A novel synthesis of light transmission from upcycled polyethylene terephthalate polymer and low-density polyethylene for greenhouse design in tropical climate

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Abstract

To support the circular economy in Thai's agriculture, the main interviewed challenges point to knowledge and knowhow for greenhouse structure and system boosting up productivities. One popular material that possibly affected productivity is transparent polymer film, which can be recycled based on material property and blowing machine condition. This paper investigates the light transmittance performance of transparent polyethylene terephthalate polymer (PET) and low-density polyethylene (LDPE) sheets for use in low-energy greenhouses in tropical climates. The aim of the study is to optimize the thermal performance and light transmittance of these materials to support plant growth and human comfort. The study focuses on seven stages of plant growth, each of which requires different light characteristics including 1) seed, 2) germinating, 3) young seedling, 4) older vine, 5) flowering, 6) fruit bearing and 7) harvesting and drying. Each stage requires different light characteristics, e.g. light intensity, red light, blue light, white light and ultraviolet (UV) and pulsed light (PL). The methodology involves selecting PET and LDPE materials, preparing samples for thermal property and lighting laboratory tests and analysing the results based on suitable criteria. The findings show that LDPE sheets have 28.78% lower light transmittance than PET sheets, making them suitable for supporting the seedling stage and older vines of plant growth. PET sheets, on the other hand, deliver a high intensity of red light, making them suitable for stimulating photosynthesis in older vines and during the harvesting process. The study highlights the importance of considering both thermal performance and light transmittance when selecting materials for low-energy greenhouses in tropical climates.

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1 INTRODUCTION

In tropical climates, agricultural activities are basically accounted as a part of Gross Domestic Product (GDP), which has been increased during the 10-year period from 68 261 million Baht in 1993 to 168 442 million Baht in 2002 [1]. The first five main types of economic plant point to 1) rice, 2) rubber, 3) farm plants, 4) horticulture and 5) perennial plants. These agricultural products cover 104 million Rais (1 Rai = 1600 m^2), and partial special products are required to be planted in pesticide-controlling farms. Agricultural greenhouses were then expanded to cover 189 782 Rais (1 Rai = 1600 m^2) for planting mostly melon and tomatoes in central and northern Thailand [2]. To meet the growing demand for these crops, agricultural greenhouses have been expanded to

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cover a significant area. However, the use of transparent materials in these greenhouses has a direct impact on both users and plants.

From this expanding structure, transparent materials are the main covering shade of agricultural greenhouses, which directly affect users and plants. Users or farmers normally consider thermal comfort including air temperature, humidity and velocity of indoor air conditions, whereas plants focus orderly on lighting, temperature and humidity relied on different growing phases. For these purposes and functions, transparent materials are possibly glass or plastic options [3] based on financial support and human comfort. These studies have been conducted to investigate the effects of different materials on plant growth and human comfort in greenhouses. However, the specific study of polyethylene terephthalate polymer (PET) and low-density polyethylene (LDPE) in relation to their effects on light transmittance and thermal performance in low-energy greenhouses in tropical climates is relatively new. This study is important because it provides insights into the optimal use of these materials in greenhouse design to support plant growth and human comfort.

This paper investigates the light transmittance performance of transparent PET and LDPE sheets for use in low-energy greenhouses in tropical climates. The study aims to optimize the thermal performance and light transmittance of these materials to support plant growth and human comfort. In addition, the paper discusses the effects of the density and heat capacity of the polymer on light transmittance performance. The thermal properties of the materials are also analysed to understand the relationship between thermal and lighting effects in the greenhouse.

2 LITERATURE REVIEWS

Normally, an agricultural greenhouse requires high retention of a dynamic environment, transparent, cleaning surface. There are several types of in-use polymer film in agricultural production [3]. Divided by sizes of utilized function in greenhouses, 1) the medium size of walk tunnel requires 80- to 220-μm-thick polymer sheet ~20-m width. There are 1–3 layers of polymers depending on technology and 6–45 months of life cycle reliant on photo stabilizer, location and pesticide. 2) Another smaller size of walk-tunnel requires a thinner-than-80-μm polymer sheet to cover only a meter-width and a meter-height tunnel, with 6–8 months life cycle. Turning to 3) mulching type of polymer film, it is normally required to be a 12- to 80-μm-thick polymer sheet with a 3-m width to control soil temperature and humidity. This film ages ~2–4 months.

2.1 General properties of PET and LDPE

This research focuses on the performance of two types of recyclable materials, PET and LDPE, which exhibit various constructional properties such as strength, tensile strength, ultraviolet (UV) light stability, light transmittance and life period. These properties are important for the use of these materials in agricultural greenhouses [3].

PET is widely used in industrial packaging and dominates the drink container market. In Europe, PET accounts for ~16% of plastic consumption, despite the fact that it cannot be biodegraded [4]. However, PET is used as a film and container in the purified recycling process, where its hot melting points are properly cut and resisted by a UV laser [5]. Combining SnO2:F (FTO) with a PET sheet can increase the ability to resist laser annealing in the industrial cutting process [6]. Another potential use of recycled PET is in recycled concrete aggregate (RCA) combined with crushed brick, 5%wt PET, 10%wt fly ash, and 10%wt slag. This material's performance is suitable for use in roads [7].

Global solar radiation (GSR) of LDPE was ~83–93% and their transmittance losses were ~7–13%. Photosynthetically active radiation (PAR) transmittance reached 80–83%, and those losses were ~4–6% covering the whole life [8]. Fourier Transform Infrared Spectroscopy (FTIR) is used to clarify gamma radiation depending on relative chemical and structural factors [9]. Other contamination of LDPE was brought possibly to the heat-transferring property of materials. For example, rising hollow glass microsphere (HGM) in LDPE composites could drop density, but this could increase thermal conductivity matched suitably to the property of envelop insulation [10, 11]. Moreover, melting points may possibly be flexible in the case of recycled and contaminated LDPE materials.

