cladded greenhouse (τPAR = 30%). The highest was glass (GL) at 89% [22]. The symbols τPAR, ρPAR, Q denote energy transmission, reflectance, and absorption, and quantum transmission. Q is a predictor for plant yield efficiency (ɳ) and other plant-related coefficients. In particular, there is a positive and direct correlation between Q and ɳ. Another practical observation is the impact of layers [23]—multilayer plastic sheets have better mechanical properties, but thickness could impact PAR transmittance.

**Table 1.** Optical and energy properties of greenhouse covering materials [22].

| Type of Material | τPAR | ρPAR | αPAR | τNIR | ρNIR | αNIR | Q |
|---|---|---|---|---|---|---|---|
| Glass | 84 | 6 | 10 | 73 | 7 | 20 | 83 |
| Low-density polyethylene film (LDPE) | 83 | 8 | 9 | 87 | 8 | 5 | 85 |
| Thermal polyethylene film (TPE) | 83 | 8 | 9 | 85 | 9 | 6 | 84 |
| Bubbled polyethylene plastic film (BPE) | 63 | 14 | 23 | 68 | 14 | 18 | 63 |
| Ethylene-vinyl acetate (EVA) | 89 | 8 | 3 | 89 | 7 | 4 | 89 |
| Three-layer (3L) coextruded film comprising of EVA and TPE | 86 | 8 | 6 | 88 | 7 | 5 | 86 |
| Violet colored polyvinylchloride-based film (VPVC) | 39 | 8 | 52 | 74 | 10 | 16 | 39 |
| Rose-colored polyvinylchloride-based ßuorescent material (FPVC). | 59 | | | 76 | | | 62 |

Beyond the material properties, the selection of the greenhouse materials is influenced by the energy requirements of the plant [4,15], budget, photo-oxidation resistance, weather, design of the greenhouse (Quonset, arch-tunnel, even-span, and uneven span) [3,24,25] and environmental sustainability (recyclability) [6,7]. The shape of the greenhouse structure is critical because it determines aperture efficiency and radiant energy capture [26]. Optimal aperture efficiency has been recorded in greenhouses with zero incident angles. Greenhouse covering materials with carbon-intensive supply chains such as plastics increase greenhouse gases [27]—a factor that can be regulated through closed-loop recycling [7], mechanical and chemical recycling [28,29].

Fiberglass greenhouse cladding materials pose challenges in the recycling process and have the least transmissivity. However, they are suitable for the covering of greenhouse structures in hot and arid areas to prevent energy losses and maintain internal cooling [24]. In contrast, 200 µm thick plastic sheets are ideal for tropical regions. A comparative analysis of different greenhouse materials (D-poly, acrylic, and glass) in cucumber cultivation affirmed that glass was most appropriate [4]. In contrast, eggplants achieved the best growth rates and canopy in greenhouses cladded with 0% UV plastic films [15]. Best tomato production was recorded in experiments where the biodegradable paper was used as mulching material in place of plastic film or bio-based films [30]. The results illustrate that the type of plant dictated the choice of greenhouse covering or mulching material. The environment also predicts the service life of the materials because plastic sheets are susceptible to photo-degradation—a process that is triggered by intense solar radiation and heat in arid and semiarid areas [9].

## 2. Properties of Greenhouse Materials

Greenhouse materials (such as plastic films) that possess ideal optical properties allow plants to absorb ultraviolet B (UV-B) radiation. UV-B radiation is beneficial because it triggers the release of secondary metabolites beneficial to human health. Metabolites such as polyphenols, carotenoids, lycopene, and anthocyanins have been proven useful in the prevention of cancer and cardiovascular diseases [31]. Moreover, plants grown under a greenhouse are exposed to fewer pathogens and fungal infections [15]. A lower exposure to pathogens translates to higher agricultural yields. On the downside, the benefits afforded by UV-B radiation involve a tradeoff between the stimulation of the metabolites and delayed crop time.

The customization of the optical properties of greenhouse covering remains an issue of interest in research. According to Mormile and co-researchers, a UV amount of 0.5–10 $KJm^2$ $d^1$ is theoretically ideal. However, experimental evidence is required to validate the theoretical propositions. The standard types of greenhouse covering materials are critiqued in the main body of the article to determine the most appropriate material from an environmental sustainability perspective.

According to Hao and Papadopoulos, the exploration of alternative and new cladding materials for greenhouses beyond the glass was triggered by the oil crisis in the 1970s and the 1980s [4]. The energy crisis motivated researchers to investigate materials whose production process was energy efficient. Research on greenhouse cladding materials has also been informed by sustainability considerations, namely $CO_2$ emissions and the need to conserve energy due to the depletion of fossil fuel reserves. Recent research suggests that plastic films and sheets are effective in the conservation of energy in greenhouses, given they utilize minimal energy compared to heating, ventilation, and air conditioning (HVAC) systems [25]. The claims concerning low energy use are further validated by the life-cycle assessment of plastic sheets and films.

Higher energy is conserved through the utilization of multiple layers of plastic films. However, the adoption of this approach involves a tradeoff between heat retention and loss of light—the incorporation of each additional sheet translates into a 10 percent loss of light [4]. The loss of light might compromise photosynthetic processes and impact plant growth. Sustainability concerns in crop production and the need for ideal pest control management systems and organic cultivation [15] have informed the development of greenhouse materials with customized properties such as higher photo-selectivity and slow insecticide release capabilities [32,33]. Other properties associated with modern greenhouse materials are limited droplet formation, reduced heat losses, accumulation of dust, and transmission of a particular wavelength of light [14,31,32,34].

### *2.1. Impact of North Wall Materials for Chinese-Type Greenhouses and Mulching on Greenhouse Microclimate*

Even though cladding materials influence plant growth rates and the quantity of PAR and UV-A radiation, the performance of the greenhouse materials and microclimate is also predicted by the usage of plastic-based mulching or bio-based mulches [30,35]. Heat retention in greenhouse structures is dependent on the type of materials used in the construction of the greenhouses. According to [30], the performance of wall materials varies depending on locality—greenhouses in arid and semi-arid areas require better insulation from heat, while pure and bioplastics have different levels of susceptibility to UV degradation. Plastic films experience the least deterioration (1.5.to. 4.5 percent) while bio-based films are degraded 100 percent.

The Chinese prefer fired clay blocks and compacted clay as shown in Figure 1 [21] while the construction of greenhouse walls and roofs using one material such as glass or plastic films and sheets is common in other countries [14,34,36]. Zhang and co-researchers reported low conductivity in the clay bricks constructed with agricultural waste (0.280 W $m^{-1}k^{-1}$) compared to porous clay blocks. The surface and cross-sectional morphology of glass straw-clay and porous clay blocks are depicted in Figure 2. The incorporation of plant materials to the clay yielded better performance in heat storage and heat absorption from the ambient. In general, the clay blocks have higher thermal conductivity compared to polystyrene boards (0.04 W $m^{-1}C^{-1}$). A lower thermal conductivity is an essential requirement in heat conservation, especially during winter.

**Figure 1.** Clay Chinese greenhouse north wall [1].

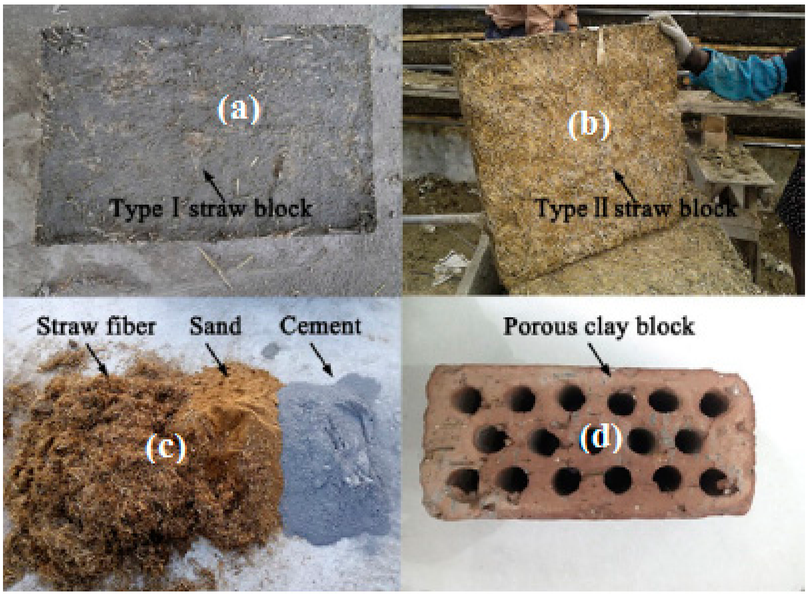


**Figure 2.** Straw fiber (**a**–**c**) and porous clay (**d**) blocks for greenhouse walls [1].

A comparative analysis of bio-based, plastic and biodegradable paper mulching materials by Zhang and co-researchers [30], Briassoulis and Giannoulis [35] in China and Greece, respectively confirmed the impact of mulching materials on plant growth (root to shoot ratio, plant biomass, root morphology, and fruit quality) and the greenhouse microclimate (electrical conductivity, pH, moisture, temperature), and presence of nutrients and enzyme.

