Supplementary Information (SI) for Environmental Science: Nano.

Supplementary Information

Lignin-Derived Carbon Dots from Leaf Waste as Sustainable Plant Sunscreens and UV-Protective Foliar Coatings

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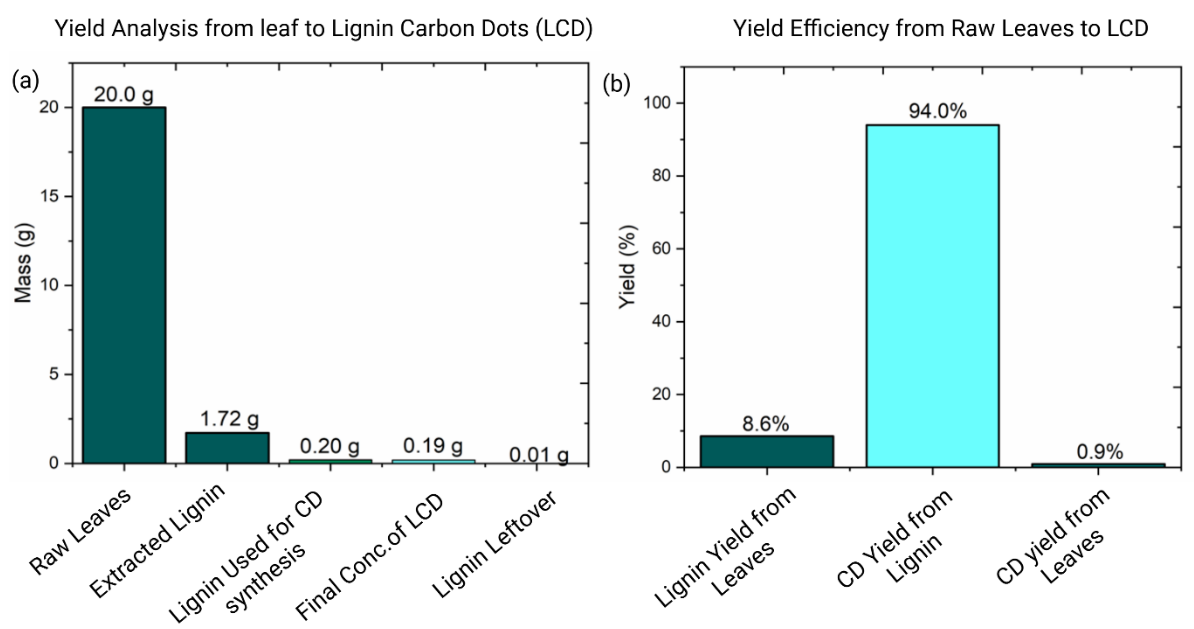

Figure S1. Yield analysis of lignin extraction and lignin carbon dot (LCD) synthesis from Norway maple (*Acer platanoides*) leaf biomass. (Left) Mass balance showing the progression from 20 g of dried raw leaves to 1.72 g of extracted lignin (8.6%), followed by 200 mg of lignin used for hydrothermal synthesis, yielding 190 mg of purified LCDs and 10 mg of residual lignin. (Right) Yield efficiencies expressed as percentages: lignin yield from leaves (8.6%), conversion of lignin to LCDs (94.0%), and overall LCD yield from raw leaf biomass (0.9%).

