Energy-Efficient Coatings: The Role of Heat-Reflecting Pigments

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Given the increasing global demand for energy and the escalating climate crisis, the development of energy-efficient materials has become increasingly important. Heat-reflecting pigments play a key role in the formulation of coatings that reduce solar heat gain, thereby contributing to passive cooling strategies in buildings, vehicles and infrastructure. By reflecting infrared light and reducing heat, infrared reflective coatings can keep objects cooler and provide significant benefits across a range of applications. The main objective of our research was to investigate the influence of pristine cellulose nanocrystal (CNC) coatings and pigmented CNC coatings on the absorbance, reflectance and transmittance of light in the UV-VIS-NIR regions. In the study four different pigments were used (one heat-reflective and three effect pigments), which differ in chemical composition and particle size.

Keywords:
heat-reflecting pigments,
cellulose nanocrystals,
energy efficiency,
solar heat,
coatings

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1 Introduction

Applications in the field of Heat Management, such as glass windows, require both protection against infrared radiation and adequate visible light transmission to ensure that the interior spaces are illuminated. To fulfill these demands materials are needed exhibiting high transmission values in a certain spectral area (e.g. visible light) while, in other areas (e.g. the NIR spectrum), the transmission of light is decreased. Materials with reduced infrared light transmission are used frequently in thermal insulation and heat management applications (Greiler et al., 2021).

For exterior coatings requiring heat protection (e.g. horticulture and architecture), inorganic pigments with strong IR reflectance are an excellent solution (Sameera et al., 2017). Energy consumption could be decreased not only by cooling, but also by using special infrared reflective coatings. When solar reflectance increases, the surface temperature decreases; solar radiation is reflected rather than absorbed. Infrared reflective coatings can keep objects cooler and have major advantages in a wide range of applications (Mara et al., 2023; Blaco et.al, 2023). A cool coating reflects a high percentage of incident infrared radiation, while transmitting high levels in the visible spectra. This will reduce the amount of solar energy entering the substrate, which results on a cool surface when exposed to the sun (Sameera et al., 2017).

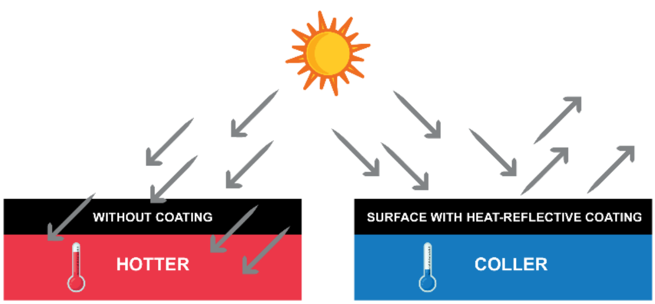

Figure 1: Schematic illustration of a heat-reflective coating.

Conventional coating technologies decrease the transmission of light while they reduce the energy of solar radiation. In contrast, heat-reflecting pigments reflect the sunlight's invisible heat radiation while allowing the majority of the visible light to pass through. Compared to conventional coating, they offer more light, less heat and higher UV absorption (Merck, 2019).

In cases of surfaces exposed to sunlight, solar energy can be transmitted, reflected, or absorbed. The electrons in a substance exposed to sunlight will absorb light wave energy and change their energy state when the frequency of the incoming light is near to their electron energy levels. In other words, the absorbed light is converted into thermal energy. The absorption of light depends on the nucleus and on the electrons. In its transmission, light moves through a substrate, and, at the reflection of different wavelengths, the angle of incidence of the light is equal to that of the reflection on smooth surfaces; consequently, the light bounces back from the surface (Mara et al., 2023).

Sunlight contains visible light and non-visible radiation such as ultraviolet light (UV-light) and infrared light (IR-light) (Greiler et al., 2021). The composition of the solar spectrum includes 52% NIR radiation (700-2500 nm), 43% visible (VIS) light (400-700 nm), and 5% ultraviolet (UV) radiation (100-400 nm). Over half of the solar radiation accounts for infrared radiation (Mansour et al., 2025, La Notte et al., 2020). The UV radiation is divided further into: UV-C (100-280 nm, which is generally created from artificial light sources), UV-B (280-315 nm, being the most energetic component of natural UV light), UV-A (315-400 nm, which accounts for the lowest energy of UV light) (Roy et al., 2023).