## *2.2. Types of Greenhouse Covering Materials*

### Glass, Plastic Sheets, and Films

The primary materials used in greenhouse cladding are glass, plastics (sheets and films), fiberglass reinforced plastics, biodegradable paper (synthesized from degraded coal or plant straw), shade cloth [36], polycarbonates, poly (lactic acid) (PLA), and polyhydroxyalkanoates (PHA) [18,30,37]. Glass is preferred as a cladding material for greenhouses due to its high transmission of PAR and reflectance of NIR leading to diminished greenhouse energy balance. In contrast, the transmission of NIR is higher in plastic sheets and films [24]. In general, plastic materials provide the least protection against night-time IR radiation compared to glass. Therefore, glass structures are suitable for plants sensitive to IR radiation. On the downside, even though fiberglass has suitable mechanical properties, it has the least desirable optical properties—such as the least light transmissivity [24].

Secondary materials include semi-transparent solar panels [1], plexiglass (rigid polymethyl methacrylate PMMA) [34], and PP nonwoven fabric Agril [24,36]. The ecological sustainability of plastics and glass was emphasized in the current review article because these materials offer distinct benefits and are affordable and commonly available. On the one hand, plastics can be molded into different shapes and casts. In addition, plastics act as electrical insulators, are resistant to acids and bases, and possess unique thermal properties and stress resistance [38]. The plastic sheets are mainly made of fiberglass, polymethyl methacrylate, or polycarbonate [39,40]. In most cases, the plastic materials are preferred because they possess the ideal UV light transmission, heat retention capabilities, ideal transmission in the photosynthetically active radiation (PAR) bandwidth [41], and are durable.

Durability is traded off with flexibility and performance in the use of plastic films, which are made of polyvinylchloride (PVC), ethyl vinyl acetate, polyethylene [40]. However, the polymer sheets should be UV-stabilized to enhance the longevity of the structures by up to 3 years [18]. Polymer sheets that are not exposed to UV stabilization degrade within 3-5 months due to UV radiation damage and other multiple photochemical reactions. In addition to UV-treatment and stabilization, the ecological sustainability of plastic films and sheets can be enhanced through the integration of bioplastics such as polycarbonates, poly (lactic acid) (PLA) and polyhydroxyalkanoates (PHA), which are synthesized from the fermentation of starch [18,37]. In particular, Shogren and co-researchers noted that the demand for bioplastics has been on the rise. In 2019, 460 million lbs of bioplastics were manufactured. However, universal adoption has been curtailed by cost, as illustrated in Table 2 [37]. The bio-plastics are slightly expensive compared to petroleum-based plastics; it costs between €0.77–0.81 to manufacture petroleum-based plastics such as PVC, PP, PET, thermal polyethylene film (TPE), ethylene-vinyl acetate film (EVA), and three-layer co-extruded film (3L) [17]. In contrast, it costs up to €12.00/kg to manufacture polyhydroxyalkanoates (PHA). Therefore, PLA and PHA plastic films are not suitable from an economic dimension. However, the higher costs are offset by ideal material properties such as elongation at break, tensile strength, and the glass transition temperature, as illustrated in Table 3. From another dimension, the cost factors can be resolved through research and development and synthesis of new materials.

**Table 2.** Cost comparison between petroleum-based and bio-plastics [37].

| Material | Source | Price (€/kg) |
|---|---|---|
| Lignocellulose fiber | Plant | 0.4–1.2 |
| Cellulose esters/ethers | Plant/petrochemical | 4.0–20.04 |
| Starch | Plant | 0.2–2.0 |
| Starch/polymer blends | Plant, Plant | 2.0–4.0 |
| Polylactic acid | Plant | 0-2.0 |
| Polyhydroxyalkanoates (PHA) | Plant | 4.0–12.02 |
| Polyethylene (PE) | Petrochemicals | 1.31–1.6 |
| Polypropylene (PP) | Petrochemicals | 1.71–2.0 |
| polyethylene terephthalate (PET) | Petrochemicals | 1.71–1.8 |
| PS | Petrochemicals | 2.0–2.4 |
| Polyvinylchloride (PVC) | Petrochemicals | 1.71–2.02 |

**Table 3.** Comparison of the material properties (thermal and mechanical) of plant-based and petroleum-based polymers [37].

| Material | Tensile Strength (MPa) | Elongation at Break (%) | Glass Transition Temperature (°C) | Melting Temperature (°C) |
|---|---|---|---|---|
| Kraft paper | 68 | 3 | | |
| Cellulose acetate | 90 | 25 | 110 | 230 |
| Corn starch | 40 | 9 | 112 | |
| PLA | 59 | 2–7 | 55 | 165 |
| PHA | 15–50 | 1–800 | 12–3 | 100–175 |
| PBS | 34 | 560 | −32 | 114 |
| PBAT | 22 | 800 | −29 | 110 |
| PEF | 35–67 | 3–4 | 85 | 211 |
| PTT | 49 | 160 | 50 | 228 |
| PE | 15–30 | 1000 | −125 | 110–130 |
| PP | 36 | 400 | −13 | 176 |
| PET | 86 | 20 | 72 | 265 |
| PS | 30–60 | 1–5 | 100 | – |
| PVC | 52 | 35 | −18 | 200 |

According to Al-Mahdouri [39], PVC and glass-reinforced polyester are UV-resistant, UV stable and thermally efficient, and can be effectively employed as thermal collectors. An issue of concern is that plastic cladding is associated with multiple undesired mechanical, thermal, and optical properties such as limited insulation capabilities in winter or tropical climate, which translate to lesser energy efficiency. Other negative effects of these materials include unregulated optical properties [42].

The above listed suitable properties illustrate why plastics are increasingly used as substitute products in place of glass in greenhouse cladding [39,40]. Even though thermoplastic and thermosetting and plastics possess ideal properties compared to glass, their application is impacted by environmental considerations because plastics are not biodegradable and are categorized as pollutants [12]. Therefore, the integration of plastic materials in greenhouses involves a tradeoff between performance and environmental degradation. On the other hand, glass has the highest heat protection (>90 percent) compared to plastic sheets and films [39,40]. Similarly, Reddy noted that heat retention in glasses was higher compared to other materials [18]. The benefits afforded by heat protection are offset by periodical variations in light transmissivity characteristics as the glass ages [18]. Moreover, glass installation is capital intensive, and there is a pronounced risk of damage due to brittleness and structural imperfections—a phenomenon that is attributed to the broad grain boundaries and low tensile strength and young's modulus [43]. In general, glass has critical limitations that impede its utilization in greenhouse cladding. However, low heat protection can be customized through the modification of the material properties.

### *2.3. Additives, Fillers, Reinforcements, and Colorants*

The properties of plastics such as heat resistance, heat loss, droplet formation, and dust forming on the film can be improved through the integration of functional additives, fillers, air bubbles [44], reinforcements (glass or carbon fibers), and colorants as illustrated in Table 4. Functional additives include stabilizers and UV absorbers whose core function is to prevent damage to plants; UV-B above 40 $KJm^2$ dcauses radiation damage to greenhouse plants [31]. The additive also predicts the UV and IR transmission rates - commercially available materials have transmission rates of between 0.7 and 0.9 [24]. Ethyl-vinyl-acetate, anti-fog, and infrared additives are also integrated into the plastics to prevent fog formation and transmission of harmful IR radiation [15]. Even though the stabilizers improve the optical and mechanical properties of the cladding materials for greenhouses, selected stabilizers contain heavy metals such as lead and cadmium, which are toxic to human health (cytotoxicity) [2,45]. Nonetheless, heavy metal stabilizers do not pose any direct risk to plants grown under greenhouses covered with PVC materials in-situ—the risk emerges during recycling. Even though there is a minimal risk in-situ, concerns about cytotoxicity and heavy metal contamination of plants have informed the synthesis of biopolymers-based photo-catalysts made of gelatin, agar, or chitosan [2].

**Table 4.** Classification of the standard plastic additives [2].

| No | Type of Additive |
|---|---|
| 1 | Functional additives such as stabilizers |
| 2 | Fillers such as clay and kaolin |
| 3 | Reinforcements such as carbon fibers and glass |
| 4 | Colorants (pigments) |

In addition to the customization of the optical properties of the cladding materials, additives and stabilizers such as carbon black reduce the risk of photo-degradation and UV damage on plastic films and sheets, and by extension, the durability of the greenhouse structures [9]. Standard reinforcements for greenhouse covering materials and walls include fiber textiles (hemp linen, jute burlap, and hemp burlap), which are integrated into bio-based plastics to form composites. Mechanical tests established that hemp line composites had the highest ultimate tensile strength (UTS) 83.5 MPa [13], percentage elongation, and resistance to creep deformation. Reinforced hemp linen composites can be employed as substitute materials to straw fibers and porous clay blocks [21] or concrete in the construction of greenhouse walls based on the mechanical properties.