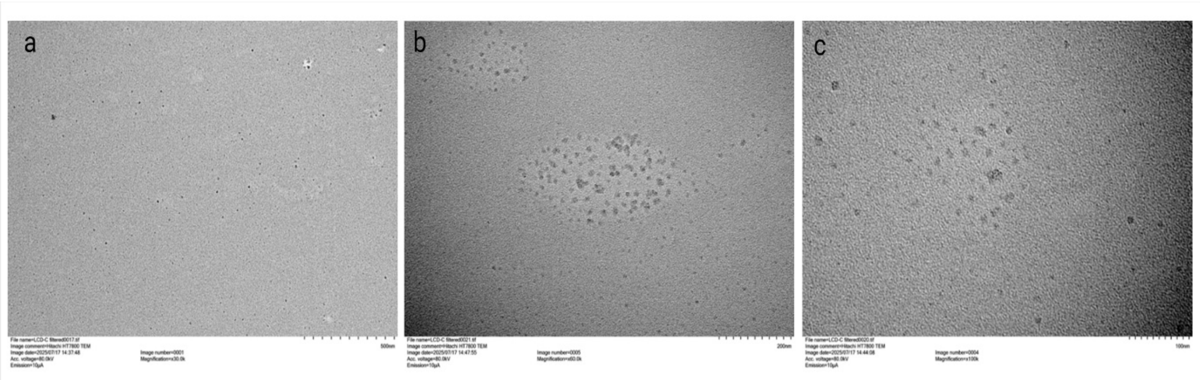

Figure S2. **Additional TEM micrographs of lignin-derived carbon dots at multiple magnifications.** Representative TEM images (a–c) provide higher-clarity views of particle dispersion and morphology across different fields of view. These images support the particle size statistics reported in Figure 1e and 1f in the main manuscript. Scale bars are shown in each panel a) 500nm b) 200nm and c) 100nm.

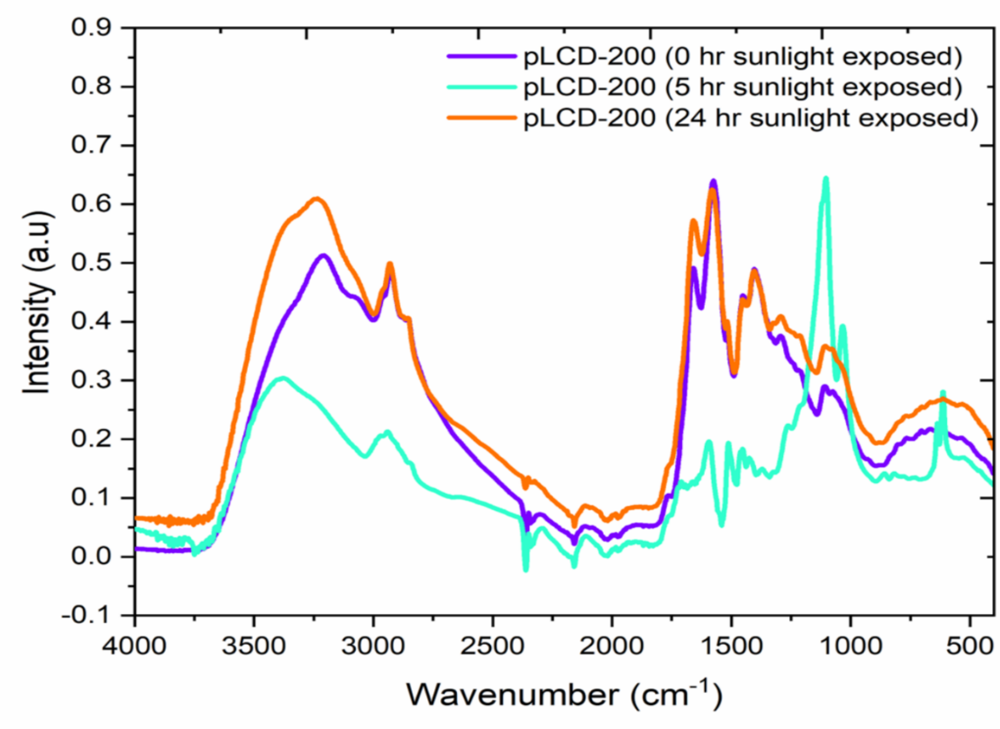

Figure S3. FITR spectra of pLCD-200 recorded at 0 hr, 5 hr, and 24 hr of natural sunlight exposure. The spectral evolution highlights changes in surface functional groups with increasing irradiation time, indicating partial photochemical modification of the partially carbonized LCDs.

