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Environmental and nanomechanical testing of an alternative polymer nanocomposite greenhouse covering material

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ABSTRACT

Greenhouse covering materials have a substantial impact on the in-house thermal conditions. The development of alternative materials which can regulate the radiation and heat penetration in the greenhouse can significantly improve the cultivation conditions as well as minimize the energy requirements for heating, cooling and ventilation. In this study polymer prototype nanocomposites were developed through the use of uniform dispersions of highly porous granules, capable of regulating the Photosynthetically Active Radiation. The investigated material was tested against its environmental performance as well as for its nanomechanical behaviour. For this purpose, two identical small-scale experimental greenhouses were employed, in which the temperature, the relative humidity and the density of solar energy (penetrating and Photosynthetically Active Radiation) were measured. The mechanical properties, namely Young's modulus and hardness of the tested material, were estimated by analysing the measured load–displacement curves delivered by nanoindentation testing. The findings of this study revealed that the proposed material has such a performance in radiation which allows its employment for temperature tolerant crops and cool growing.

1. Introduction

Energy consumption for greenhouse heating represents a serious concern for greenhouse operators throughout the world (Kavga et al., 2012). To achieve high quality greenhouse control, indoor and outdoor greenhouse conditions have to be continuously measured, a process which is costly and time consuming. Thus, the development of alternative reliable methods to control the indoor and outdoor greenhouse conditions would provide a useful solution and, at the same time, would appreciably reduce both time and cost. Aiming to reduce energy consumption, numerous alternatives have been proposed and implemented during the last decades in greenhouse technology. Among them, we note the use of double glazing, the insulation of side walls, the introduction of thermal screens, the use of different types of covering materials such as glass, Polyethylene (PE) and Polyvinyl chloride (PVC), the development of zigzag covering in order to restrict transmission losses, the development of Fresnel lenses for the south-facing roof cover (Lamnatou and Chemisana, 2013; Souliotis et al., 2006) and PV installations for shading and electrical production (Trypanagnostopoulos et al., 2017).

The scope of current study was to test and validate under relevant environmental conditions an advanced greenhouse covering consisting of a polymer nanocomposite with upgraded thermal and nanomechanical properties. The investigated single layered material was developed with the use of uniform dispersions of free standing and highly porous granulated nanoparticles of single and mixed oxides, capable of regulating the Photosynthetically Active Radiation (PAR) and the luminance levels within the greenhouse. In terms of this study, the thermal and nanomechanical properties of one type of advanced covering was tested for a time period of five months. The nanopowders, consisting of TiO_2, were mixed with Low Density Polyethylene (LDPE) in the form of heterogeneous granules. In Section 2 a brief theoretical background, as well as the recent advancements in the field of greenhouse covering is presented. The methods and materials used are covered in Section 3. Section 4 discusses the findings of this study in terms of the thermal and the nanomechanical properties of the proposed

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Nomenclature

Abbreviations and symbols

E	Young's modulus [MPa]
EVA	Ethylene-Vinyl Acetate
H	hardness [MPa]
NEAR IR	infrared radiation of the solar spectrum
FAR IR	thermal radiation
ISE	Indentation Size Effect
LDPE	Low Density Polyethylene
PAR	photosynthetically active radiation at the horizontal plane
PE	polyethylene
PO	polyolefin
PVC	polyvinyl chloride
SPM	scanning probe microscopy
STD	Standard Deviation
UV	ultraviolet

material. The comparison is performed against a compatible commercialized greenhouse covering (THERMO-LUX). The findings of the study are concluded in the last section.

2. State-of-the-art in greenhouse covering materials

The existing solutions of common plastics in the market for greenhouse covers, are mainly based on LDPE and Ethylene-Vinyl Acetate (EVA) which commonly face the critical problem of limited or unregulated optical performance in addition to poor insulation in hot/freezing climates, both of which cause a low energy efficiency within the strictly controlled greenhouse environment. The optical, thermal and mechanical properties of novel greenhouse covering materials has been the subject of several scientific studies conducted in the recent years. This section aims to present the state of the art in this field.

Al-Mahdouri et al. (2013) obtained the spectral optical properties of four greenhouse covering materials: LDPE, Polyolefin (PO), Polyvinylchloride (PVC) and Fused Silica Glass (FSG). In this study the diffuse reflectance and transmittance of the covering materials were measured using spectrophotometric method. The results showed highest inside air and ground surface temperatures in the silica glass greenhouse, PVC and PO greenhouses had comparable thermal performances, and LDPE greenhouse showed the lowest thermal energy conservation.