Apart from preventing the radiation damage of plants, the additives and UV absorbers prevent the growth of pathogens (pest and disease) [3]. Additionally, the infrared light absorbers (generally in the range between 700 and 2500 nm) suppress heat losses and prevent longwave radiation. Similarly, the long wave absorbers (2500–40,000 nm) suppress heat losses from the plants shielded by the greenhouse while the light diffusers facilitate the dispersion of light within the greenhouse, which prevents the light burn phenomenon. The surfactant and antistatic agents help to reduce the accumulation of dust on the plastic film and the surface tension, respectively [12]. Other additives that are employed to augment the performance of greenhouse plastic additives include red light emission enhances, glossy surfaces, and color pigments. However, the latter have minimal benefits in greenhouse cladding and are briefly reviewed below.

As illustrated in Table 5, the functionality of the materials for greenhouses is also augmented by pigments (pigment volume fraction). Aldaftari and co-researchers reported the effectiveness of diamond particle-based pigment in radiation control in greenhouse cladding materials [20]. The use of pigments in radiation control offers a low-cost alternative compared to the utilization of air conditioning systems (HVAC). In contrast to the pigments, diamond particle-based and $TiO_2$ pigment possessed unique optical properties—the coatings facilitated the reflection of incident radiation in the near-infrared region (800 to 2500 nm) but transmitted shorter visible wavelength [20].

The mechanism of action of the diamond-based pigments yielded the following benefits. First, it reduced the quantity of heat in circulation within the greenhouse. Second, it provides sufficient light for photosynthesis. Beyond diamond particles, there are other materials employed in the development of radiation protection pigments for greenhouse materials, as shown in Table 4. Following the comparison of diamond particles with $TiO_2$ particles (the standard), the former material possessed the best properties - transmittance was highest in the shorter visible wavelength (VIS). In contrast, the reflectance of light was most pronounced in the near-infrared region [20]. In place of diamond-particles, $TiO_2$ can be employed in low-cost applications because the material also exhibits significant scattering efficiency (d = 1.19 μm) in the NIR and pronounced transmittance (~95%) in the VIS region for particles with a diameter of 0.1 μm as shown in Figure 3 [20]. The only challenge is the impact of particle sizes on scattering efficiency and transmittance—higher particle diameters led to more significant scattering efficient but lower transmittance. The mechanism through which the black body emissions schematics illustrate the particle sizes influence transmittance and scattering efficiency in the VIS and NIR regions in Figures 3 and 4.

**Table 5.** Pigment volume fraction (fv), optimization parameter (OP), and particle diameter of selected pigments for greenhouse cladding materials [20].

| Material | d[μm] | fv [%] | OP | Material | d[μm] | fv [%] | OP | Material | d[μm] | fv [%] | OP |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Diamond | 1.19 | 0.89 | 0.32 | Zr | 0.39 | 0.09 | 0.12 | CuO | 0.7 | 10 | −0.05 |
| GaN | 1.42 | 1.13 | 0.31 | Ti | 0.39 | 0.09 | 0.11 | Fe2O3 | 0.59 | 10 | −0.07 |
| AlN | 1.96 | 2.15 | 0.27 | TiC | 0.39 | 0.09 | 0.11 | Air | 5.88 | 10 | −0.07 |
| LiI | 3.48 | 5.99 | 0.26 | VN | 0.39 | 0.09 | 0.11 | LiCl | 14.25 | 10 | −0.08 |
| $HfO_2$ | 2.15 | 2.78 | 0.26 | Be | 0.35 | 0.1 | 0.09 | Al2O3 | 14.25 | 10 | −0.09 |
| $ZrO_2$ | 1.96 | 2.15 | 0.26 | W | 0.35 | 0.1 | 0.09 | Ethanol | 4.12 | 10 | −0.09 |
| $LiNbO_3$ | 1.94 | 2.15 | 0.25 | TiN | 0.35 | 0.1 | 0.06 | ZnO | 2.89 | 10 | −0.09 |
| $KNbO_3$ | 1.94 | 2.15 | 0.23 | Pt | 0.35 | 0.1 | 0.04 | LiF | 3.46 | 10 | −0.13 |
| $Si_3N_4$ | 2.87 | 4.64 | 0.22 | Ni | 0.35 | 0.1 | 0.03 | KF | 4.92 | 10 | −0.13 |
| LiBr | 7.11 | 20 | 0.21 | Zn | 0.35 | 0.1 | 0.02 | KI | 17.01 | 10 | −0.13 |
| Mg | 0.39 | 0.11 | 0.2 | Al | 0.35 | 0.1 | 0.01 | MgF2 | 4.92 | 10 | −0.13 |
| $Nb_2O_5$ | 1.37 | 1.29 | 0.18 | Pb | 0.35 | 0.1 | 0 | CaF2 | 2.42 | 10 | −0.14 |
| $Y_2O_3$ | 3.83 | 7.74 | 0.18 | Cu | 0.49 | 10 | 0 | NaBr | 20.31 | 10 | −0.14 |
| Graphite | 0.46 | 0.09 | 0.16 | SiC | 0.7 | 10 | 0 | KCl | 0.59 | 10 | −0.14 |
| TiO2 | 0.97 | 0.7 | 0.15 | Au | 0.35 | 10 | 0 | NaNO3 | 28.94 | 10 | −0.16 |
| Cr | 0.5 | 0.11 | 0.14 | Co | 0.41 | 10 | 0 | CaCO3 | 28.94 | 0.01 | −0.16 |
| $TiSi_2$ | 0.39 | 0.09 | 0.12 | MoO3 | 1 | 10 | −0.01 | Quartz | 28.94 | 0.01 | −0.16 |
| $Fe_3O_4$ | 1.15 | 0.28 | 0.12 | InP | 0.49 | 10 | −0.03 | NaCl | 28.94 | 0.01 | −0.16 |
| VC | 0.38 | 0.09 | 0.12 | H2 O | 4.92 | 10 | −0.04 | KBr | 28.94 | 0.01 | −0.16 |

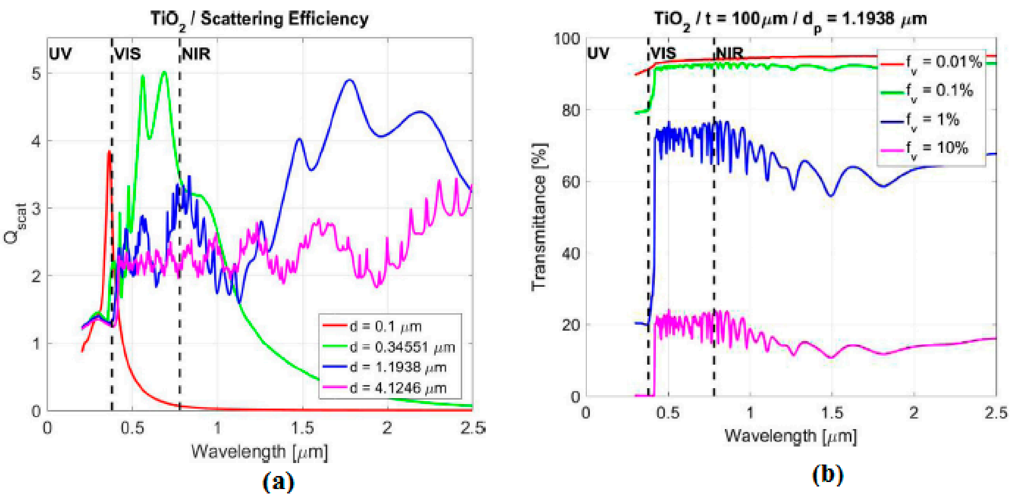


**Figure 3.** Scattering efficiency (**a**) and transmittance (**b**) of TiO2-based pigments [5].

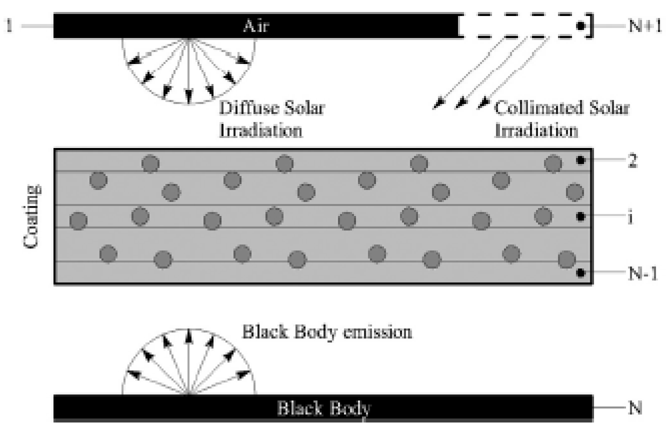


**Figure 4.** Black body radiation phenomenon [5].

Apart from acting as pigments for greenhouse cladding materials, $TiO_2$ nanoparticles have been used to develop nano-based coats for transparent solar distillers (TSD), which are multipurpose greenhouse cladding materials that are also used to harness solar energy to desalinate water [46]. Rabhy and co-researchers note that the application of the $TiO_2$ nanoparticle-based coat improved the optical and thermal properties of the absorber layer—precisely the rate of condensate formation and daily yield.