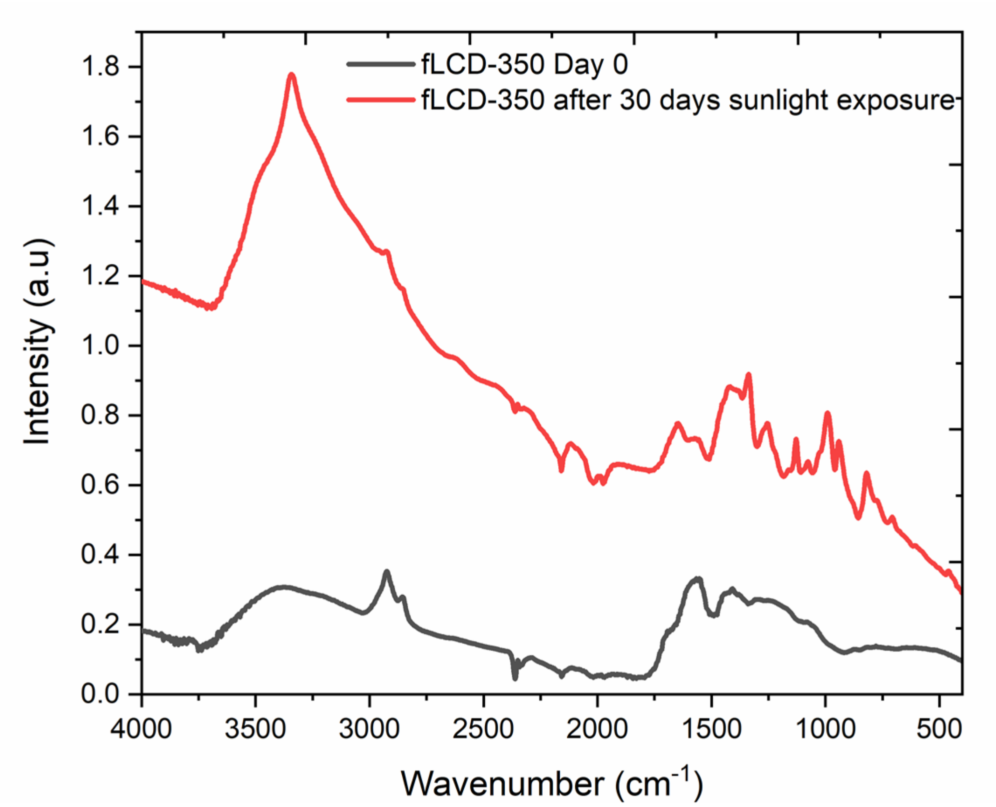

Figure S4. FTIR of fLCD-350 recorded at day 0 and after 30 days of natural sunlight exposure. The two spectra show that the major vibrational bands are retained after prolonged exposure, indicating chemical stability of the material on aging.

3.6 Photokinetic Stability of fLCD-350 versus pLCD-200 under Sunlight

Table S1. Key parameters (from 420–450 nm for pLCD and 710–730 nm for fLCD)

Parameter	**Value**
k (pLCD decay, h^{-1})	~0.010
Half-life pLCD	~69 h (≈3 days)
k_g (fLCD growth, h^{-1})	~0.002
Doubling time fLCD	~350 h (≈15 days)
R^2 pLCD fit	good
R^2 fLCD fit	moderate