Turning to the ability to maintain food quality, LDPE film was possibly developed to restrict >60% fungal spores by an antifungal agent, whereas the mechanical strength was dropped by a long time UV condition [12]. LDPE film examined the ability of antibacteria when blending with grapefruit seed extract (GSE) and thermo-plasticized starch (TPS) [13].

The biodegradation potential of LDPE by bacterial consortia is ~64% from pre-treated UV for 1 hour within a 160-day study and room temperature at 37°C [14]. To blend LDPE with chitosan, thermal degradation can slightly increase. In addition, other plastics blended by 40%wt chitosan led to greater potential of biodegradation as well [15].

Transparent covering polymers can be made from LDPE, Linear Low Density Polyethylene (LLDPE) and Polyethylene (PE), which provide 88–90% transmittance of the light, ranged in PAR (400- to 700-nm wavelength). The thickness can be ~100–200 μm with a 3- to 5-year life cycle. It is possible to mix a 7% UV filter or absorber into a polymer sheet. To point out a higher technological example, ethylene tetrafluoroethylene (ETFE) can be used as a specific character film to perform high light transmittance, high heat and chemical resistance. Transparent ETFE film allows both UV and infrared (IR) to be transmitted to indoor functional areas with 10 times lighter weight compared with glass materials. It is also an electrical insulator, which can be adapted for industrial products such as solar cell panels, electrical film and large constructional architecture [15].

2.2 Occupant comfort

Natural light provides electromagnetic radiation within different wavelengths, possibly divided into three groups of visible light

Table 1. *Effects of different light wavelength on plant growing stages*

Stages of plant	Lights						
	Violet	Blue	Orange	Red	Red-blue	White	Pulse
	380–436 nm	436–495 nm	589–627 nm	627–770 nm			
Seed & germination	Blue—low intensity is necessary [19, 29]						
Young seedling	Blue—rubisco amount, compact size and reduced biomass [26]				Red:blue & white—photosynthesis, biomass production [32]		
Older vine	UV-A affects morphological development and light interception and the reduction of a leaf's metabolite accumulation [21, 34]	Blue—resist powdery mildew infection in melon [31] lower height of general plants [28]	Orange—high effect of photosynthesis	Red—hypocotyl elongation, cotyledon expansion, plant height, and leaf area [21, 26]	Red:blue—plant morphology [23], Tomato growth [23]		
Flowering	Orange—high effect of photosynthesis [20]						
Fruit bearing	Blue—lower plant's weight [33]			Red—ripening stage of tomato [27]			
Harvest and drying					Red:blue—yield quantity, chemical reaction [23]		
Post-harvest	UV-C reduces *Listeria innocua* [36] and *Alicyclobacillus acidoterrestris* spores in post-harvest fruits [37]		Far-red affects an increase of firmness and lycopene in cold condition [12]		Pulse—antibacterial performance with UV-C [35, 36]		

(VL), IR light and UV light. Visible light ranges between 380 and 780 nm, which provides seven different colors. These wavelengths affect human visible perception and human skin. In the visible light range, blue light (400–500 nm) wavelength impacts harmfully on human eyes and vision. Infrared IR light is in the range of 700–2400 nm, which cannot be seen visibly, but provides high temperatures with 53% heat from the sun's radiation. This wavelength stimulates generally dark spots on facial skin and finally up to skin cancer. For UV light, the wavelength is ∼3% of the sun's radiation and ranges ∼100–400 nm, which impacts harmfully on human skin, from burning the external skin layer to cancer. There are four types of UV light including UVC (100–280 nm) at space level only, 5% of UVB (280–315 nm) possibly burning the external skin, 90% 0f UVA (315–400 nm) producing dark spots leading to cancer and UV-Tmax (380–400 nm) affected DNA changing and cancer [16, 17].

To consider human comfort, a suitable wavelength of light should be in visible light within 400–700 nm. For longer wavelengths, heat can be generated in a functional environment when shorter wavelengths result harmfully in skin impacts.

2.3 Light wavelengths and plant growth

Focusing on plant impact, light is important for plant growth [18], which have PAR ranges from 400 to 700 nm with red and blue colors. UV light (200–400 nm) can stop photosynthesis and destroy a plant's DNA. Visible light or PAR (400–700 nm) supports plant growth and generates chlorophyll molecules type a and b [19]. Near-infrared (NIR) light (700–2500 nm) affects heat collection in the greenhouse and eventually withers leaves and flowers. Light transmittance in PAR of greenhouse covering polymer is ∼88–90% for general plants, when indoor plants may require only 50–70% of PAR transmittance. In this study, both impacts on plant elements and stage of growth will be examined.

In the case of affecting a plant's elements, different wavelengths of light are linked directly to the quality and various types of growth. Invisible light ranging <390 nm, e.g. UV, can stop a plant's growth when IR light (longer than 810 nm) can stretch longer internode. Visible violet light (390–410 nm), dark blue light (411–425 nm) and blue light (426–492 nm) influence phototropism of floral plants, e.g. facing to the sun of the sunflower. Visible blue lights at 430- and 453-nm wavelengths are necessary for photosynthesizing chlorophyll A and B, respectively. Visible green light (493–525 nm) possibly stops a plant's growth, whereas yellow light (536–568 nm) and orange light (587–647 nm) can support germination of seeds. Red light (648–760 nm) affects both stopping and supporting germinations depending on the species of plant. Red light lengths at 642 and 662 nm are found to support photosynthesis of chlorophyll A and B, respectively, when far red light (761–810 nm) is proven to stop germination of seeds [3, 16, 17].

Sweet melon yield needs 50 × 50 cm of growing space, which relies on growing stages during a period of 4–6 weeks. There are seven stages of plant growing, which are: examine seed, germinating, young seedling, older vine, flowering, watermelon bearing, harvesting and drying, as shown in Table 1. Planting criteria in each stage can refer to chemicals, leaves, branches, height, number of nodes, number of flowers and fruits [20].

Far-red (FR) light can raise the leaf's area when the remaining biomass in lettuce and reduce phytochemical matter in lettuce [21]. FR light and low temperature can improve post-harvest for maturity stage of tomatoes. FR indicated an increase of firmness and lycopene acting in cold conditions [22].