Beyond the modification of the optical properties of polymers, $TiO_2$ has biocompatible antimicrobial properties [2], which are essential for plant growth, considering fungal and bacterial infections retard plant growth. Additionally, novel polymers such as LLDPE with slow-releasing capabilities for pesticides have been developed to suppress the spread of insect-vector diseases in plants such as tomato yellow leaf curl disease [33,47]. The mobile release capabilities are augmented by halloysite nano-composite films [33]. However, the development of novel polymers introduces new health challenges for humans as noted by Seven and co-researchers [4]. Such health concerns have not been effectively addressed.

### 2.4. Distillers

Apart from the incorporation of the pigments, the performance of the greenhouse materials for greenhouses can be modified through the incorporation of the solar distillers [6] and organic PVs. Standard materials for solar cells are phenyl-C61-butyric acid methyl ester (PCBM) and are poly (3-hexylthiophene) (P3HT) and fullerene-conjugated polymer derivatives. The organic materials are preferred due to suitable charge transfer and optical absorption properties compared to silicon materials [7]. The roll-to-roll process can address the cost barriers in organic PV materials.

The solar distillers feature photovoltaic solar cells, which convert solar radiation to energy. The energy is consequently used to generate desalinated water for commercial agriculture. In addition to the distillation of water, the distillers reduce the in-house temperatures and the incident solar radiation through condensation and evaporation as shown in Figure 5 [11]; it is of note that there are three layers namely the cover glass, water layer, and the absorber glass and insulation layer. The second layer poses a challenge due to the high levels of transmission—a phenomenon that is regulated by absorber glasses with low transmittance of infra-red radiation. In principle, the distillers achieve the same function as pigments and additives in the transmission and reflection of infrared and UV radiation [11]. However, in contrast to the traditional systems, the performance (transmittance and reflectance) of the solar distillers is influenced by the rate of plant transpiration, mass flux, which are calculated using the governing equations below. The ideal roof pitch angle varies between 15 and 42 °C [8]. However, the pitch can be influenced by latitude. Low altitude areas are warmer and therefore require higher roof pitches to control internal air temperatures.

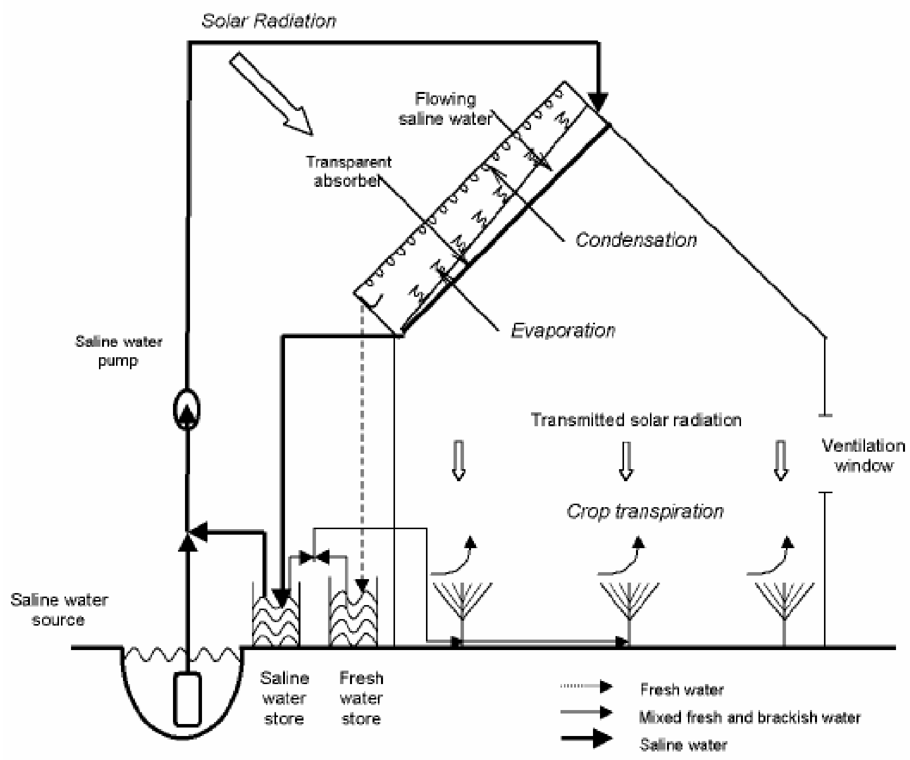


**Figure 5.** Solar distillers as greenhouse covering materials [9].

### 2.4.1. Mass Flux

The mass flux of the solar distillers is influenced by the parameters outlined in Equation (1), where pw and pg denote partial pressures of water vapor at saturation for the water and the glass; hc denotes heat transfer coefficient for convention and L is the latent heat of vaporization of the water [11]. Mass flux is also influenced by the ambient temperature, given that there is a direct link between ambient temperature and partial pressures.

$$m = 16.273\ 10^{-3} h_c \left(p_w - p_g\right) / L \tag{1}$$

### 2.4.2. Transpiration Rate

The following parameters in Equation (2) define the transpiration rate of the crops; Iabs - the amount of long and short wave radiation absorbed by the crop canopy per unit area. S—the thermal energy generated or stored by the plant canopy as a result of biochemical reactions such as photosynthesis. However, the role of thermal energy can be disregarded in transpiration calculations. LAI, re, and ri -denotes the leaf area index. External canopy resistance, internal canopy resistance to vapor flow, respectively. In addition, ea and eas denote the true vapor pressure of air and the saturated vapor pressure, respectively. The green symbols γ and δ denote psychrometric constant and the "slope of saturation vapor pressure curve" [11].

$$W_{tr} = \frac{\frac{\delta}{\gamma}\left(I_{abs} - S\right) + \frac{2LAI\rho C_P}{\gamma \cdot re}(eas - ea)}{\left(1 + \frac{\delta}{\gamma} + \frac{ri}{re}\right)L} \tag{2}$$

2.4.3. Reflectance and Total Transmittance

Apart from the transpiration rates and the mass flux, the performance of the solar distillers is influenced by the reflectance coefficient, as demonstrated in Equations (3) and (4); it is of note that the wavelength impacts stomata opening and plant transpiration. The symbol $\tau_{g,w}$ denotes the cumulative transmission coefficient for the water and glass layers. The reflectance coefficients for the glass and water are represented by $r_g$ and $r_w$, respectively [11]. The transmittance of the glass and water layers is calculated using the formula in Equation (4).

$$r_{g,w} = \left[r_g + r_w - 2r_g r_w\right] / \left[1 - r_g r_w\right] \quad (3)$$

$$\tau_{tot} = \frac{\int_{\lambda=300}^{\lambda=400} I(\lambda)\tau t(\lambda_{UV})d\lambda + \int_{\lambda=400}^{\lambda=700} I(\lambda)\tau_t(\lambda_{PAR})d\lambda + \int_{\lambda=700}^{\lambda=2200} I(\lambda)\tau_t(\lambda_{NIR})d\lambda}{\int_{\lambda=300}^{\lambda=2200} I(\lambda)d\lambda} \quad (4)$$

Even though the impact of all other variables has been addressed, the performance of the solar distillers is influenced by the following assumptions; the mass of air within the greenhouse is negligible, the transfer of heat from the floor to the ground is negligible [11], there is an envelope in the greenhouse temperatures, there is uniform mixing of air, and adequate moisture is present on the plant canopy. Such assumptions might not always hold depending on the season and the types of plants; it is hypothesized that during winter, there would be significant heat losses from the floor of the greenhouse to the ground. Heat losses from the floor are also influenced by the type of flooring material; concrete versus gravel or soil, and if a plastic mulch/film is on the floor, and the color of the flooring (white versus black). The claims made above are validated by the data in Table 6, which illustrates that the maximum temperatures were highest in June and July [46].