In a study conducted by Emekli et al. (2016) the changes on light transmittance of greenhouse covering materials produced by CO-EX technology with multi-layered CO-EX UV + IR + EVA and UV + IR + EVA + AD additives during their service life of 24 months were studied. The physical properties, the global solar radiation and the PAR transmittance of the greenhouse covering materials were determined. Initial global solar radiation transmittances were determined as 92.7% and 83.6% for UV + IR + EVA and UV + IR + EVA + AD and the losses of the global solar radiation transmittances at the end of their service life were measured at 7.3% and 13.2%, respectively.

Dehbi and Mourad (2011) investigated the performance of mono- and tri-layers low density polyethylene LDPE films as greenhouse covering materials in north-west Africa (Algeria). The degradation and fracture behaviour with regard to abrasion of the three layers LDPE was studied and compared with that obtained for monolayer film often used in North Africa for plasti-culture devices. The results revealed that the degradation performance of the tri-layers film was found to be quietly better than that of the mono-layer film, with regard to the mechanical and surface energy properties. The lifespan of these films under natural conditions was estimated to be 10 and 5 months for the tri-layer and mono-layer films, respectively.

Kittas et al. (2006) assessed the consequences of UV absorbing film on the behaviour and production of an eggplant crop by comparing two different UV absorbing films (0 and 3% UV transmittance) to a standard Polyethylene (PE) film (5% UV transmittance). Results showed that the eggplants grown in the greenhouse with 0% transmission to UV light were about 21% taller and had about 17% higher leaf product (leaf length × width) than the plants grown in the greenhouse with 5% transmission to UV light.

The effects of UV stabilised polyethylene (UV + PE), IR absorbers polyethylene (IR + PE), double layers of polyethylene (D-Poly) and single layer of polyethylene (PE), as greenhouse covers, on aubergine growth, productivity and energy requirement were investigated (Cemek et al., 2006). It was found that the late and final yields of plants grown in D-Poly houses were higher than those grown in UV + PE, IR + PE and PE. The light transmission was measured to be the highest in PE, intermediate in UV + PE and IR + PE, and the lowest in D-Poly houses. Relative humidity was the highest in D-Poly, intermediate in IR + PE and UV + PE, and the lowest in PE houses. The plants in D-Poly houses grew and developed faster than those in IR + PE, UV + PE and PE houses.

In addition, Mobtaker et al. (2016) investigated six most commonly used shapes of greenhouses including: even span, uneven span, vinery, single span, arch and quonset type from energy consumption point of view under the climatic condition of Tabriz, Iran. The greenhouses were studied for both east-west and north-south orientation and the length width and height of them were kept the same. The effects of north brick wall on the energy consumption of greenhouses were studied and considered in model. The results showed that the additional energy requirement to maintain the temperature desirable for the plants' growth was lowest in an east-west oriented single span greenhouse with north brick wall. It was also concluded that north wall insulation can reduce heating demand of the greenhouse by as much as 31.7%.

United States Patent No. 6,699,559, by Milburn (2004) presented a method of making a glazing system comprising a plastic resin and plurality of inorganic particles, having substantially matching refractive indices. The inorganic particles in this patent presented a strong absorption/emissivity in the thermal infrared wavelength regions (FAR IR) and negligible absorption in the visible region (400–700 nm). The inorganic particles had a size selected from the group consisting of a first range less than 200 nm and a second range between 1 and 30 μm. The blending of the inorganic particles with the plastic resin formed a substantially clear composite film.

An alternative method of heating the plants in a greenhouse, which was originally proposed in the late 1970s as a result of the first oil crisis, is the use of low-intensity FAR IR (Kavga et al., 2013, 2008). The poor insulating properties of the greenhouse covering materials presently used (i.e. PE, PVC, Fiber-glass, etc.) result in heat losses which may reach up to 50% of the overall greenhouse energy consumption during its operation (Cemek et al., 2006; Zhang et al., 1996). Common plastics currently used in the market for greenhouse covering mainly consist of LDPE and EVA (Milburn, 2004; Truckai, 2004; Kambe et al., 2003; Boccaccini and Silva, 2008). These materials commonly face the critical problem of limited or unregulated optical performance. In addition, LDPE and EVA have a moderate insulating performance under hot or freezing climatic conditions, both of which cause a low energy efficiency within the strictly controlled greenhouse environment.

3. Methods and materials

3.1. Polymer prototype nanocomposites

The investigated polymer prototype nanocomposites were developed with the use of uniform dispersions of highly porous granules,