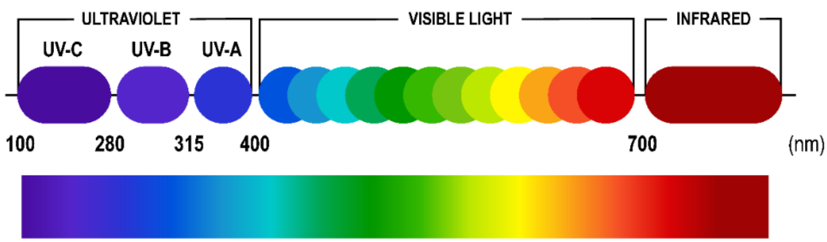

Figure 2: The solar spectrum.

Near infrared light plays an important role in heat generation. The absorbed sunlight increases the temperature and requires more cooling energy, additionally it can cause physical damage (Mara et al., 2023). However, these radiations on absorption result in heating up of the surface of the material which is exposed to the sunlight. A significant amount of heat is absorbed into the surface through conduction (Jose et a., 2019).

2 Materials and methods

In this study a commercially available cellulose nanocrystals "CNCs" (Table 1) as a binder and four different special pigments were used (Table 2), which were coated in a machine direction using a K Control Coater / meter bar coating (wire diameter: 0.05 mm, wet film deposit: 4 µm) on translucent paper (G = 100 g/m^2). The coating formulation was based on pigments mixed with cellulose nanocrystals (CNCs) at a ratio of 20:100. Before the measurement the samples were placed in standard conditions of 23 °C and 50% humidity for one day.

Table 1: Properties of the cellulose nanocrystals (CNCs).

Parameter	**Specification**
Chemical name	$C_6O_5H_{10}$
Colour	White-translucent
Form	Aqueous suspension, 2-5wt.% solids
Surface	Hydrophilic
Average size (Scherrer method, SEM)	10-15 nm wide,150-300 nm length
Crystallinity (XRD:Segal method)	90,3 %
Initial decomposition temperature	285 °C
Density	Aqueous gel: 1.04 g/cm^3
Lihnin content	Negligible

Table 2: Properties of the pigments.

Pigment label	**Trade name**	**Form**	**Pigment type**	**Chemical composition**	**Particle size**
HRP	Iriotec 9770	Powder	Heat - reflecting pigment	Mica coated with SiO_2, TiO_2, SnO_2	5 -60 µm
EP1	Symic A001	Powder	Effect pigment	Synthetic mica	1 - 15 µm
EP2	Spectraval W	Powder	Effect pigment	Natural mica	5 - 25 µm
EP3	Pyrisma T30-23	Powder	Effect pigment	Mica-based iron oxide	5 - 35 µm

A Scanning Electron Microscope - SEM (JSM-5610JOEL) was used to evaluate the pigment particles. The absorption (A), transmission (T) and reflectance (R) spectra of the coated pigments were obtained with a Lambda 950 UV-VIS-NIR spectrometer (PerkinElmer, USA) in the range of wavelengths from 200 nm to 2500 nm, at 10-nm intervals.

Figure 3 shows a SEM image of the cellulose nanocrystals (CNCs).

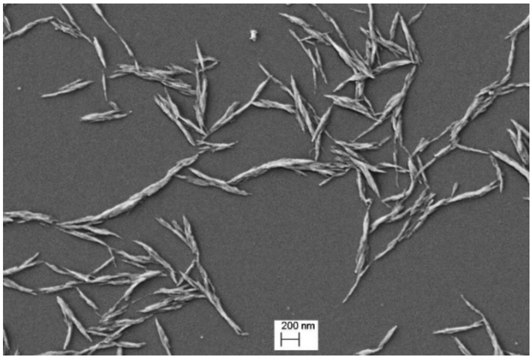

Figure 3: SEM image of the cellulose nanocrystals
Source: (Nanocrystacell, 2023).