**Table 6.** Temperature and wind speed variations across different seasons [46].

| Month | Global Solar Radiation on the Horizontal Direction (MJ) | TMinimum (°C) | TAverage (°C) | TMaximum (°C) | Wind Speed (m/s) |
|---|---|---|---|---|---|
| January | 7.84 | 8.48 | 13.26 | 19.66 | 3.61 |
| February | 11.08 | 8.52 | 14.07 | 20.93 | 3.97 |
| March | 15.53 | 10.59 | 16.82 | 24.13 | 4.09 |
| April | 20.33 | 13.76 | 20.88 | 28.93 | 4.13 |
| May | 23.34 | 17.12 | 24.45 | 32.46 | 4.02 |
| June | 25.37 | 20.22 | 27.44 | 35.39 | 4.24 |
| July | 28.41 | 22.12 | 28.89 | 36.55 | 4.22 |
| August | 26.21 | 22.79 | 29.1 | 36.55 | 3.88 |
| September | 21.86 | 21.4 | 27.18 | 34.38 | 3.73 |
| October | 16.52 | 18.16 | 23.27 | 29.89 | 3.5 |
| November | 12.13 | 14.12 | 18.89 | 25.22 | 3.37 |
| December | 10.28 | 10.11 | 14.69 | 20.94 | 3.44 |

## 3. Performance of Plastics and Glass-based Greenhouse Cladding Materials

The performance of the greenhouse cladding materials were evaluated based on the following criteria; mean daytime and nighttime temperature, carbon dioxide concentration within the greenhouse, water vapor pressure deficit, specific leaf weight, leaf chlorophyll content, and dry matter content [10]. In addition, the ray emission model (REM) was employed to estimate the heat losses within the greenhouse. The selection of the above parameters was informed by previous research studies that adopted these techniques to analyze the optical properties, thermal performance, and supplemental lighting of silica glasses, PVC, polyolefins, LDPE, double inflated polyethylene (D-poly), and acrylic [5,16,17]. In particular, Al-Mahdouri and co-researchers adopted the REM method to evaluate the thermal performance of plastic and glass cladding materials because it was a rigorous technique for evaluating heat losses within a greenhouse [16,17]. The data in Table 5 were obtained from three separate greenhouses for three months. The letters a, b, and c are used to denote significant variations.

The data suggest that the three greenhouse materials had comparable performance in retaining heat within the greenhouse structure (daytime and night-time temperatures. However, there was considerable variation in water vapor pressure deficit if glass materials were employed to clad the greenhouse structures. The p-value used to determine significance was 0.5. The VPD was the lowest in double inflated polyethylene [4]. Low VPD levels induce calcium deficiency and reduction in the plant foliage and fruit yield [5]. In contrast, $CO_2$ concentration was most pronounced in greenhouse structures covered with acrylic materials. The variations in VPD levels between glass and polyethylene are attributed to differences in heat conduction and differences in humidity depending on the season.

Following the comparison of the three materials, glass was a suitable material when it is necessary to maintain high VPD and low to average $CO_2$ concentrations. In contrast, glass was preferred if the regulation of $CO_2$ levels was an issue of interest. The data is comparable to Papadopoulos and Hao's research, which reported low light transmissivity in acrylic materials compared to D-poly or glass [5]. As noted in the earlier sections, the seasonal weather variations impact heat retention and VPD levels in the different covering materials [5]. Papadopoulos and Hao noted that the VPD levels in D-poly and acrylic greenhouses did not always remain low. The VPD of acrylic and D-poly materials was comparable to glass in January and February, as shown in Table 7. However, there were considerable differences in March, April, and July - a factor that impacted plant maturity and fruit development.

**Table 7.** Nighttime and daytime temperatures, water vapor pressure deficit and carbon dioxide concentration of cucumber plants [4].

| Type of Greenhouse Cladding Material | Temp (°C) | | VPD (KPa) | | $CO_2$ Concentration (µl $l^{-1}$) | |
|---|---|---|---|---|---|---|
| | Day | Night | Day | Night | Day | Night |
| Glass | 21.32 ± 0.06 | 17.51± 0.04 | 1.15 ± 0.02 | 1.04± 0.02 | 922.85 ± 7.04 | 549.00± 4.10 |
| D-poly | 21.50 ± 0.04 | 17.66± 0.03 | 0.86 ± 0.02 | 0.79± 0.02 | 981.68 ± 4.22 | 563.38± 3.94 |
| Acrylic | 21.60 ± 0.10 | 17.87± 0.03 | 1.00 ± 0.03 | 0.96± 0.02 | 926.81 ± 5.21 | 525.37± 3.54 |

The highest leaf weight (top, middle, and bottom) was recorded in glass-cladded greenhouses, as shown in Table 6. Similarly, the chlorophyll content (bottom, middle, and new) was highest in the glass-cladded greenhouses. Despite these differences, the rate of photosynthesis was comparable. On the downside, the glass covers resulted in greater solar irradiation—a factor that led to more significant dry matter content and fruit dry matter content. Both D-poly and glass greenhouses had higher fruit yields compared to acrylic greenhouses. In general, glass and D-polymer were ideal materials compared to acrylic due to the optimization of chlorophyll content and photosynthesis [4]. However, acrylic greenhouses had the best fruit weight, which translated to better fruit grades.

The yield reported by [4] contrasts with [5] who reported that D-poly materials provided the best yield - the difference can be attributed to the plant under cultivation; data in Tables 7 and 8 are specific to cucumber cultivation while Table 9 is specific to tomatoes. Therefore, the suitability of D-poly, acrylic, and glass covering materials is dependent on the types of plants grown in the greenhouse and the weather. Other studies have suggested that acrylic covering materials could offer better performance compared to D-poly and glass, but aging (photo-degradation and oxidation) and weathering were primary risk factors [5].

**Table 8.** Specific leaf weight, leaf chlorophyll content, and dry matter content of cucumber plants [4]. The letter "a" represents the mean values; "b" denotes new ± leaf blades from laterals.

| Plant Parameters | Plant Region | Type of Greenhouse Cladding Material | | | |
|---|---|---|---|---|---|
| | | Glass | D-poly | Acrylic | LSD0.05 |
| Specific leaf | Newb | 34.89 a | 33.12 a | 35.96 a | 6.51 |
| | Topb | 35.51 a | 33.98 a | 32.78 a | 3.08 |
| weight (g $m^{-2}$) | Middleb | 30.78 a | 30.87 a | 27.11 b | 3.42 |
| | Bottomb | 31.23 a | 28.89 ab | 27.99 b | 2.76 |
| Leaf chlorophyll | Newc | 47.18 a | 41.80 a | 44.94 a | 10.9 |
| | Topc | 54.61 a | 53.12 a | 55.29 a | 6.31 |
| content (mg $cm^{-2}$) | Middlec | 60.37 a | 52.43 b | 50.59 b | 3.9 |
| | Bottomc | 50.27 a | 39.19 b | 43.91 ab | 8.37 |
| Dry matter content (percentage) | Leaves | 10.25 a | 10.33 a | 10.73 a | 0.78 |
| | Stem | 7.18 a | 6.91 a | 6.98 a | 0.97 |
| | Petiole | 5.62 a | 4.68 a | 5.17 a | 1.39 |

**Table 9.** Tomato plant parameters under D-poly, acrylic, and glass greenhouse materials [5]. "The letter a denotes the measurements taken before the plants reached the overhead wires." The letter b illustrates there were significant differences.

| Parameters | Glass | D-poly | Acrylic |
|---|---|---|---|
| Plant height (cm) | 154.8 b | 173.4 a | 160.7 ab |
| Leaf number to the first cluster | 9.40 a | 9.14 a | 9.15 a |
| Total leaves/plant | 29.40 a | 29.72 a | 28.83 a |
| Leaf area ($cm^2$ $leaf^{-1}$) | | | |
| Top | 328.6 b | 360.8 a | 334.2 b |
| Middle | 955.7 a | 919.4 a | 1057.3 a |
| Bottom | 1141.6 a | 1151.0 a | 1104.7 a |
| Specific leaf weight ($gm^2$) | | | |
| Top | 64.20 a | 55.69 a | 58.48 a |
| Middle | 50.31 a | 49.06 a | 46.66 a |
| Bottom | 49.90 a | 42.00 b | 46.37 a |
| Leaf dry weight (%) | | | |
| Top | 12.73 a | 11.54 a | 12.55 a |
| Middle | 9.61 a | 9.11 a | 9.01a |
| Bottom | 9.16 a | 8.64 a | 8.55 a |
| Diameter (mm) | 21.6 a | 20.6 a | 21.4 a |
| Clusters per plant | 7.85 a | 7.58 a | 7.82 a |
| Total flowers per plant | 34.74 a | 34.47 a | 34.43 a |
| Fruit set rate (%) | 77.4 a | 84.1 a | 82.5 a |

### *3.1. Percentage of UV-Transmittance*

The optical properties of LDPE plastic sheets are dependent on the percentage of UV-A and UV-B transmittance (0%, 3%, and 5% transmittance) [15]. The data in Tables 8 and 9 illustrates that the different UV transmittance percentages influenced the transmission of different UV wavelengths, which determine PAR and UV-B radiation reaching the plants and the rate of photosynthesis and damage to the canopy.

The values in Table 10 affirm that plastic films with 0% UV transmitted the least UV-B rays as illustrated by the low greenhouse radiation transmission coefficient ($\tau$). In contrast, the rate of UV-B transmittance was highest in 5% UV plastic films [15]. The percentage of UV-A and UV-B transmittance had a domino effect on water vapor pressure deficit, plant canopy, and fruit quality, as shown in Table 11; less exposure to harmful UV-B radiation resulted in higher plant weight and fruit weight (0% UV plastic films). Based on the empirical data, 0% UV plastic films were best suited for greenhouse cladding based on the optical properties. However, the 3%UV plastic films resulted in better leaf width and photosynthesis.

