Original scientific paper

A study of optical properties of coatings based on functional pigments and cellulose nanocrystals across the solar spectrum

ABSTRACT

This study investigates the optical properties of coatings based on functional pigments and cellulose nanocrystal (CNC) across the solar spectrum (UV-VIS-NIR: 200-2500 nm). The coatings were formulated using CNC aqueous suspension as a sustainable, bio-based binder. Four different pigment types (one IR-absorbing and three pearlescent) were incorporated into the CNC matrix and coated onto the translucent paper substrate. Spectrophotometric measurements revealed significant differences in optical properties among coatings. The coating based on IR-absorbing pigment exhibited the highest overall absorbance, especially in the NIR region, the lowest reflectance across the entire solar spectrum, but the highest transmittance in the NIR (≈85-90% between ≈900-1800 nm). Coatings based on the pearlescent pigments showed lower overall absorbance but higher UV reflectance. The results highlight the potential of using CNCs as a binder with functional pigments to create sustainable functional coatings on transparent substrates where more light, less heat, and higher UV absorption are needed.

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First received: 11.12.2025.
Revised: 6.2.2026.
Accepted: 6.4.2026.

KEY WORDS
functional pigments, optical properties, coatings, solar spectrum, cellulose nanocrystals

Introduction

The design of coatings that control solar radiation in a spectrally selective way is increasingly important in energy, transportation, packaging, and advanced functional surfaces. The coating and pigment industries have developed a broad range of functional pigments designed to interact selectively with solar radiation. Solar energy can be transferred, reflected, or absorbed by surfaces that are exposed to sunlight. Solar spectrum consists of 52% NIR radiation (700-2500 nm), 43% visible (VIS) light (400-700 nm), and 5% ultraviolet (UV) radiation (280-400 nm). Near infrared light plays an important role in heat generation (La Notte at al., 2020; Mara et al., 2023).

Pigments are important materials in industrial coatings that not only provide colour but also impart special properties such as thermal control.

The classification of pigments can be approached from several perspectives, such as their chemical composition, source (origin), color, crystallographic structure, their interaction with light, and, most importantly, their functional properties. Pearlescent pigments belong to the group of special effect pigments and are composed of plate-shaped crystals unlike conventional pigments. The transmission through a coating containing pearlescent pigments is influence by two effect the absorption of the pigment and interference effects. Silica or mica are almost transparent materials for light. However, metal oxides like titania or iron oxide absorbs UV-light and can for this decrease the transmission in the spectral area of UV-light (Ahn et al., 2022; Greiler & Mahltig, 2021). NIR pigments are mainly classified into two groups: inorganic compounds and organic compounds. A preference for organic pigments is reported due to their non-toxicity, biocompatibility, and their cost-effectiveness.

In addition, organic reflective materials are soluble in standard solvents, thereby increasing compatibility with polymers. The addition of NIR pigments to coatings offers a wide range of benefits. One of the standout advantages is the enhanced durability of the coatings, the reduced thermal degradation (Mansour & Farha, 2025; Rossi, Russo & Bouchakour Rahmani, 2020).

The choice of binder plays an equally important role in determining the optical properties of the coating. Cellulose nanocrystals (CNCs) also known as cellulose nanowhiskers or nanocrystalline cellulose, derived from renewable biomass, offer a sustainable alternative to conventional polymer binders. CNCs are typically produced from lignocellulosic biomass (i.e., plants), due to the natural abundance and commercial availability of these sources. There is also growing interest in valorizing other lignocellulose biomass to produce CNCs, including nonwoody plants (e.g., bamboo, sugar cane and maize), as well as bast fibers from plants such as ramie, hemp, and jute (Frka-Petesic et al., 2023).

CNCs exhibit high mechanical strength, rigidity, and optical transparency, making them ideal for applications in nanocomposites, coatings, and drug delivery. CNCs typically exhibit rod-like shapes with widths ranging from 3 to 20 nm (Tofanica et al., 2025). Their nanoscale dimensions minimize light scattering, enabling the formation of clear films even at relatively high solid content. Furthermore, CNC-based matrices provide environmental benefits by reducing reliance on petroleum-derived polymers and support circular economy principles (Droguet et al., 2022; Jeon, Oh & Kim, 2025; Ruberto et al., 2024).

Recent studies have demonstrated the feasibility of CNC-based coatings for optical and barrier applications, including photonic films and effect pigments, highlighting their potential for sustainable functional coatings (Chen, Zhang & Wu, 2023; Xu et al., 2018). Sirviö et al. showed that CNCs exhibited very high UV-absorption properties, especially in UVA and UVB regions and high transparency in the visible light region (around 90% with 0.1% of CNCs). The fabricated CNCs functioned as lightweight-reinforcing fillers with high UV-absorption capability when incorporated into a poly(vinyl alcohol) (PVA) matrix (Sirviö et al., 2016).