The cellulose nanocrystals (CNCs), a kind of rod-like nanoparticles obtained from sulphuric acid hydrolysis of natural cellulose sources such as wood, cotton, tunicates and bacteria, have gained great interest owing to their abundant sources, biocompatibility, high specific surface area, high thermal stability and unique optical properties. CNC suspensions can self-organise into chiral nematic liquid crystal structures, and this helical-layered structure can be retained in solid films via an evaporation-induced self-assembly process, thereby leading to iridescent colour (Feng et al., 2023).

3 Results and Discussion

Figure 4 shows the scanning electron microscope (SEM) micrographs of all four pigments at 500x magnification used in this study. In both pigments examined (EP1 and EP4), the "corn flake" morphology is clearly recognisable, in which the particles appear as thin, irregular flakes with sharp edges and relatively smooth surfaces.

Pigment HRP (Iriotec 9770, Figure 4a) is a mica-based heat-reflecting pigment. It reflects the invisible heat radiation from sunlight while allowing most visible light to pass through. It enables the diffusion of visible light while reducing UV and NIR transmission. It provides more light, less heat, and higher UV absorption, exhibiting properties similar to sun-protective filters on all transparent substrates.

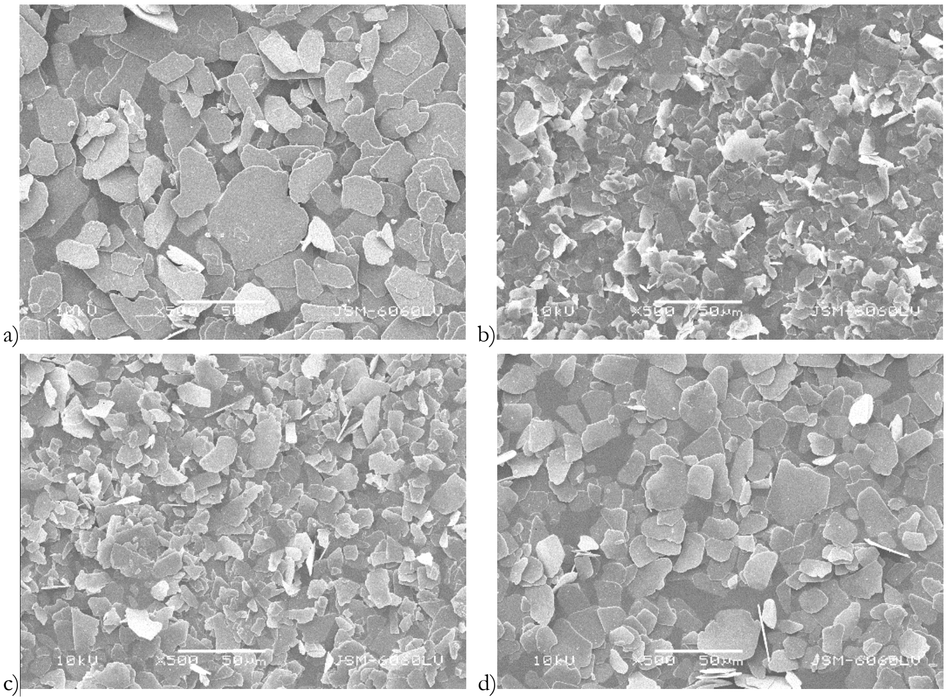

Figure 4: SEM images of the pigments:
a) HRP, b) EP1, c) EP2 and d) EP3.

Pigment EP1 (Symic A001, Figure 4b) is an interference silver-coloured, pearlescent pigment based on synthetic mica. It offers weather-resistance, and provides new styling possibilities for exterior and architectural powder coating applications.

Pigment EP2 (Spectraval White, Figure 4c) is a pearlescent pigment based on natural mica. It offers an interference and silky effect.

Pigment EP3 (Pyrisma T30-23, Figure 4d) is an interference pigment with specially developed titanium dioxide interference layers based on natural mica (Coating Ingredients Master Catalogue, 2017).