**Table 10.** Percentage of spectral transmittance in plastic with UV absorption properties.

| Percentage | Global Solar Radiation | UV-A Radiation | UV-B Radiation |
|---|---|---|---|
| UV5% | 75.7 | 6.9 | 3.3 |
| UV3% | 71.3 | 6.1 | 2.3 |
| UV0% | 76.9 | 0.1 | 1.4 |

**Table 11.** Impact of UV-A and UV-B transmittance in plastic LDPE sheets [15]. In parenthesis, the values a and b represent the averages.

| UV Absorbance | Weight per Plant (g Plant$^{-1}$) | | Fruit Number per Plant | Mean Fruit Weight (g Fruit$^{-1}$) | |
|---|---|---|---|---|---|
| UV5% | 1025 | (484) a | 4.55 (2.0) a | 225 | (129) b |
| UV3% | 935 | (642) a | 4.45 (2.4) a | 210 | (106) b |
| UV0% | 1234 | (328) a | 4.64 (1.1) a | 266 | (125) a |

Apart from the impact on plant growth (photosynthesis, water vapor pressure deficit, plant canopy, and fruit weight) [48], UV transmittance was a critical predictor of the performance of distillers and photovoltaic panels integrated greenhouse (PVIG). Chen and co-researchers simulated the performance of glass, EVA, ARC, PV cells and confirmed there were considerable variations in light transmissivity, absorbance, and reflectance, depending on the thickness of the material [3,13], density, and thermal conductivity as shown in Table 12. Shading of the structures was a secondary determinant for performance [14].

**Table 12.** Optical properties of materials integrated to photovoltaic panels for greenhouses.

| Materials | Transmission of Light | Reflectance | Absorbance |
|---|---|---|---|
| Glass | 95% | 4% | 1% |
| Ethylene-Vinyl Acetate (EVA) | 97% | 0% | 3% |
| ARC | 97% | 3% | 0% |
| PV Cell | 0% | 7% | 93% |
| External shading screen | 50% | 3% | – |
| Interior curtain | 40% | 3% | – |

### 3.2. *Secondary Factors*

Even though the performance of greenhouse covering materials is dependent on the individual attributes of the material (UV and IR reflectance and transmission, and heat transfer), the utilization of phase change materials [10,23] such as calcium chloride hexahydrate in the construction of greenhouse walls coupled with the use of supplementary lighting [4], and percentage of UV blockage impacted the performance of greenhouse materials.

#### 3.2.1. Phase Change Materials (PCM)

Heat retention and energy balance (thermal radiations, sensible heat flux, solar radiations, and latent heat flux) within a greenhouse structure are depicted in Figure 6 under standard conditions. The heat losses and gains within a greenhouse structure, especially in extremely hot or cold environments, can be modified by phase change materials such as eutectics, salt hydrates, and organic compounds. The utility of these materials is dependent on thickness because PCMs rely on chemical bonds to store and release energy [15,49]. Guan and co-researchers established that a greenhouse thickness of about 50 mm was suitable for Chinese solar greenhouses [13]—a decline in thickness induced a decline in heat capacity.

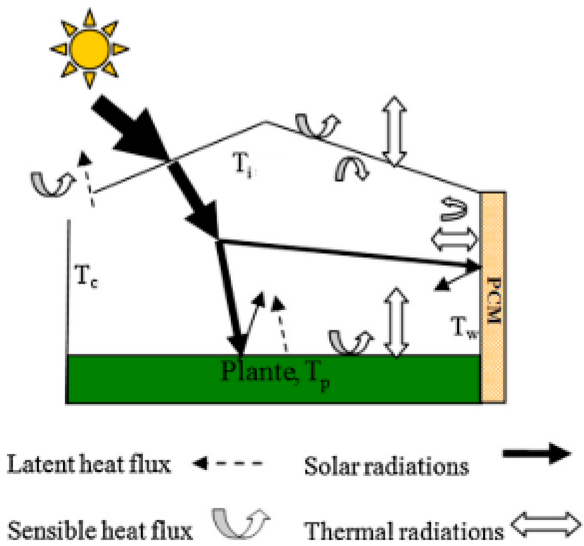


**Figure 6.** Energy balance within a greenhouse structure under ambient conditions [16,17].

Presently, hydrated calcium chloride ($CaCl_2{\cdot}6H_2O$) [16,17], metallic multilayered, and dielectric multilayered based on plastic films [18] have been explored in greenhouse structures due to high latent heat of fusion, customizable melting temperature, and low cost. On the downside, the inorganic salt accelerates the thermal degradation (corrosion) of the greenhouse structure—a challenge that can be regulated by the use of concrete substitutes or the passivation. From a sustainability perspective, the use of PCM does not pose any harm to the environment because the salt hydrates and organic compounds are recyclable.

### 3.2.2. Supplemental Lighting

Supplemental lighting (400 Watts) with HPS lamp fixture technique was employed by Hao and co-researcher to complement natural lighting and activate photosynthesis through photosynthetic photon flux density in the greenhouse structures made of D-poly, acrylic, and glass. In particular, the lighting was provided for 16 h [4]. In the course of the experiments, there was a marginal improvement in plant transpiration and stomata conductance in plants exposed to supplemental lighting. However, the heat from the high pressure sodium lamps (HPS) was not integrated into the equations. The observation is consistent with empirical evidence concerning the impact of light on stomata movement [36]. Even though HPS lamps were employed, daily light was critical for stomata movement. The movement of the stomata leads to $CO_2$ fixation and water loss, which might translate to higher humidity.

The stomata opening induced by supplemental lighting can be regulated by covering greenhouses with materials that limit the transmission of photosynthetically active radiation (PAR). However, the approach is only useful in the morning [36]. The small increase in stomata conductance and plant transpiration and was only confined to greenhouses cladded with D-poly and glass materials. A reduction in plant transpiration and stomata conductance was noted in greenhouses covered with acrylic. Apart from the type of greenhouse covering material, Bárcena and co-researchers note that the light intensity moderates stomata conductance - high light intensity translated to more significant stomata movement, $CO_2$ fixation, and water loss, which improves the post-harvest quality of sensitive plants such as lettuce [36]. Additionally, under low light levels, the electrical (EC) of the nutrient solution must be higher than the EC in high light conditions. The transpiration system changes outlined above would also require modification of the fertilizer ratios to ensure that proper nutrient levels are maintained. Tipburn in lettuce can be addressed by irrigation. However, the irrigation level has to be sustained at "critical soil matric potential threshold" [19]. The recycling of plastic films and sheets used in the covering of greenhouse structures is reviewed below.

## 4. Environmental Sustainability: Recycling of Cladding Materials for Greenhouses

The recycling process is critical considering that glass, petroleum product-based plastic films and sheets are non-biodegradable, and agricultural processes generate about 0.615 million tons of waste in Europe and 5.3 million tons globally each year [20]. In addition, there has been a growing demand for PVC and other types of plastics, especially in Western Europe. A study by the European Commission notes that between 1960 and 2004, the demand for plastics increased from 1000 kilotonnes to 6000 kilotonnes [21]. The demand is linked to the ideal material properties of plastics such as low energy demand during manufacturing, recyclability, UV-stability, multi-applications, and cost. Considering that it is not practical to regulate the demand for PVC, recycling remains the most viable option.

### *4.1. Mechanical and Chemical Recycling*

The sustained demand for plastics poses considerable environmental challenges considering that the recycling process is carbon-intensive, as shown in Table 13. The estimated carbon emissions are based on international standards and life-cycle assessments. The calculated and theoretical gross carbon emissions from paper are the highest (1576 kg $CO_2$ e/t), while low-density polyethylene has the least carbon emissions (29 kg $CO_2$ e/t). The carbon emission attributed to the recycling of various forms of glass is 395 kg $CO_2$ e/t. Based on the carbon emission, the recycling of paper, wood, glass, polyvinyl chloride, high-density polyethylene is less ecologically sustainable compared to the recycling of polyethylene terephthalate and low-density polyethylene.