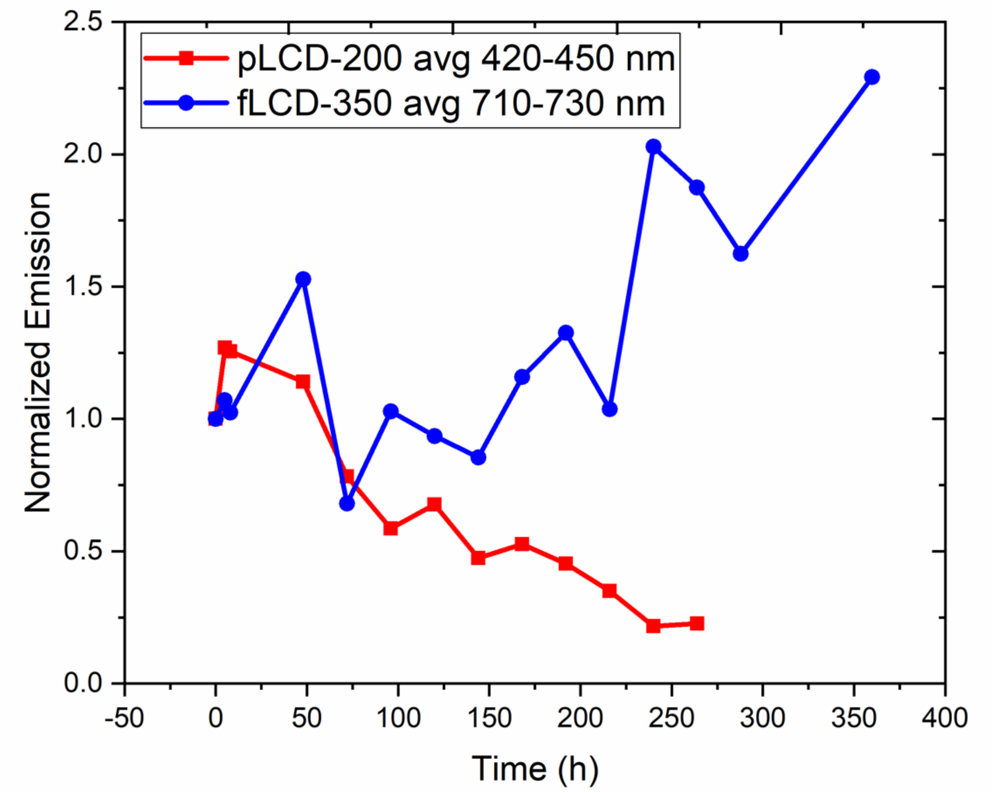

Figure S5. Normalized emission data of LCDs during extended sunlight exposure. Red squares represent pLCD 200 averaged over the 420–450 nm absorption band and blue circles represent fLCD-350 averaged over the 710–730 nm near infrared emission band. pLCD-200 showed a steady first order decay, dropping to less than half of its initial absorbance within about 70 hours and approaching 20% by 250 hours. In contrast, fLCD-350 displayed gradual photo-brightening, with its normalized emission rising almost twofold over the 15-day period. This contrasting kinetic behavior reflects the oxygen rich surface of pLCD-200, which is prone to ultraviolet driven oxidation and quenching, versus the highly graphitized, low oxygen surface of fLCD-350 that resists photodegradation and develops additional light absorbing states under prolonged sunlight.

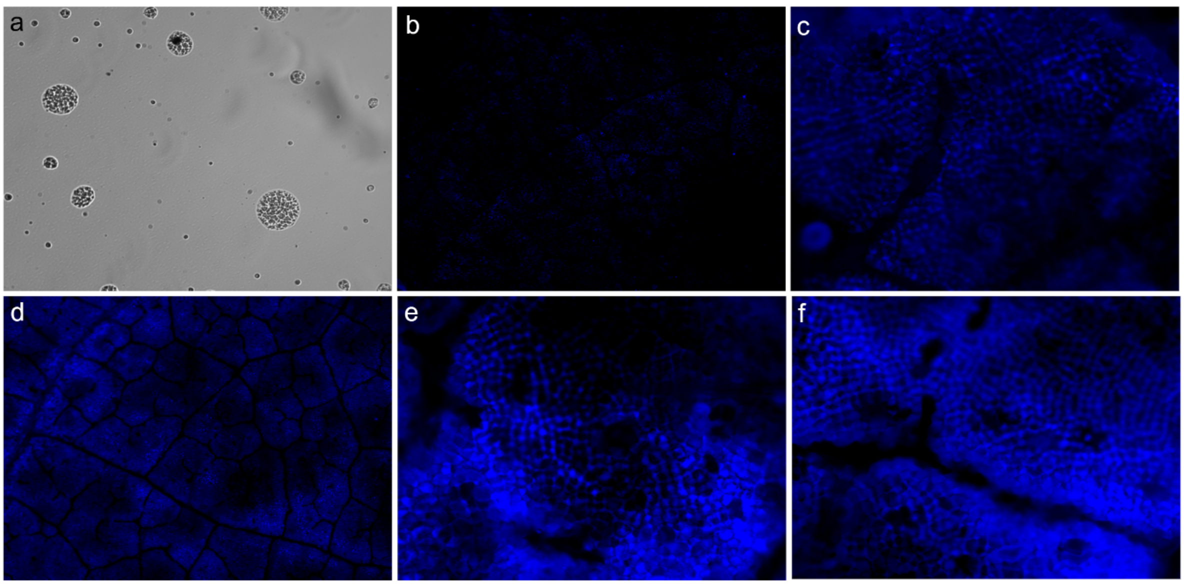

Figure S6. Fluorescence microscopy images showing sodium-alginate–combined fLCD-350 sprayed on soybean leaves and exposed to natural sunlight. (a) Bright-field image of film-forming droplets on a hydrophobic polystyrene Petri dish, captured with a Carl Zeiss Discovery V1 system using ZEN 2.6 software. (b,c) Control leaves imaged at 2.5× and 20× magnification, respectively. (d,e) Sprayed leaves at day 0 imaged at 2.5× and 20× magnification. (f) Sprayed leaves at day 10 imaged at 20× magnification.