Figure 5 shows the absorbance spectra of two types of coatings: pristine CNC and pigmented CNC (labels HRP, EP1, EP2 and EP3), measured across a wide wavelength range (200–2500 nm), which includes the **UV, visible (VIS), and near-infrared (NIR)** regions of the spectrum.

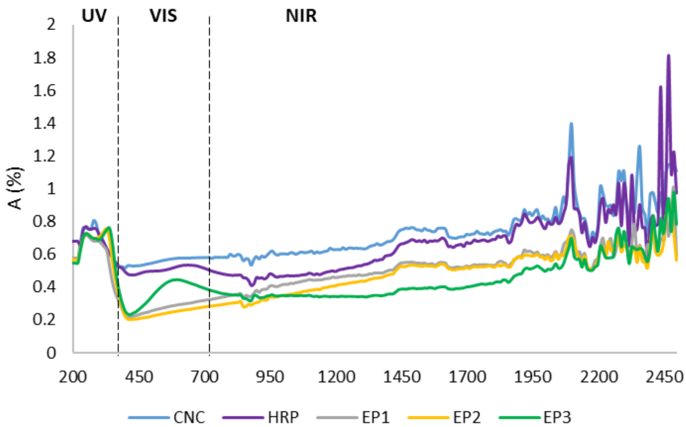

Figure 5: Absorbance spectra of pristine CNC and pigmented CNC coatings in the UV-VIS-NIR regions.

In the physical sense, absorption describes the reception of an angle, a particle or wave. More precisely, the absorption of light is defined as the total or partial, wavelength-dependent transfer of electromagnetic energy to matter. Thus, absorption comes along with a conversion into another form of energy like heat. Black materials like carbon pigments are almost ideal absorbers (Kehren, 2010). All the samples showed relatively high absorbance in the UV region. The highest peak was achieved by the pristine CNC coating at 250 nm, being A = 0,77%. In the VIS region, the absorbance decreased for all the samples. In the case of the pigments` evaluation, pigment EP2, which is based on natural mica, showed the lowest absorbance, while pigment HRP (the heat-reflecting pigment) showed the highest. Pigments EP1, EP2 and EP3 obtained the lowest peaks in the UV region between 410 and 440 nm. In the NIR region, all the samples tended towards higher absorbance, with the peak value was for pigment HRP at 2470 nm being A = 1.8%. On average, CNC had the highest values in the VIS and NIR regions.

The results of the reflectance spectra of pristine CNC and pigmented CNC coatings in the UV-VIS-NIR regions are shown in Figure 6.

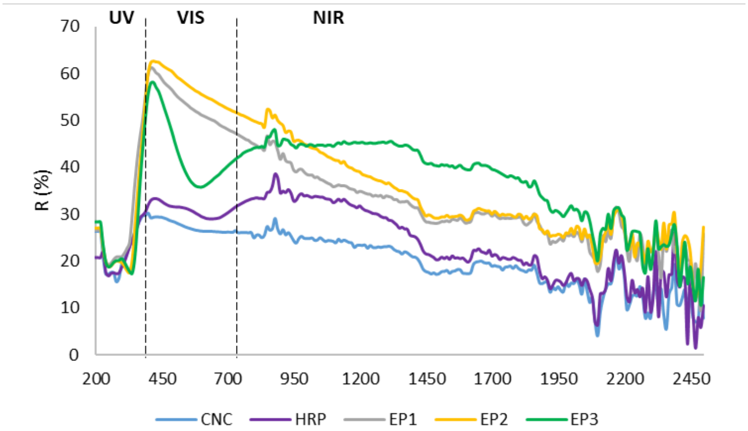

Figure 6: Reflectance spectra of pristine CNC and pigmented CNC coatings in the UV-VIS-NIR regions.