**Table 13.** Carbon footprint associated with recycling of selected greenhouse covering materials [8].

| Type of Material | Calculated Emission Factor | | Literature Emission Factors | | |
|---|---|---|---|---|---|
| | Gross | Net | No. of Reference Studies | Range | Average |
| | kg$CO_2$ e/t | kg$CO_2$ e/t | | kg $CO_2$ e/t | kg $CO_2$ e/t |
| Green glass | 395 | −314 | 6 | −762 to −201 | −417 ± 176 |
| Brown glass | 395 | −314 | 6 | −762 to −201 | −417 ± 176 |
| Clear glass | 395 | −314 | 6 | −762 to −201 | −417 ± 176 |
| Mixed glass | 395 | −314 | 6 | −762 to −201 | −417 ± 176 |
| Paper | 1576 | −459 | 7 | −3891 to 390 | −1195 ± 1303 |
| Mixed plastics | 339 | −1024 | 6 | −2324 to 1470 | −788 ± 1007 |
| Mixed plastic bottles | 336 | −1084 | 5 | −2324 to 1470 | −922 ± 1321 |
| Polyethylene terephthalate | 155 | −2192 | 6 | −2324 to −566 | −1570 ± 600 |
| High-density polyethylene | 379 | −1149 | 5 | −2324 to −253 | −1055 ± 792 |
| Polyvinyl chloride | 379 | −1549 | 3 | −2324 to −566 | −1259 ± 936 |
| Low-density polyethylene | 29 | −972 | 4 | −1586 to −850 | −744 ± 981 |
| polypropylene | 379 | −1184 | 3 | −2324 to −566 | −1279 ± 925 |
| Wood | 502 | −444 | 5 | −2712 to 1 | −619 ± 882 |
| Chipboard & MDF | 502 | −444 | 5 | −2723 to 1 | −620 ± 886 |
| Composite wood materials | 502 | −444 | 3 | −1266 to 1 | −357 ± 431 |
| Soil | 41 | 27 | 2 | −2 to 2 | 0 ± 2 |
| Plasterboard | 59 | 4 | 2 | −139 to 33 | −53 ± 122 |
| Paint | 364 | 86 | 1 | – | −2840 |

According to Rorrer and co-researchers [6], mechanical methods are ideal recycling methods for polyethylene, polyvinylchloride, ethyl vinyl acetate, and other polymer materials employed in the recycling of polymers. However, recycling methods do not yield virgin polymers due to the integration of plastic additives [12]. The recycled polymers have a lower value (about €1 per kg—values converted) due to chemical inhomogeneity and other undesirable properties such as diminished optical properties. The process of recycling materials used in the covering of greenhouses is dependent on the extent of cross-linkages. One of the critical challenges of mechanical recycling is degradation and the loss of the virgin polymer structure [7]. Another issue of concern is that additives and stabilizers cannot reverse the process.

Despite the limitations of modern recycling methods, mechanical recycling is ideal compared to discarding the plastic materials in landfills and the manufacture of synthetic fertilizer [28,29]. In particular, depositing agricultural plastic waste in landfills is unsustainable based on the large volumes generated annually [28,29]. The claim is further informed by the adoption of diol deconstruction, vinyl ester synthesis, and UPE synthesis, which return the virgin cross-linking, as illustrated in Figure 7.

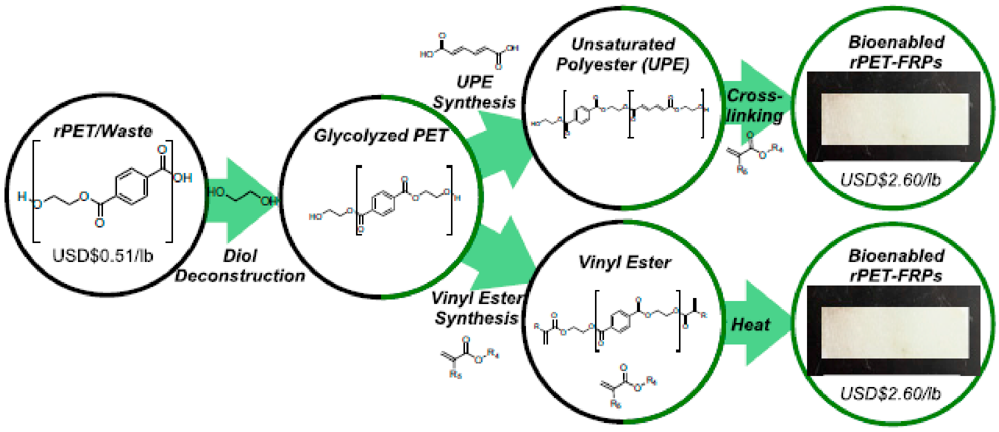


**Figure 7.** Conversion process for low-value Polyethylene terephthalate (PET) waste to high-value bio-enabled reclaimed PET and fiberglass-reinforced plastics (FRP) [22].

From an ecological perspective, the utility of mechanical recycling of plastics is only beneficial if the plastics are sorted and the products recycled for applications that are typical of plastics. Therefore, the utilization of plastic waste to generate substitutes for concrete, such as wall and flooring materials, is non-value adding [45]. As noted in the previous section, the PVC greenhouse materials contain heavy metal stabilizers, which might be released into the environment during mechanical recycling. After considering the limitations of mechanical recycling, chemical recycling is explored. Chemical recycling of plastics involves mixing the PVC plastic waste with other materials that contain low PVC content [45]. The only constraint is that effective chemical recycling methods are still under development.

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### *4.2. Closed-Loop Recycling*

Closed-loop recycling is a novel technique for reprocessing used plastic films and plastics and generating post-consumer plastic films for greenhouse applications. In place of mechanical and chemical recycling to generate cement substitutes, closed-loop recycling methods generate post-consumer material (PF) with nearly similar optical and mechanical properties as virgin plastics, as confirmed by the IR spectra in Figure 8; this is achieved through the integration of additives and stabilizers [7]. The approach has the potential to reduce the contribution of the agricultural sector, which is critical considering that the agricultural sector contributes about 30 percent of the greenhouse gases [50,51]. The broad peak at 2950 cm$^{-1}$ represents C-H stretch (aromatic ring stretch) [52] while the narrow peaks at 1450 cm$^{-1}$ and ~1700 cm$^{-1}$ confirm the presence of C-H bends and C=O bonds (aliphatic aldehydes) [53]. The oxygen species in the carbonyl groups elevate the risk of oxidation damage - a process that can be reversed by photo-stabilization [54]. In brief, the changes to the molecular structure are negligible and can be further addressed through the synthesis of mono-polymer blends.

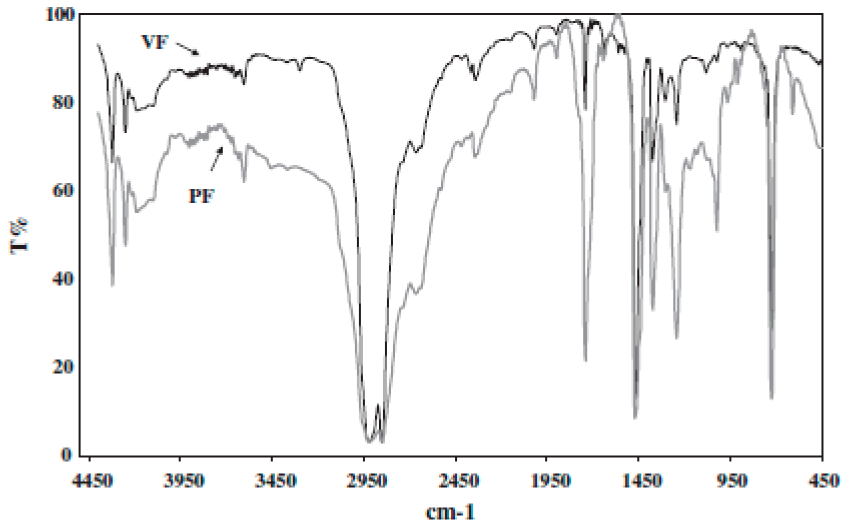


**Figure 8.** IR Spectra of the virgin (VF) and post-consumer plastics (PF) generated via closed loop-recycling [23].

Closed-loop recycling involves the following processes, reprocessing, rebuilding of the molecular structure and blending using film-blowing, thermo-mechanical, commercial ethylene-glycidyl methacrylate, micro-twin-screw extruder, and radical generator techniques [7]. The rebuilding of the molecular structure involves branching and cross-linking during melting, and photo-oxidation of the polyethylene rights to generate long chains of polymers. However, the formation of biofilm and accumulation of dust on greenhouse cladding materials has been proven to impact recycling and should be critically addressed in upcoming studies. The only primary constraint is the presence of carbonyl groups, which increase the risk of photo-oxidation damage. In addition to the reduction of the carbon footprint, closed-loop recycling restores the molecular structure, which was deformed during recycling.

The photo-stabilization of PF (or recycled polymers from used greenhouse materials) helps to deactivate photo-degradation and weathering processes using UV absorbers such as 2, 4-di-tert-butyl-6-(5-chlorobenzotriazol-2-yl)phenol (Tinuvin 327), antioxidants such as Sandostab P-EPQ (P-EPQ) and light stabilizers [54]. The quantity of the stabilizers should be about 2500 ppm, but the improved performance is time-dependent optimal performance has been reported between 1500 and 1700 hours [54]. The net benefit of the process is an improvement in the durability of plastic materials and films made of LDPE, LLDPE, and EVA, among other polymer materials. Dintcheva and Mantia note that the best performance of the materials was achieved if the stabilizers were integrated before extrusion [54]. The best improvement in the tensile strength was reported in PF polymers that combined UV absorbers and antioxidants, as shown in Figure 9. Similarly, treatment with stabilizers resulted in an improvement in the dimensionless elongation.