Red and blue lights have been claimed to impact plant growth in different stages, in particular metabolic processes, photosynthesis light and the cannabinoid process. It was also found that blue and red ratios influenced yield quantity, chemical reaction and plant morphology [23]. Red and blue light combination at high temperatures can increase tomato growth, whereas red light and low temperature are important for other processes of tomato plants [24, 25]. Only red light positively affects hypocotyl elongation, cotyledon expansion, plant height and leaf area, whereas the red-blue light combination promotes morphology and physiology of the early stage in tomato. Blue light stimulates the seedling process of tomatoes, e.g. rubisco amount, compact size and reduced biomass [26]. In addition, red light is found to impact on the ripening stage of tomatoes, which relates directly to ripening-related regulators and ethylene biosynthesis [27].

Blue light is necessary for maintaining the development process of plants, and different sensitivities responding to light should be considered in each species' requirements [28]. The blue light condition also involves the seedling process, in particular pigmentation, lipid peroxidation and osmoprotectant accumulation [29] and stimulates antioxidant contents by ascorbate peroxidase and dehydroascorbate reductase activity [30] in tomato. Blue light can also resist powdery mildew infection in melon, which relates dependently to H_2O_2 accumulation. Moreover, the ratio of red and blue light at 3:1 can protect melon seed well from that infection [31]. Blue and white lights can improve the thickness of the cell wall, Ca and pectin levels, whereas far-red and dark conditions affect microfibrillar growth [32]. Based on ray tracing simulation, blue light with 27% intensity related negatively to the dry weight of tomato plants, while providing a positive impact on the latter morphology and light interception [33]. Blue light also results in lower height of general plants, but it is the opposite growth in the cucumber [28].

Different wavelengths of light are found to affect biomass, photochemical accumulation and antioxidant capacity in lettuce studies. Ultraviolet A (UV-A) possibly reduces the area of leaf and less nitrate and biomass matter, whereas seven other chemicals are increased, especially chlorophyll, protein, sugar, vitamin C, flavonoid, polyphenol and anthocyanin contents [21]. UV-A light within 315–400 nm close to blue light at 400–500 nm was found to have a similar effect on plants. UV-A supported morphological development and light interception [34].

Based on hygiene control of fruit transportation, UV-C light is found to reduce Enterobacteriaceae and total microbial counts and melon leakage [35], but there is no impact on fruit color and firmness during storage. UV-C radiation of 13.44 W/m^2 within 20 min is recommended to reduce *Listeria innocua* [36] and *Alicyclobacillus acidoterrestris* spores in post-harvest fruits. It also preserves the quality of juice, retaining color and retaining antioxidant activity [37].

In the case of tomatoes, it is possible that light intensity can increase the level of leaf epinasty when ignoring the impact of leaf chlorosis [35]. Rising light intensity influences plant hormones by indicating reduction of jasmonic acid (JA), salicylic acid (SA) and zeatin (ZT) and increase in aminocyclopropane-1-carboxylic acid (ACC) [38]. In case of high irradiance, low diffuse radiation fraction (HILD) can reduce light distribution in the tomato's greenhouse and carbon uptake and light use increase by 4.58–5.30% of efficiency [39]. Low-light stress also decreases sucrose content, sucrose phosphate synthase (SPS) and sucrose synthase in the synthesis direction (SS-s) in melon leaves and it reduces the activities of acid invertase (AI), neutral invertase (NI), and sucrose synthase in the cleavage direction (SS-c) from the early stage of melon development [40].

Moreover, PL was analysed to be inactive kinetics for four types of microbial bacteria including *Escherichia coli* ATCC 35218, *L. innocua* ATCC 33090, *Salmonella Enteritidis* MA44 and *Saccharomyces cerevisiae* KE162. It is possible that PL relates negatively to juice absorbance in strawberry and orange juice [32]. In addition, PL with nine J.cm-2 can maintain a post-harvest defense mechanism in melon by limiting ethylene and consequently increasing polyamines [41]. With 180- to 1100-nm wavelength of light, the 90-s pulsed range can decrease *Cryptosporidium parvum* oocysts in the case of post-harvest products of cilantro, mesclun, lettuce, spinach and tomato [42].

Last but not least, it was proven that the material's crystallinity related directly to density and thermal property of transparent material, which higher density can delay speed of light and eternally change the wavelength of light [43, 44].

To summarize, transparent materials affected users and plants and all types of wavelength provide both negative and positive impacts on different growth phases of a plant. In general, there are three lights directly affecting plant growth, especially blue, red and white lights. Blue light is better for the early stage of seed, germination and seedling before negatively impacting on height later. White light and the popular proportion of a 3:1 red:blue light mixture is suitable for the seedling stage. For some specific light types, UV and PL negatively affect the growth stage of a plant, but provide high potential for post-harvest hygiene and protection from bacteria. Far-red light can result in the color and ripening process of the red plant. Low intensity of light provides a positive impact on the growth stage, but it depends on the species of plant too. From the literature reviews, the light performance of transparent materials can be compared and the impact on plant growth discussed later.

3 METHODOLOGY

The methodology involves selecting transparent PET and LDPE materials, preparing samples for thermal property and lighting laboratory tests and analysing the results based on suitable criteria. The aim of the study is to optimize the thermal performance and light transmittance of these materials to support plant growth and human comfort.

