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CDs microcapsules polyurethane film with improved light environment, self-healing and high strength for plant greenhouses to promote plant growth

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ABSTRACT

Carbon dots (CDs) have photoconversion performance and have a wide range of applications in agriculture. However, the solution of CDs is susceptible to quench under evaporation of sunlight and is easy to run-off when influenced by the external environment. Here, PVA-coated CDs were used to overcome the solid-state quenching and to prepare CDs microcapsules-polyurethane Film for plant cultivation. In this work, CDs microcapsules which can convert ultraviolet light into blue light for plant growth, were prepared by the “water/oil/water” method, and light-converting CDs microcapsules polyurethane film (CMPF) was prepared by doping CDs microcapsules with polyurethane. The study showed that polyurethane film has good mechanical properties and self-healing ability, the CMPF was able to effectively promote the growth of lettuce, and the effect was most significant at the CDs microcapsules concentration of 4000 mg/L. Compared with the blank group, the fresh and dry weights were increased by 177 % and 143.5 %, respectively, and the content of chlorophyll *a*, chlorophyll *b*, carotenoids, and soluble protein were increased by 14.5 %, 188.5 %, 43.3 %, and 17.9 %, respectively. Application of CDs to modulate plant lighting growth regulators for efficient use of ultraviolet (UV) light.

1. Introduction

Plant energy is mainly converted from the energy of light, and light signals are used to induce and influence plant growth and development, morphogenesis, secondary metabolism and nutritional quality. (Kang et al., 2020) In the natural environment, blue light from sunlight is one of the main spectral regions utilised by plants for photosynthesis and plays an important role in the morphogenesis and physiological metabolism of the plant. (Briggs, 2002) For example, the blue light region is the main region of the characteristic peak of photosynthetic chlorophyll uptake in plants, which affects the accumulation of carbohydrates in plants, (Wang et al., 2015) but the UV and green light in the solar spectrum is not so essential for plants. (Sai et al., 2018) Therefore, by improving the light environment in which plants grow, it is possible to promote plant photosynthesis. (Ding et al., 2019).

Currently, most of the means of regulation to improve photosynthesis and the light environment required for plant growth are based on artificial light sources. For example, light-emitting diode light sources, (Zhang et al., 2015; Frąszczak and Kula-Maximenko, 2021; hortsci-article-p1293.pdf) high-pressure sodium lamps. (Poel, 2017; Blom and Zheng, 2009) Despite the many advantages of the artificial light production model, there are still many problems to be solved, with running costs such as high electricity consumption being the most significant impediment to development. (Bian et al., 2015; Chen et al., 2020) In recent years, fluorescent CDs have attracted widespread interest in the field of plant lighting due to their biocompatibility, (Liang et al., 2021; Qin et al., 2022) good light conversion, (Zhao et al., 2019; Yang et al., 2019) ability to be absorbed and transported by plants (Li et al., 2021)

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and low price. (Meng et al., 2019) On the one hand, CDs have good optical properties, (Pan et al., 2015) converting UV light from sunlight into visible light that can be effectively absorbed by plants, which can transfer energy to chloroplasts or convert light energy, increasing the rate of photosynthetic electron transfer and thus speeding up the conversion of light energy to active chemical energy in photosynthesis and regulating plant growth and metabolism. (Zhang et al., 2018) On the other hand, without the use of artificial resources, light conversion can enhance the use of natural light from the sun, which has the advantage of being green and sustainable development. (Li et al., 2018) Gong et al. (Gong and Zhao, 2018) found that CDs, when excited by sunlight, can convert ultraviolet light into blue light, which is more needed by plants, and thus promote photosynthesis in chloroplasts. Li (Li et al., 2021) found that blue CDs promoted photosynthesis in rice plants and plant growth increased significantly. However, there are two problems with the use of CDs as a light conversion material to improve the light environment for growing crops: CDs solution will become solid after evaporation and drying, and there is a quenching phenomenon in the solid-state photoluminescence of CDs, (Zhou et al., 2017) which seriously affects their solid-state photoluminescence quantum yield. In addition, CDs are susceptible to weather effects such as rain and dew due to their lack of viscosity, and they pass away.