Yang et al. (2024) investigate VO_2 nano-rod coated mica composites pearlesecnt pigment for temperature control packaging. Furthermore, in the study conducted by Toy, E. et al., the effect of particle size on color and NIR reflectivity of $(Fe,Cr)_2O_3$ black pigment was investigated (Toy et al., 2025).

In this context, the present work focuses on coatings formulated with various types of pigments and CNC as a binder. The primary objective was to evaluate the spectral absorbance, reflectance, and transmittance of these coatings across the UV-VIS-NIR range. By combining functional pigments with a bio-based binder, this work aims to advance solutions for thermal control without deterioration of the optical properties of coatings.

Materials and methods

The CNC aqueous suspension (2-5 wt.% solids) used in this study as a binder was provided by the manufacturer *Nanocrystacell*, Slovenia (Table 1). Four different types of coatings were formulated using various pigment types (Table 2), which were incorporated into the CNC suspension (20 wt% pigment concentration). A translucent paper substrate (G = 100 g/m²) was used, which was coated using a K Control Coater/meter bar (wire diameter: 0.05 mm, wet film deposit: 4 µm). The paper was conditioned to a standard atmosphere of (23 ± 1)°C and (50 ± 2)% relative humidity for 24 hours before coating.

A Scanning Electron Microscope- SEM (JSM-5610JOEL) was used to evaluate the pigment morphology and pigment size distribution. The absorption (A), transmission (T), reflectance (R) spectra of coatings were obtained with Lambda 950 UV-VIS-NIR spectrometer (PerkinElmer, USA). Spectral data were collected over a broad wavelength range from 200 nm to 2500 nm, covering the ultraviolet, visible, and near-infrared regions of the electromagnetic spectrum. A step size of 10 nm was selected to ensure high-resolution spectral profiles. This approach enabled a comprehensive analysis of how each pigment influences light-matter interactions within the coating.

Table 1

Properties of cellulose nanocrystals (CNCs)

Parameter	Specification
Chemical name	$C_6O_5H_{10}$
Color	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 pigments

Label	Trade name	Form	Pigment type	Chemical composition	Particle size
HRP	Iriotec® 9230	Powder	IR-absorbing pigment	Tin antimony grey cassiterite	90% < 10 µm
EP1	Miraval® 5424	Powder	Pearlescent pigment	Synthetic calcium aluminum borosilicate (59-77%) coated with titanium dioxide (22-32%), silicone dioxide (1-8%) and stannic oxide (0-1%)	20-200 µm
EP2	Symic E001	Powder	Pearlescent pigment	Mixture of synthetic flurophlogopite (79-90%), titanium dioxide (10-20%) and tin oxide (< 1%)	20-150 µm
EP3	Colorstream® T10-03	Powder	Multi-color effect pigment	Silicon dioxide (51-64%) coated with rutile titanium dioxide (35-45%) and tin oxide (1-4%)	5-50 µm

Results and discussion

Scanning electron image analysis

A 500x magnification scanning electron microscope (SEM) image of each of the four pigments utilised in this study is displayed in Figure 1.

Figure 1/a shows clusters of pigment particles with predominantly rounded or polyhedral shapes, while Figure 1/b-c shows a »corn flake« morphology, in which the particles appear as thin, irregular flakes with sharp edges and comparatively smooth surfaces.

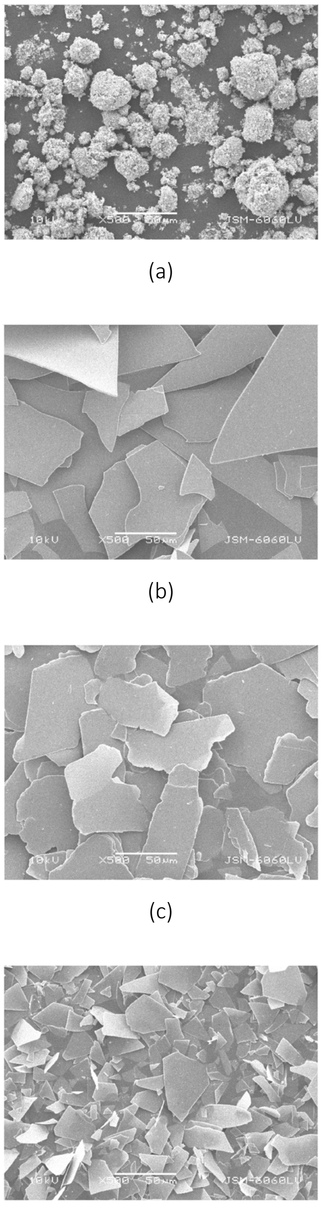
Pigment labelled IRP (Iriotec® 9230) is a mica-based layer pigment with 90% of particles smaller than 10 µm. Infrared-absorbing pigments are functional materials designed to absorb light in the near-infrared (NIR) region of the electromagnetic spectrum (typically 700-2500 nm) while often remaining transparent or only slightly colored in the visible range.