There are three steps of the experiment procedure. 1) To select the PET and LDPE materials, a mixed proportion of material weight test was conducted at 100, 80, 50 and 20% combinations. The results of this test were used to select pure PET and LDPE materials for the study. 2) For the thermal property tests, samples

Table 2. *Thermal properties of PET and LDPE material*

Materials		PET		LDPE	
Sampling conditions		Sample: PET (200 μm), 3.2000 mg Module: DSC 3+/700/1739-, 08.05.2019, 10:08:30 Sample holder: aluminum Light 20 μl Weight: 23.2 mg Material: aluminium Method: 40–300 (10 C/min)_Air, dt 1.00 s, 40.0–300.0°C, 10.00 °C/min Synchronization: enabled		Sample: LDPE (200 μm), 1.8000 mg Module: DSC 3+/700/1739-, 08.05.2019, 10:08:30 Sample holder: aluminum light 20 μl Weight: 23.4 mg Material: aluminium Method: 40–300 (10 C/min)_Air, dt 1.00 s, 40.0–300.0°C, 10.00 °C/min Synchronization: enabled	
Results	Integral	Exothermic cold crystallization: 120.29 mJ (normalized 37.59 Jg-1)	Endothermic melting point: −183.68 mJ (normalized −57.40 Jg-1)	1st mixed material: −8.80 mJ (normalized −4.89 Jg-1)	2nd mixed material: −15.46 mJ (normalized −8.59 Jg-1)
	Onset	120.57°C	235.76°C	118.51°C	121.76°C
	Peak	125.22°C	249.59°C	119.96°C	123.28°C
	Endset	129.62°C	257.32°C	121.49°C	123.62°C
	Glass transition temperature	72.80°C		n/a	
	Midpoint ISO	72.66°C		n/a	
	Cp	219.3 (J/K• mol)	305.4 (J/K• mol)	46.2–62.7 (J/K• mol)	

of PET and LDPE sheets with a thickness of 200 μm were prepared and weighed to 3.20 and 1.80 mg, respectively. Differential scanning calorimetry (DSC) was used to identify the general performance of the materials. 3) For the lighting laboratory tests, the same samples were used to measure light transmittance using a UV–Vis–NIR spectrophotometer, model Cary 7000. The results were analysed based on suitable criteria for human thermal and vision comfort and beneficial effects on plant growth. The results were obtained by measuring light transmittance using a UV–Vis–NIR spectrophotometer and analysing the data based on the different stages of plant growth and the light characteristics required for each stage. The methodology is organized to present the findings of the study based on the different stages of plant growth and the light characteristics required for each stage.

From another material mixed-proportion test, all proportion of combination between PET and LDPE examines the broken surface and unmixable layer of film because of different temperatures of melting and solidity points. Then, pure PET and LDPE are selected for real application test. For thermal and lighting laboratory tests, selective sampling PET and LDPE sheets are prepared by cutting shape 200-μm thickness and are weighed to 3.20 and 1.80 mg, respectively. To identify properties of PET and LDPE, DSC is used for testing the glass transition, melting point, crystallization and heat capacity. Based on DSC data in Eq. (1), the heat capacity (Cp) at constant pressure at 25°C can be calculated from the Equation 1 of heat integration [45–47].

$$C_p = (\Delta H/\Delta T)_p \tag{1}$$

Where $C_p = \textit{heat capacity}\,(J/K)$

$\Delta H = \textit{different heat}(J)$

$\Delta T = \textit{different temperature}(K)$

In addition, lighting criteria for growing plants are reviewed, which included typology, phase of growth, light intensity and light color. In the case of transparent materials, a UV–Vis–NIR Spectrophotometer model Cary 7000 examines absorptance, percent of transmission and percent of reflectance. Based on this research, the mode of test is Universal Measurement Accessory (UMA) transmission and the scan range of the wavelength covers 200–2000 nm in the case of liquid, powder, film, plastic, acrylic, etc. The spectrophotometer covers a scanning period ranging between 200 and 1000 nm, data interval at 1.0 nm, scan rate at 600 nm/min and detector angle at 180 degrees. Furthermore, the criteria for thermal property will be validated by comparing with general in-use transparent polymer and light transmittance at 88–90% before discussing the effects on a plant's growth.

4 RESULTS AND DISCUSSION

Based on seven stages of plant growth, each of which requires different light characteristics. The findings show that LDPE sheets have lower light transmittance than PET sheets, making them suitable for supporting the seedling stage and older vines of plant growth. PET sheets, on the other hand, deliver a high intensity of red light, making them suitable for stimulating photosynthesis in older vines and during the harvesting process.

From the experiment procedure, the three steps of the experiment can be clarified in particular: 1) selected results of PET and LDPE samples, 2) thermal property test and 3) light transmittance test. For the first step of material proportion selection, there is another academic report explaining collaborative and detailed mixed material process. The outcome from the PET mixture proportion was not well blended with other plastic types