In order to solve the above problems, solid CDs are mainly prepared in the form of microcapsules coating or luminescent films. (Qu et al., 2015) Microcapsules, as a new type of encapsulation material with the advantages of good biocompatibility, targeting and slow release, are now widely used in agriculture, capable of encapsulating a large number of CDs. (Ulbrich et al., 2016; Salunkhe et al., 2013) The use of PVA-coated CDs for the preparation of microcapsules not only prevents the solid-state fluorescence quenching of CDs and achieves solid-state luminescence. (Feng et al., 2017) And because the surface of PVA has a large number of hydroxyl groups, it can be more easy to combine with the foliage, and can improve the combination with the foliage, will be sprayed on the foliage of the plant, can improve the light environment of the plant, and promote the growth of the plant. (Mngadi et al., 2021) At the same time PVA is very biodegradable and does not affect the environment. Further consideration of the application to the cultivation of edible vegetables requires consideration of food safety issues. Although the low toxicity of CDs has been reported in many cases, spraying CDs microcapsules directly on vegetables still has food safety issues.

Therefore, it would be a better solution to prepare CMPF with light conversion effect by dispersing microcapsules within polyurethane for vegetable cultivation as a greenhouse film to improve the light environment. Polyurethane is a new type of functional material with self-healing function, which can automatically repair the damaged area and restore its elasticity. (Yang et al., 2020; Behera et al., 2021) In the field of polyurethane research, the typical thermally reversible Diels-Alder (D-A) reaction is the preferred choice for the construction of thermally induced dynamic crosslinked networks with good thermal reversibility, minimal side reactions, mild reaction conditions and high yields. (Dong et al., 2022) Integration of a dual dynamic network of dynamic and non-covalent bonds into polymers for high healing efficiency and improved mechanical properties. (Guo et al., 2021; Kim et al., 2023) Traditional greenhouse film in the process of use, easy to scratch, breakage and other problems, the use of light conversion, can be self-healing, high mechanical strength of polyurethane preparation of greenhouse film, can not only be able to promote the growth of vegetables, but also to extend the service life of the greenhouse film.

In this work, PVA-coated blue fluorescent CDs were used to obtain CDs microcapsules with fluorescence in the solid state, which can emit strong blue fluorescence under the excitation of 365 nm UV light, and the CDs microcapsules have good slow release and adhesion properties, it can be a good foliar fertiliser for ornamental green plants. The prepared CDs microcapsules were compounded on polyurethane to prepare a self-healing, high-strength and light-convertible CMPF. Applying CMPF to greenhouse film for growing lettuce not only extends the service life of the greenhouse film, but also effectively promotes lettuce growth. The effect of CDs microcapsules films prepared with different concentrations of CDs microcapsules on the growth of lettuce was investigated. The results showed that the effect was most significant at the content of 4000 mg/L. CDs were applied to regulate the plant lighting growth regulator to achieve the effective use of UV light for the purpose of sustainable development. Applying CDs to regulate the light environment for plant growth, increasing the utilization of UV light for sustainable development purposes.

2. Results and discussion

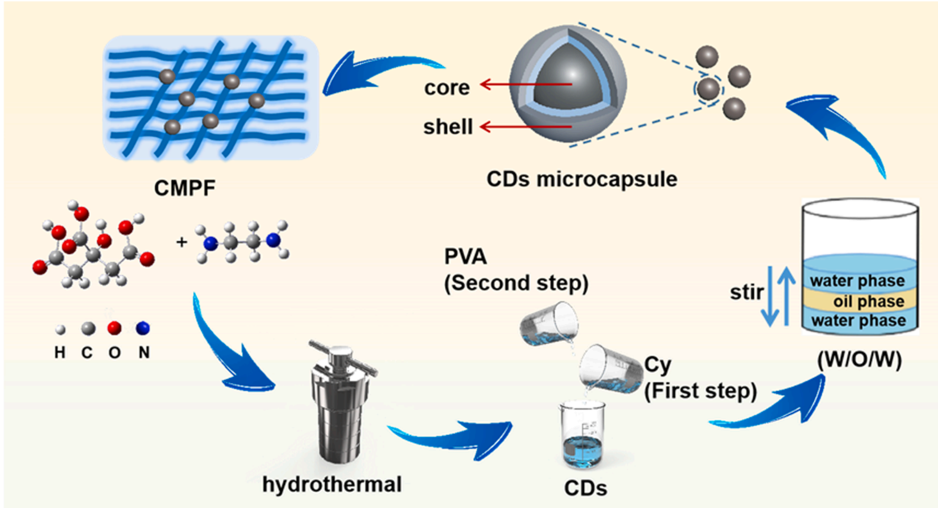
The blue fluorescent CDs were prepared by one-step hydrothermal method using citric acid and ethylenediamine as raw materials, and the CDs microcapsules were prepared by “water/oil/water” method, and finally the CDs microcapsules were compounded on polyurethane to prepare the CMPF with light conversion performance, high mechanical strength and self-repairing, and the process is shown in Scheme 1.