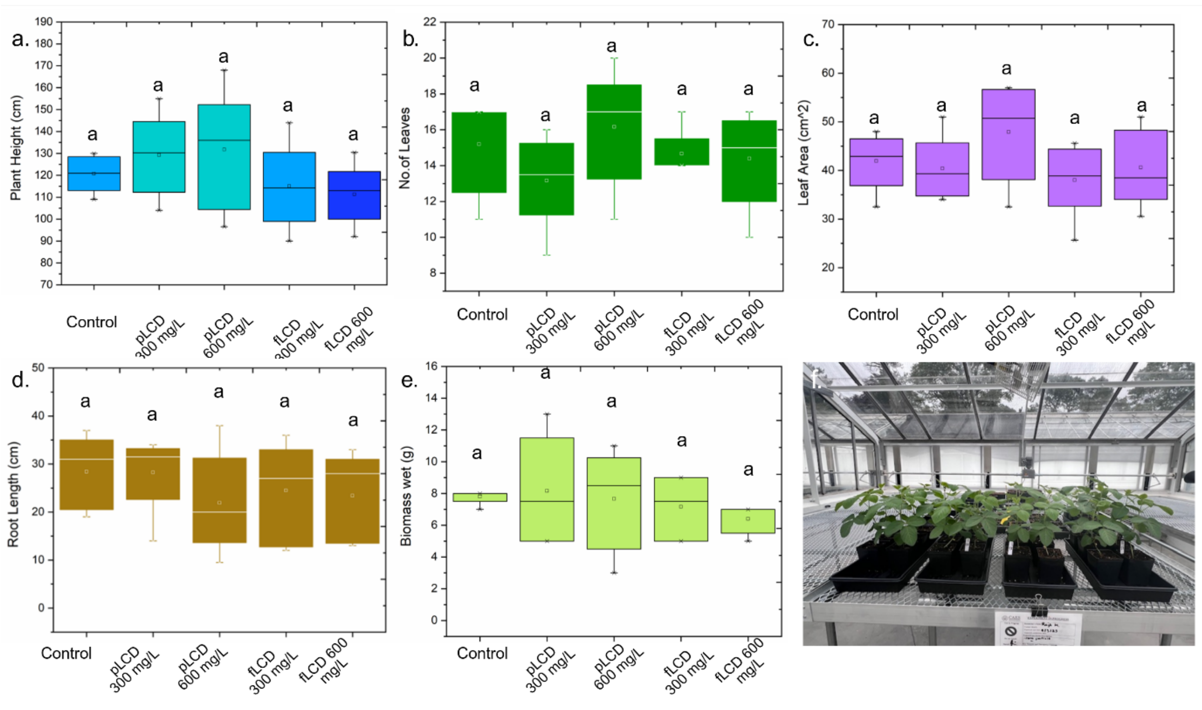

Figure S7. Growth responses of soybean plants treated with pLCD and fLCD. Soybean plants were foliarly sprayed with partially carbonized lignin carbon dots (pLCD) or fully carbonized lignin carbon dots (fLCD) at 300 or 600 mg/L and compared with untreated controls. Boxplots show (a) plant height, (b) number of leaves, (c) leaf area, (d) root length, and (e) wet biomass. Different letters above boxes indicate significant differences among treatments ($p < 0.05$, one way ANOVA followed by Tukey test). Treatments: 1 = Control untreated, 2 = pLCD 300 mg/L, 3 = pLCD 600 mg/L, 4 = fLCD 300 mg/L, and 5 = fLCD 600 mg/L. **Figure S7 f.** Soybean plants grown under natural sunlight in a glasshouse following foliar application of lignin carbon dot (LCD) treatments.