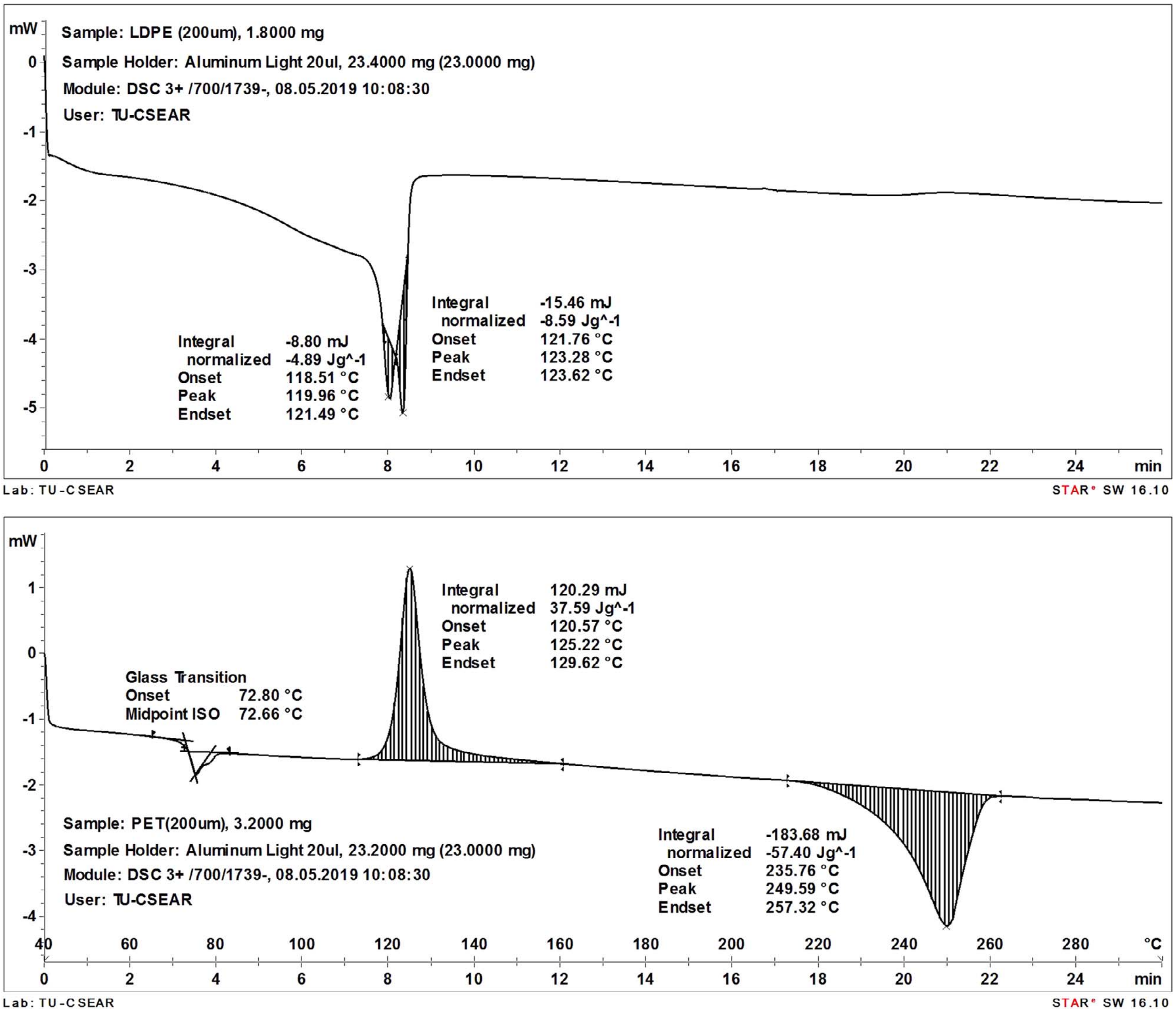

Figure 1. *DSC thermogram of PET and LDPE.*

because of different melting and solidity points. The surface of the material is layered and easily peeled if the mixed temperature is <120°C. Turning to another plastic type, LDPE can be blended with other recycled plastic ingredients except PET. Subsequently, non-mixture types of PET and LDPE are selected to be tested for thermal property and light transmittance performance. Based on laboratory tests, PET and LDPE material properties including light transmittance are reported. Moreover, analyses of results are discussed and compared with literature reviews of lighting impacts.

4.1 Thermal property of material

To focus on the DSC laboratory, PET and LDPE thermograms report different heat behavior. The conditions of the sampling material are prepared at 200-μm thickness, and both PET and LDPE materials weigh 23.2 and 23.4 mg, respectively, as shown in Table 2. For thermal behavior of PET material, there are three phases of glass transition, exothermic cold crystallization and endothermic melting points that explain the general properties of the material. In contrast, LDPE material strictly explains only the melting point of a material without glass transition and exothermal cold crystallization, which identify low strength properties of the material. Moreover, the heat capacities of PET at exothermic and endothermic points are 219.3 and 305.4 J/K• mol, respectively, when those of LDPE are ~46.2–62.7 J/K• mol.

Based on a constant rate of heat, Figure 1 shows a typical temperature scan of PET in which the first heating trough is glass transition temperature at 72.80°C followed by exothermic cold crystallization peak at 125.22°C and an endothermic melting peak at 249.59°C. While identifies, the curve of the LDPE thermogram illustrates the second run of heating, which identifies two different melting points depending on different chemical mixtures.

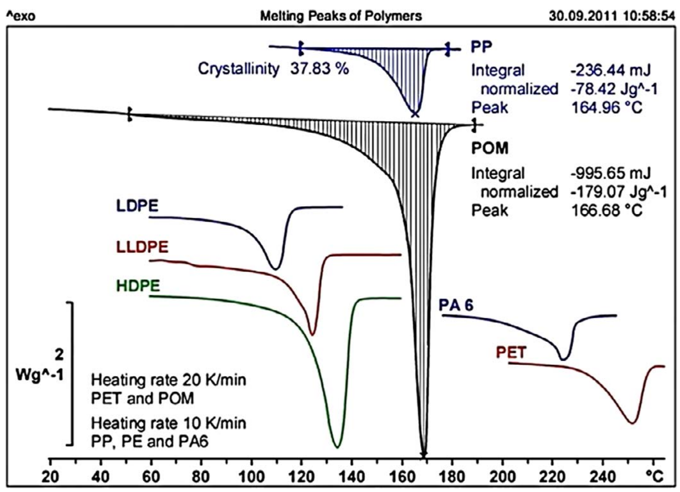

Figure 2. *Melting peak of polymers based on DSC thermogram.*

The thermal properties of LDPE demonstrate melting peaks of 2 mixed polymers at 119.96 and 123.28°C. To compare with general points of melting peak of polymers in Figure 2, both PET and LDPE results are validated similarly to general melting peak behaviors [48].

To discuss the thermal performance of polymers, even LDPE can be mixed by multiple types of polymers within similar melting points. But PET is melted at much higher temperatures compared with LDPE. The heat behaviors between PET and LDPE are different, as a glass transition and crystallization stages in terms of PET. This results in an unmixable process between PET and LDPE materials for forming a transparent material. Another focus point is a different heat capacity, of which PET contains a higher capacity of heat reflecting from a higher density of material compared with LDPE. This is also related to the heat transferring process of the building envelope. In addition, to find out the thermal property from the laboratory and equation 1, heat capacity and outdoor temperature are novel keys to calculate heat transfer and affect indoor comfort environment. In parallel research, the agricultural outdoor environment in central Thailand was monitoring environment data including temperature, air humidity and light transmittance data.