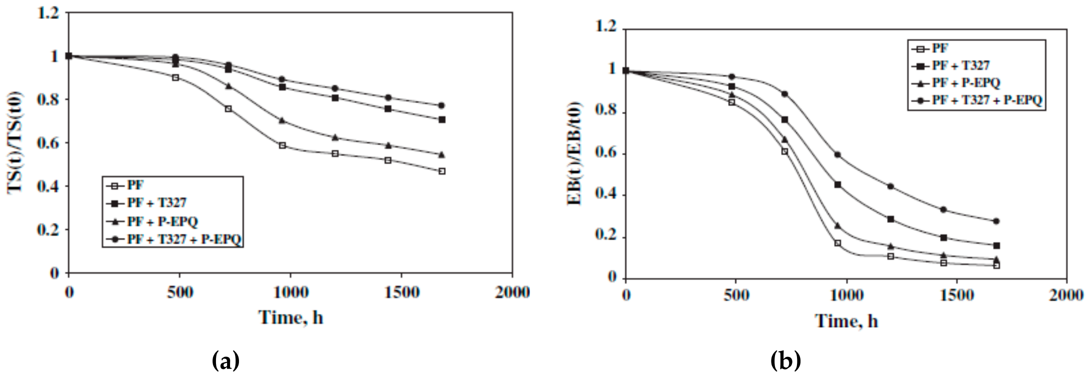


**Figure 9.** Tensile strength (**a**) and dimensionless elongation (**b**) performance of un-stabilized and photo-stabilized post-consumer plastics [24].

## *4.3. Synthesis of Bio-Based Polymers*

The synthesis of polymers from renewable feedstock or carbon dioxide coupling is emerging as a green and facile route for the manufacturing of bio-based polycarbonates, which can be used as greenhouse covering materials. The starting materials are epoxy monomers, plant or industrial and fatty acid chains, as shown in Figure 10 [23]. The only constraints are that different biomass products yield polymers with different functional groups, levels of cross-linking, optical, and mechanical properties.

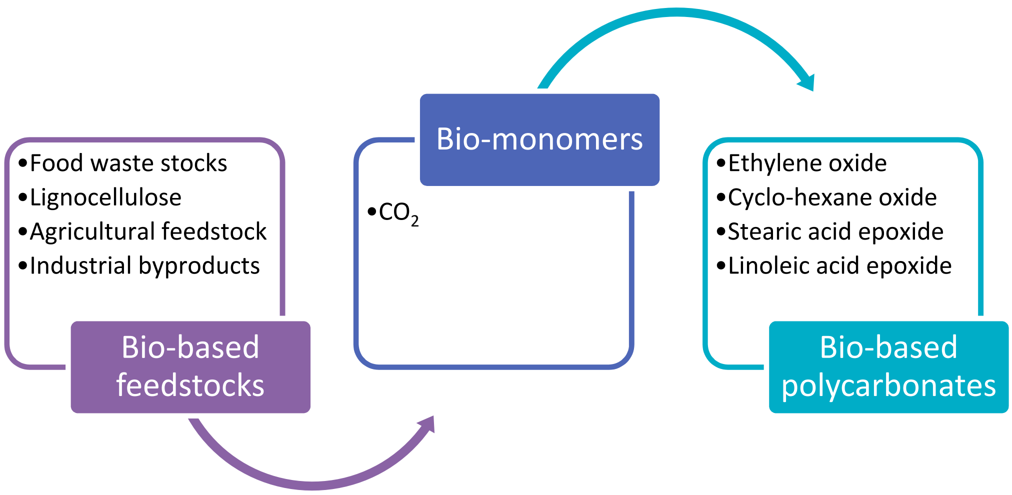


**Figure 10.** Synthesis of bio-based polymers [25].

Even though various methods have been developed to reduce the carbon footprint, such as closed-loop systems, and synthesis of bio-based polymers, it is impractical to eliminate the entire carbon footprint due to natural greenhouse gas emissions (methane, carbon dioxide, and nitrous oxides) from manufacturing plants [55,56]. However, upcycling improves the sustainability of greenhouse materials.

## *4.4. Environmental Impact*

The environmental impact of greenhouse cladding materials is considered from two dimensions. First, carbon emissions and the life cycle assessment (LCA) in the production phase. Second, the waste generated during their use in greenhouses.

### 4.4.1. Results from the Production Phase

The environmental impact of greenhouse cladding materials is considered from the context of production, especially the life cycle assessment (LCA). Greenhouses cladded with polycarbonate sheets emit about 1.45 kg $CO_2$ eq $m^{-2}$ $year^{-1}$. The LCA impact of glass is 2.94 kg $CO_2$ eq $m^{-2}$ $year^{-1}$ [26]. Based on these values, glass cladding materials have higher negative effect compared to plastics in the production phase. The values reported above are consistent with LCA analysis for glass and polymer materials used for other applications beyond greenhouses listed in Table 13.

The negative ecological effects of greenhouse cladding materials can be addressed through the incorporation of PCMs. Soares and co-researchers hypothesized that PCMs reduced the negative environmental effect by 10% [27]. However, the estimates are only valid if summer conditions are maintained all year. Even though LCA is the standard criteria adopted to determine the environmental impact in the production of materials, Anton and co-researchers [26] argue that the method is inconclusive because it does not incorporate emissions associated with the corrosion of steel support structures in greenhouses or the corrosion prevention methods. Therefore, complementary methods should be adopted in upcoming studies.

### 4.4.2. Environmental Impact in the Use as Greenhouse Covering Materials

The waste generated in the course of the useful life of the greenhouse covering materials can be used to predict the environmental impact. A comparative analysis of the waste generated by LDPE versus EVA and ETFE in Table 14 confirms that LDPE or EVA class B resulted in the highest accumulated waste quantity (up to 27,203 kg/ha) [28], if the useful life of the greenhouse is 15 years. Based on this analysis, ETFE plastic films have the least environmental impact compared to EVA (classes B-E) and LDPE.

**Table 14.** Accumulated waste quantity generated by different plastic films for greenhouse covering [28].

| Film Type | Cumulated Film Surface Area ($m^2$/ha) | Cumulated Waste Quantity Range (kg/ha) |
|---|---|---|
| LDPE or EVA, B Class | 195,000 | 22,669–27,203 |
| LDPE or EVA, C Class | 130,000 | 18,135–21,158 |
| LDPE or EVA, D Class | 91,000–104,000 | 14,810–19,344 |
| LDPE or EVA, E Class | 65,000 | 12,090–13,601 |
| ETFE | 13,000 | 2210–2431 |

## 5. Conclusions

Advances in nanotechnology and materials science have led to the development of new and novel materials, including nano-based coats for transparent solar distillers (TSD), phase change materials, halloysite nano-composite films with slow-pesticide release capabilities, antimicrobial nano-$TiO_2$, photoselective polymers, UV stabilizers, and additives. Cucumbers, eggplants, and tomatoes grown in glass, D-poly, and acrylic covered greenhouses had better leaf canopy, leaf chlorophyll content, fruit weight, and quality compared to open field cultivation. The choice and performance of various polymers were contingent on the presence of additives, stabilizers, PCMs, and plant transpiration rates. However, multiple ecological challenges remain unresolved, such as the number of carbon emissions emitted during the recycling of various materials, anthropogenic contamination of the environment by heavy metal stabilizers in PVC, and chemical inhomogeneity of the post-consumer plastics. There also concerns about greenhouse gas emissions ($CO_2$, $N_2O$, and $CH_4$) under controlled farming environments. Even though low-carbon and scalable techniques synthesis of bio-based polymers via polymerization of $CO_2$ have been developed, they do not conclusively address the current environmental challenges. Future research on clean materials for greenhouse cladding should address the current constraints in material performance.

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## List of Acronyms

| | |
|---|---|
| Bubbled polyethylene plastic film | BPE |
| Electrical conductivity | EC |
| Ethylene-vinyl acetate | EVA |
| Heating, ventilation, and air conditioning | HVAC |
| Linear low-density polyethylene | LLDPE |
| Low-density polyethylene film | LDPE |
| Near infrared | NIR |
| Phase change materials | PCMs |
| Phenyl-C61-butyric acid methyl ester | PCBM |
| Photosynthetically active radiation | PAR |
| Poly (3-hexylthiophene) | P3HT |
| Polyethylene | PE |
| Polyethylene terephthalate | PET |
| Polyhydroxyalkanoates | PHA |
| Polypropylene | PP |
| Polyvinyl chloride | PVC |
| Post-consumer plastics | PF |
| Ray emission model | REM |
| Rose-colored polyvinylchloride-based fluorescent material | FPVC |
| Thermal polyethylene film | TPE |
| Ultraviolet | UV |
| Violet colored polyvinylchloride-based film | VPVC |
| Virgin plastic | VF |

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