Pigment labelled EP1 (Miraval® 5424) is based on borosilicate glass and are therefore exceptionally transparent with a high sparkle and low color influence on colored formulations with a particle size of 20-200 µm.

Pigment labelled EP2 (Symic E001) is an interference silver pigment based on synthetic mica. It is a mixture of synthetic fluorphlogopite, titanium dioxide and tin oxide. It is a pearlescent pigment based on artificial mica.

Pigment labelled EP3 (Colorstream® T10-03 Tropic Sunrise) is a multicolor effect industrial pigment. It exhibits iridescent color gradients and limitless styling possibilities with ever-changing highlights.

It offers interference, improved chroma and pearlescent effects. It is based on synthetically manufactured silicon dioxide platelets coated with titanium dioxide (Specialchem, 2026).

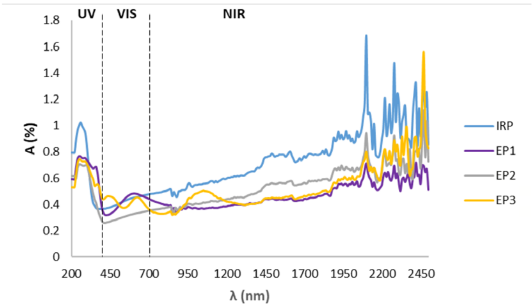


(a) (b) (c) (d)

» **Figure 1:** *SEM images of pigments: a) IRP, b): EP1, c) EP2 and d) EP3 at 500x magnification*

Optical properties of coatings

Figure 2 presents the absorbance (A, %) of four coatings based on different pigments measured across the solar spectrum from 200 to 2500 nm, covering the UV, visible (VIS), and near-infrared (NIR) regions.



» **Figure 2:** *Absorbance spectra of various coatings in the UV-VIS-NIR regions*

Coating based on infrared absorbing pigment (labelled IRP) has the highest overall absorbance, especially in the NIR region (700-2450 nm), where it rises steadily, with the highest peak at 2100 nm, reaching A = 1.7%.

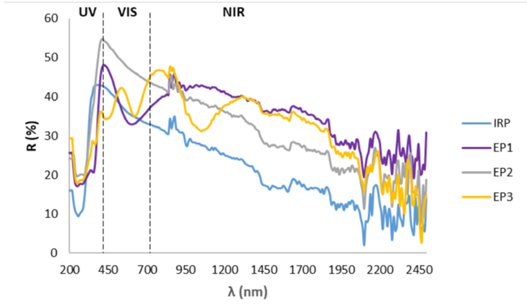
In the UV region coating based on IRP starts high (~0.8-1%) but dips near 450 nm before gradually increasing again. In the visible region (400-700 nm) absorbance decreased considerably for all coatings. The IR-absorbing pigment is specifically tuned to absorb near-infrared (NIR) radiation. It functions by capturing the energy of IR photons and converting them into thermal energy before they can pass through a substrate (like a window or plastic sheet).

Pigment IRP, however, is a light-colored pigment that absorbs heat and light just like black pigment. In light-colored coatings, it contributes to shorter drying times and higher production capacities at lower energy cost (Susonity, 2025). On the other side, coatings based on pigments EP1-EP3 have much lower absorbance and remain relatively flat across the spectrum, with slight increases in the NIR region.

The difference in NIR absorbance between coatings based on IRP and EP pigments becomes substantial above 1200 nm, and especially beyond 2000 nm, where IRP's performance is significantly higher.

Compared with pigments of other colors, black pigments like carbon black absorb visible light (400-700 nm), as well as near-infrared (NIR) light (700-2500 nm), which accounts for approximately 50% of solar radiation to store heat (Mansour & Farha, 2025).

Figure 3 presents the reflectance (R, %) of different coatings across the entire solar spectrum.