4.2 Light transmittance

From the UV–Vis–NIR spectrophotometer, the range of scanning is 200–1000 nm, with interval of 1.0 nm and a scan rate at 600 nm/min. The percentages of transmittance from PET and LDPE are reported in Figure 3.

To test light transmittances of 200-μm-thickness PET and LDPE, Figure 3 illustrates the curve of transmittance percent relying on a range of wavelength between 200 and 1000 nm. PET allows light wavelengths between 310–1000 nm, and light wavelength from 400 nm can provide >80% light transmittance. To specify red and blue wavelengths, light transmittance has nearly 90%. Turning to LDPE material, it can be seen that light

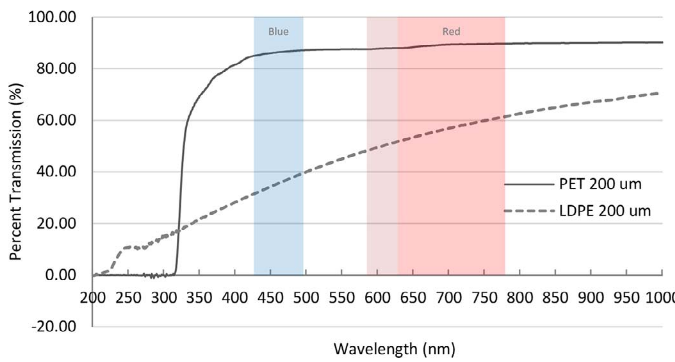

Figure 3. *Light transmission of PET and LDPE.*

transmittance of 200–1000 nm wavelength increases constantly from 0 to 70%. For blue light, light transmittance averages to ~35%, whereas red light transmittance is ~55%. The proportion of blue and red light impacts the growth of plants by stimulating the germination and the seedling process. Red light transmittance also affects an increase in indoor heat and lower air humidity, which relates directly to human thermal comfort.

To discuss the light transmittance of material, Table 3 explains the impacts of transmitted wavelength on plants and human comfort. All wavelength transmittances of PET are too high-intensity and provide a negative impact on the vining process, whereas too high of an intensity can lead to a glare effect on human eyesight [16, 17]. On another side of LDPE's light transmittance, low transmittance and low intensity of light are suitable for light distribution, affecting all stages positively [20]. A half transmittance depends on natural light, which is lower expectations in some working functions, but it should be suitable for circulating areas. The proportion of 1:3 blue:red mixtures from LDPE provides suitable light [23] for early stages of plant growth, e.g. seed, germination and seedling process. In addition, red and UV lights increase chlorophyll a and b in the photosynthesis system. Blue light negatively affects eye health, whereas red light brings about high temperatures in the indoor ambient environment.

To summarize results, the methodology involved selecting the materials, preparing samples for thermal property and lighting laboratory tests and analysing the results based on suitable criteria. It was found that LDPE sheets have lower light transmittance than PET sheets, making them suitable for supporting the seedling stage and older vines of plant growth. PET sheets, on the other hand, deliver a high intensity of red light, making them suitable for stimulating photosynthesis in older vines and during the harvesting process. The study also found that LDPE sheets can be melted at a lower temperature compared with PET sheets.

When discussing the circular economy, it was found that recyclable and mixable LDPE plastic is more suitable for greenhouse transparent roof materials than glass and PET. LDPE provides different light ranges that are suitable for most stages of melon growth. In addition, LDPE transparent material was found to have lower environmental impacts in terms of life cycle assessment

Table 3. *Conclusion of PET and LDPE light transmittances affecting plant and human*

Materials	Light			Impacts	
	Color	Wavelength	Transmittance	Plants	Human
PET	Visible PAR Blue Red IR	380–770 nm 400–700 nm 400–480 nm 630–680 nm 700–1000 nm	87% 87% 85% 90% 90%	- Intensity too high - Negative impact as burning leaf [38]—Light filter is required	- Intensity too high and glare effect—burning skin impact [16, 17]
LDPE	Visible PAR Blue Red Infrared	380–770 nm 400–700 nm 400–480 nm 630–680 nm 700–1000 nm	42.5% 42.5% 35% 52.5% 62.5%	- Lower intensity of light [20]—Suitable for all growth process and photosynthesis - 1:3 blue:red proportion [23]—Suitable light for germination and seedling—suitable for chlorophyll a & b boosting up	- Suitable intensity depending on outdoor source - Affect eye health - Heat up ambient temperature

and MET (Materials, Energy, and Toxicity) Matrix [3], which can reduce the need for other energy-consuming devices to light up and protect plants from the outdoor environment in tropical climates in a sustainable approach. Furthermore, blending LDPE at a lower temperature can reduce the carbon emissions of recycling production.

5 CONCLUSIONS

The study found that LDPE sheets have lower light transmittance than PET sheets, making them suitable for supporting the seedling stage and older vines of plant growth. PET sheets, on the other hand, deliver a high intensity of red light, making them suitable for stimulating photosynthesis in older vines and during the harvesting process. The study also found that LDPE sheets can be melted at a lower temperature compared with PET sheets.

To investigate thermal properties and light transmittance of transparent material for a greenhouse, type of PET and LDPE sheet was prepared at 200-μm thickness of each polymer type. The thermal property of PET from DSC thermogram offers glass transition at 72.80°C, crystallization peak at 125.22°C and endothermic melting peak at 249.59°C. On the other hand, LDPE thermal property rigids to endothermic melting peaks with 2 mixed materials at 119.96 and 123.28°C, respectively. Because of different melting peaks, PET and LDPE are not suggested to be mixed together for transparent material. Using the UV–Vis–NIR spectrophotometer, light transmittances and impacts on plants are analysed. With seven stages of plant growth, light wavelengths propose negative and positive effects on plants. For the early stages of 1) seed, 2) germination and 3) seedling, the proportion of 1:3 blue:red lights from LDPE transparency can support as well as natural white light. White light impacts all stages of a plant's photosynthesis at 4) older vine, 5) flowering and 6) fruit bearing. Specific UV and pulse lights improve hygienic protection to 7) the harvesting and drying process of plant growth. Based on PET transmittance, the light intensity of every wavelength is too high and has a negative impact on burning leaves and human skin. Light transmittance of PET and LDPE averaged at 73.21 and 44.43%, respectively. Furthermore, based on high transmittance rate in every wavelength in case of flowable ventilation wall, PET affected an increase of ambient temperature and the reduction of air humidity. From the transmittance of blue and red wavelength, LDPE was proven to be more suitable for a greenhouse's transparent material.