As demonstrated in Figure 6, the reflectance in the UV region was the lowest for all the samples. The CNC film exhibited the lowest overall reflectance across the spectrum. Its reflectance remained mainly between 20–35%, with only a moderate rise in the VIS region. This behaviour is typical for cellulose-based coatings, which are generally transparent to semi-transparent and do not scatter NIR radiation strongly. In the VIS region, significant differences appeared between the pigments (HRP, EP1–EP3). The pigment based on natural mica, E2, achieved the highest reflectance values, with a peak R value of 62.6% at 420 nm, while the heat-reflecting pigment HRP showed the lowest reflectance values in all three regions (UV, VIS, NIR). The heat-reflective pigment (HRP) showed moderately elevated reflectance in both VIS and NIR, but remained lower compared with the EP pigments. Its reflectance stayed in the ~25–45% range. The solar reflectance of a material depends on its surface orientation, which varies the spectral and angular distributions of the incident sunlight. The position of the sun and atmospheric conditions, such as resistance due to clouds, humidity, wind and temperature, also influences the solar reflectance of a material. Solar heat gain is the solar power absorbed per unit surface area, which is related t strongly o solar reflectance (Jose et a., 2019).

Figure 7 shows the transmittance spectra of pristine CNC and pigmented CNC coatings in the UV-VIS-NIR regions.

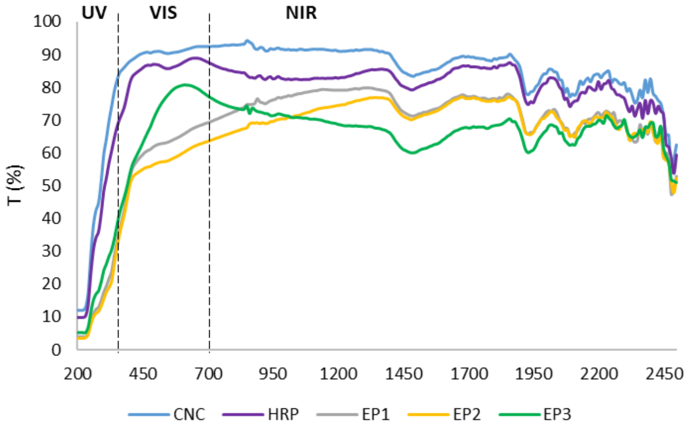

Figure 7: Transmittance spectra of pristine CNC and pigmented CNC coatings in the UV-VIS-NIR regions.

Transmittance is defined as the light passing through an object that is not reflected or absorbed (Kehren, 2010). Among all the pigments, the heat-reflecting pigment (HRP) exhibited the highest values across all three regions (UV-VIS-NIR), with the transmission peak occurring between 630 and 700 nm. This higher transmission can be explained by the chemical composition of pigment HRP. The transmission through a coating containing pigments is influenced by two effects, the absorption of the pigment and the interference effects. Silica or mica are almost transparent materials for light. However, metal oxide like titania or iron oxide absorbs UV-light and can, by this, decrease the transmission in the spectral area of UV-light. A high percentage transmittance indicates that little or no light is being absorbed (Greiler et al., 2021).

The transparency of CNCs is an essential property for their application in optically clear materials. They exhibited high optical transparency in the visible light range. The films exhibited transmittance values exceeding 80 %, indicating their suitability for transparent applications (Arockiasamy et al., 2024).

4 Conclusion

This study demonstrated that incorporating special-effect and heat-reflective pigments into cellulose nanocrystal (CNC) coatings influences their optical properties significantly across the UV–VIS–NIR spectral regions. The pristine CNC films showed the lowest reflectance and moderate absorbance and transmittance, confirming their inherently transparent and weakly scattering nature. When pigments were incorporated into the CNC coat, clear spectral differences emerged that were strongly dependent on the pigment composition and particle morphology.

Among the evaluated pigments, the effect pigments (EP1, EP2 and EP3) exhibited the highest reflectance values, particularly in the visible and near-infrared regions. In contrast, the the heat-reflective pigment (HRP) showed only moderate reflectance, but provided the highest transmittance across all three spectral regions.

The absorbance measurements confirmed further that CNC-based coatings containing pigments EP series maintain the lowest absorbance in the VIS region, whereas the heat-reflective pigment (HRP) demonstrated the highest absorbance in all the measured spectra. Overall, the results show that the pigment type dictates the balance between reflectance, absorbance and transmittance strongly in incorporating into CNC coating.

This work provides a foundation for the further development of CNC-based, energy-efficient coating systems for use in heat-sensitive applications.

Acknowledgment

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