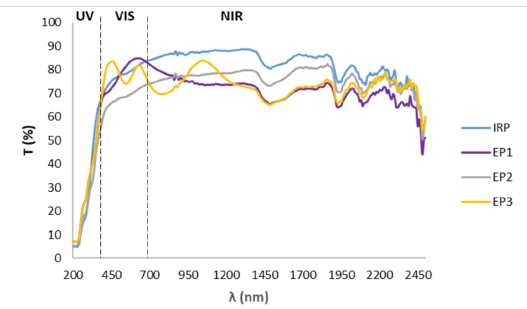


» **Figure 3:** *Reflectance spectra of various coatings in the UV-VIS-NIR regions*

As noted in Figure 3, all coatings show moderate reflectance in the UV region (200-400 nm). Coatings based on EP pigments (EP1-EP3) exhibit higher UV reflectance, especially EP2, which peaks above 54% at 420 nm. Coating based on IRP shows the lowest reflectance in the entire solar spectrum. In the visible region (400-700 nm), reflectance increased compared to lower wavelengths, with the coating based on EP2 reaching the highest reflectance values at the transition from the UV to the visible spectrum. Coating based on IRP has significantly lower reflectance across the VIS region (30-40%), in the NIR region (700-2500 nm) reflectance continuously decreases with increasing wavelength. Unlike "cool" pigments designed for high NIR reflectivity to reduce urban heat (which can reach over 95% reflectance), IR-absorbing pigments are characterized by low reflection in their target IR range (Kuzman et al., 2025).

Coatings slightly increase with the peak at 880 nm, reaching R = 45% for EP1 and with the peak at 860 nm, reaching R = 47% for EP3. In the deeper NIR region (>1900 nm), reflectance for IRP drops below approximately 15%. IRP pigment reflects the sunlight's invisible heat radiation while allowing the majority of the visible light to pass through. It offers more light, less heat and higher UV absorption, allows diffusion of visible light while reducing UV and NIR transmission and exhibits properties similar to sun-protective filters on all transparent substrates (Susonity, 2025).

Figure 4 presents the transmittance (T, %) of different coatings across the entire solar spectrum.



» **Figure 3:** *Transmittance spectra of various coatings in the UV-VIS-NIR regions*

Transmittance refers to how much light passes through a material compared to the amount of light that initially hits it. A material with high transmittance (close to 100%) lets most light through (like clear glass), while low transmittance means the material blocks or absorbs most light (like tinted glass or opaque objects) (Paschotta, 2019). All coatings exhibit very low transmittance below 260 nm (<20%) and rises sharply toward the VIS region for all coatings. Among all, the coating based on EP2 achieved the lowest transmittance in the visible region. The coating based on IRP shows the highest transmittance over most of the NIR (≈85-90% between ≈900-1800 nm) with several narrow features and modest depressions. In contrast, coatings based on EP1-EP3 show systematically lower T (≈70-85%), indicating reduced light transmission. A pronounced drop in T for all samples near ≈2400-2500 nm was observed.

Conclusions

The present study successfully evaluated the spectral absorbance, reflectance, and transmittance of coatings formulated with various functional pigments and cellulose nanocrystals (CNC) as a binder across the UV-VIS-NIR range (200 nm to 2500 nm), achieving the primary objective of the work. This research aimed to advance solutions for thermal control without deteriorating the optical properties of the coatings by combining functional pigments with a bio-based binder.

Four different pigments were used, with three being pearlescent pigments (EP1, EP2, EP3) and one being an infrared-absorbing pigment (IRP). Scanning Electron Microscope (SEM) analysis showed that the IRP pigment particles formed clusters with mainly rounded or polyhedral shapes. In contrast, the pearlescent pigments (EP1, EP2, EP3) displayed a characteristic "corn flake" morphology, appearing as thin, irregular flakes with sharp edges.

The optical property analysis showed significant differences based on pigment type. The coating containing the infrared-absorbing pigment (IRP) exibited the highest overall absorbance, which increased steadily across the Near-Infrared (NIR) region (700-2500 nm), peaking at 2100 nm. In contrast, the coatings with the pearlescent pigments (EP1-EP3) showe lower absorbance, remaining relatively constant across the spectrum. The IRP coating had the lowest reflectance across the entire solar spectrum, with its reflectance continuously decreasing in the NIR region. In contrast, the EP pigment coatings exhibited the highest reflectance in the visible (VIS) region.

Regarding transmittance, the IRP coating exhibited the highest values over most of the NIR range (approximately 85-90% between 900 and 1800 nm), indicating significant light transmission. This is consistent with the IRP pigment's property of allowing most visible light to pass through while absorbing invisible heat radiation. In contrast, coatings based on EP1-EP3 showed consistently lower transmittance in this range.

Overall, the combination of specific pigments and CNC as a binder offers a promising, sustainable pathway for developing functional coatings that provide effective thermal control and exhibit properties similar to sun-protective filters on transparent substrates.

Funding

The authors would like to acknowledge the financial support of Horizon Europe projects UPSTREAM (GA 101112877) and REMEDIES (GA 101093964).

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