This research into transparent materials has the potential to be applied for greenhouse transparent materials, which can provide lower impact in the circular economy area and lower carbon emissions. The result can contribute to further thermal transferring processes and calculations. Furthermore, the limitations of the research regarding the relation between thermal comfort and lighting impacts need to be clarified by real-time monitoring data, which was conducted in parallel with this research. To provide further suggestions for future research, indoor heat monitoring during the summer should be conducted to estimate the potential of materials that may melt under high-temperature conditions throughout the year.

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AUTHOR CONTRIBUTIONS

Jitiporn Wongwatcharapaiboon (Conceptualization, Formal analysis, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing—original draft, Writing—review & editing [equal]), Chanikarn Chankasem (Conceptualization, Data curation, Formal analysis, Investigation, Methodology [equal]), Pusit Lertwattanarak (Conceptualization, Supervision [equal]), and Saffa Riffat (Conceptualization, Supervision, Validation [equal])

REFERENCES

[1] National Statistical Office. 2013. *Area of Holdings by Activity of Holding and Region Year: 2003 and 2013*. National Statistical Office http://statbbi.nso.go.th/staticreport/Page/sector/EN/report/sector_11_6_EN_.xlsx (5 January 2022, date last accessed).

[2] Office of Agricultural Economics. Agricultural Economic Report 2019 and Outlook for 2020. 2019.

[3] Wongwatcharapaiboon J. 2020. Circular economy: case studies in upcycled industrial waste glass in Thailand. In: Office of Academic Research and Administration, Eastern Asia University ed. *6th International Conference "Green ASIA and Sustainability Forum: BCG in Action; the New Sustainable Growth Engine (Bio-Circular-Green Economy)"*. Bangkok, Thailand, pp 14-24.

[4] Nisticò R. Polyethylene terephthalate (PET) in the packaging industry. *Polym Test* 2020;**90**:106707.

[5] Wu C, Li M, Huang Y *et al.* Cutting of polyethylene terephthalate (PET) film by 355 nm nanosecond laser. *Opt Laser Technol* 2021;**133**:106565.

[6] Li B-J, Yang G-Y, Huang L-J *et al.* Performance optimization of SnO2:F thin films under quasi-vacuum laser annealing with covering a transparent PET sheet: a study using processing map. *Appl Surf Sci* 2020;**509**:145334.

[7] Arulrajah A, Perera S, Wong YC *et al.* Stabilization of PET plastic-demolition waste blends using fly ash and slag-based geopolymers in light traffic road bases/subbases. *Constr Build Mater* 2021;**284**:122809.

[8] Emekli NY, Büyüktaş K, Başçetinçelik A. Changes of the light transmittance of the LDPE films during the service life for greenhouse application. *J Build Eng* 2016;**6**:126–32.

[9] Moez AA, Aly SS, Elshaer YH. Effect of gamma radiation on low density polyethylene (LDPE) films: optical, dielectric and FTIR studies. *Spectrochim Acta A Mol Biomol Spectrosc* 2012;**93**:203–7.

[10] Zhu BL, Wang J, Zheng H *et al.* Investigation of thermal conductivity and dielectric properties of LDPE-matrix composites filled with hybrid filler of hollow glass microspheres and nitride particles. *Compos Part B* 2015;**69**:496–506.

[11] Zhu BL, Zheng H, Wang J *et al.* Tailoring of thermal and dielectric properties of LDPE-matrix composites by the volume fraction, density, and surface modification of hollow glass microsphere filler. *Compos Part B* 2014; **58**:91–102.

[12] Shin J, Liu X, Chikthimmah N *et al.* Polymer surface modification using UV treatment for attachment of natamycin and the potential applications for conventional food cling wrap (LDPE). *Appl Surf Sci* 2016;**386**:276–84.

[13] Wang L-F, Rhim J-W. Grapefruit seed extract incorporated antimicrobial LDPE and PLA films: effect of type of polymer matrix. *LWT* 2016;**74**:338–45.

[14] Skariyachan S, Taskeen N, Kishore AP *et al.* Novel consortia of Enterobacter and pseudomonas formulated from cow dung exhibited enhanced biodegradation of polyethylene and polypropylene. *J Environ Manag* 2021;**284**:112030.

[15] Kusumastuti Y, Putri NRE, Timotius D *et al.* Effect of chitosan addition on the properties of low-density polyethylene blend as potential bioplastic. *Heliyon* 2020;**6**:e05280.

[16] Devrani T. 2018. Development of automated mapping methods for birch woodlands in the Norðurhraun lava field, Hekla. (Master Degree of Forest Information Technology), Faculty of Forest and Environment, University of Applied Sciences and Faculty of Forestry, Warsaw University of Life Sciences, Reyjavik & Warsaw.

[17] Kern S, Özsoy-Çiçek B. 2017. Remote Sensing. In Gümrükcü H, Ersoy G, Simsek AI, Dincer FCY (eds.). The Polar age from a global perspective-3 – Historical and legal perspective - Ecological Transformation. pp. 175-206. Ankara: Siyasal Kitabevi TümHaklari Saklidir, Ankara, Akdeniz Üniversity.

[18] Levine RP. The mechanism of photosynthesis. *Sci Am* 1969;**221**:58–72.

[19] Watjanatepin N, Boonmee C. Which color of light from the light emitting diodes is optimal for plant cultivation? *J Sci Technol* 2017;**25**: 158–76.

[20] Adeyeye AS, Akanbi WB, Olalekan KK *et al.* The growth and yield performance of sweet melon as affected by planning spacing in North East Nigeria. *Int J Res Agric For* 2017;**4**:17–21.

[21] He R, Zhang Y, Song S *et al.* UV-A and FR irradiation improves growth and nutritional properties of lettuce grown in an artificial light plant factory. *Food Chem* 2021;**345**:128727.

[22] Affandi FY, Verdonk JC, Ouzounis T *et al.* Far-red light during cultivation induces postharvest cold tolerance in tomato fruit. *Postharvest Biol Technol* 2020;**159**:111019.

[23] Danziger N, Bernstein N. Light matters: effect of light spectra on cannabinoid profile and plant development of medical cannabis (Cannabis sativa L.). *Ind Crop Prod* 2021;**164**:113351.

[24] Kong L, Wen Y, Jiao X *et al.* Interactive regulation of light quality and temperature on cherry tomato growth and photosynthesis. *Environ Exp Bot* 2021;**182**:104326.

[25] Li Y, Liu C, Shi Q *et al.* Mixed red and blue light promotes ripening and improves quality of tomato fruit by influencing melatonin content. *Environ Exp Bot* 2021;**185**:104407.

[26] Izzo LG, Hay Mele B, Vitale L *et al.* The role of monochromatic red and blue light in tomato early photomorphogenesis and photosynthetic traits. *Environ Exp Bot* 2020;**179**:104195.

[27] Zhang J, Zhang Y, Song S *et al.* Supplementary red light results in the earlier ripening of tomato fruit depending on ethylene production. *Environ Exp Bot* 2020;**175**:104044.

[28] Liang Y, Kang C, Kaiser E *et al.* Red/blue light ratios induce morphology and physiology alterations differently in cucumber and tomato. *Sci Hortic* 2021;**281**:109995.

[29] D'Amico-Damião V, Lúcio JCB, Oliveira R *et al.* Cryptochrome 1a depends on blue light fluence rate to mediate osmotic stress responses in tomato. *J Plant Physiol* 2021;**258-259**:153374.

[30] Zushi K, Suehara C, Shirai M. Effect of light intensity and wavelengths on ascorbic acid content and the antioxidant system in tomato fruit grown in vitro. *Sci Hortic* 2020;**274**:109673.

[31] Jing X, Wang H, Gong B *et al.* Secondary and sucrose metabolism regulated by different light quality combinations involved in melon tolerance to powdery mildew. *Plant Physiol Biochem* 2018;**124**:77–87.

[32] Falcioni R, Moriwaki T, Perez-Llorca M *et al.* Cell wall structure and composition is affected by light quality in tomato seedlings. *J Photochem Photobiol B Biol* 2020;**203**:111745.

[33] Kalaitzoglou P, Taylor C, Calders K *et al.* Unraveling the effects of blue light in an artificial solar background light on growth of tomato plants. *Environ Exp Bot* 2021;**184**:104377.

[34] Zhang Y, Kaiser E, Zhang Y *et al.* UVA radiation promotes tomato growth through morphological adaptation leading to increased light interception. *Environ Exp Bot* 2020;**176**:104073.

[35] Manzocco L, Da Pieve S, Maifreni M. Impact of UV-C light on safety and quality of fresh-cut melon. *Innovative Food Sci Emerg Technol* 2011;**12**:13–7.

[36] Abadias M, Colás-Medà P, Viñas I *et al.* Application of an innovative water-assisted ultraviolet C light technology for the inactivation of microorganisms in tomato processing industries. *Food Microbiol* 2021; **94**:103631.

[37] Fundo JF, Miller FA, Mandro GF *et al.* UV-C light processing of cantaloupe melon juice: evaluation of the impact on microbiological, and some quality characteristics, during refrigerated storage. *LWT* 2019; **103**:247–52.

[38] Pham DM, Chun C. Growth and leaf injury in tomato plants under continuous light at different settings of constant and diurnally varied photosynthetic photon flux densities. *Sci Hortic* 2020;**269**:109347.

[39] Jiang Y, Ding X, Wang J *et al.* Decreased low-light regulates plant morphogenesis through the manipulation of hormone biosynthesis in Solanum lycopersicum. *Environ Exp Bot* 2021;**185**: 104409.
[40] Shin J, Hwang I, Kim D *et al.* Evaluation of the light profile and carbon assimilation of tomato plants in greenhouses with respect to film diffuseness and regional solar radiation using ray-tracing simulation. *Agric For Meteorol* 2021;**296**:108219.
[41] Yang L, Chen J, Sun X *et al.* Inhibition of sucrose and galactosyl-sucrose oligosaccharide metabolism in leaves and fruits of melon (Cucumis melo L.) under low light stress. *Sci Hortic* 2019;**244**:343–51.
[42] Sousa AED, de Almeida Lopes MM, Moreira ADR *et al.* Induction of postharvest resistance in melon using pulsed light as abiotic stressor. *Sci Hortic* 2019;**246**:921–7.
[43] Erdmann M, Kupsch A, Müller BR *et al.* Diesel-induced transparency of plastically deformed high-density polyethylene. *J Mater Sci* 2019;**54**: 11739–55.
[44] Maruhashi Y, Iida S. Transparency of polymer blends. *Polym Eng Sci* 2001;**41**:1987–95.
[45] Craighead S, Huang R, Chen H *et al.* The use of pulsed light to inactivate Cryptosporidium parvum oocysts on high-risk commodities (cilantro, mesclun lettuce, spinach, and tomatoes). *Food Control* 2021;**126**:107965.
[46] Privalov PL, Potekhin SA. Scanning microcalorimetry in studying temperature-induced changes in proteins. *Methods Enzymol* 1986;**131**: 4–51.
[47] Gill P, Moghadam TT, Ranjbar B. Differential scanning calorimetry techniques: applications in biology and nanoscience. *J Biomol Tech* 2010;**21**: 167–93.
[48] Laboratory Laboratory Solutions from METTLER TOLEDO. Differential Scanning Calorimetry (DSC) – online training course. 2012.