2.1. Morphology and chemical composition of CDs and CDs microcapsules

Firstly, the morphology and chemical composition of the CDs and CDs microcapsules were investigated. Fig. 1a shows a high angle annular dark field scanning transmission electron microscope image of CDs, which shows good dispersion of CDs, and the inset of Fig. 1a shows the particle size distribution of the CDs, which are mostly concentrated at 5 nm. Transmission electron micrographs of the CDs show them to be spherical (Fig. 1b). The inset of Fig. 1b shows a high-resolution transmission electron micrograph of the CDs, and the lattice spacing of the CDs was calculated to be 0.23 nm, corresponding to the (1 0 0) crystal plane of the graphene carbon atoms. (Jeong et al., 2023) Fig. 1c shows an SEM image of a CDs microcapsule showing a core–shell structure with a much larger particle size compared to CDs, which according to the inset of Fig. 1c is about 90 um. Fig. 1d shows photoelectron diffractograms (XRD) of CDs and CDs microcapsules, both with diffraction peaks appearing at 18°, corresponding to the (1 0 0) crystallographic plane of the graphene carbon atom, (Xie et al., 2018) indicating that the non-qualitative structure of the CDs was not altered by encapsulation with PVA. The surface chemistry of CDs and CDs microcapsules was explored using FT-IR spectroscopy, as shown in Fig. 1e, both CDs and CDs microcapsules have absorption peaks at 3430 cm^{-1}, 2890 cm^{-1}, 1705 cm^{-1} and 1610 cm^{-1} corresponding to the functional groups C-OH, (Dai et al., 2022) C–H, (Li et al., 2022) C = O (Guo et al., 2022) and C = C (Zhang et al., 2019) respectively. The CDs showed an asymmetric stretching vibrational absorption peak of C-NH-C at 1080 cm^{-1}; (Xu et al., 2022; Wang et al., 2021) while no vibrational absorption peak of C-NH-C was detected in the CDs microcapsules. The surface elemental and functional group composition of the CDs and CDs microcapsules were further analysed by X-ray photoelectron spectroscopy (XPS) and the XPS spectra showed (Fig. 1f) that the CDs had a distinct O signal at 531 eV, an N signal at 400 eV and a C signal at 284 eV. (Zhu et al., 2021) In contrast, the CDs microcapsules only show an O signal at 531 eV and a C signal at 284 eV. Fig. S1a-c show the high resolution energy spectra of the CDs and Fig. S2a-b show the high resolution energy spectra of the CDs microcapsules. (Park et al., 2021) the XPS and FT-IR results are consistent due to the fact that the CDs are heavily diluted after preparation into CDs microcapsules, resulting in almost no detection of the N element, and the inability of the FT-IR and XPS to detect the internal elements as the CDs are encapsulated by PVA. In summary, it was demonstrated that the PVA did not react chemically with the CDs and effectively encapsulated them internally and was not an ordinary physical blending.

2.2. Slow release behaviour and adhesion properties of CDs microcapsules

Electron leap in the UV is the reason why CDs can fluoresce. (Liang



Scheme 1. Schematic of CDs microcapsules polyurethane film preparation.

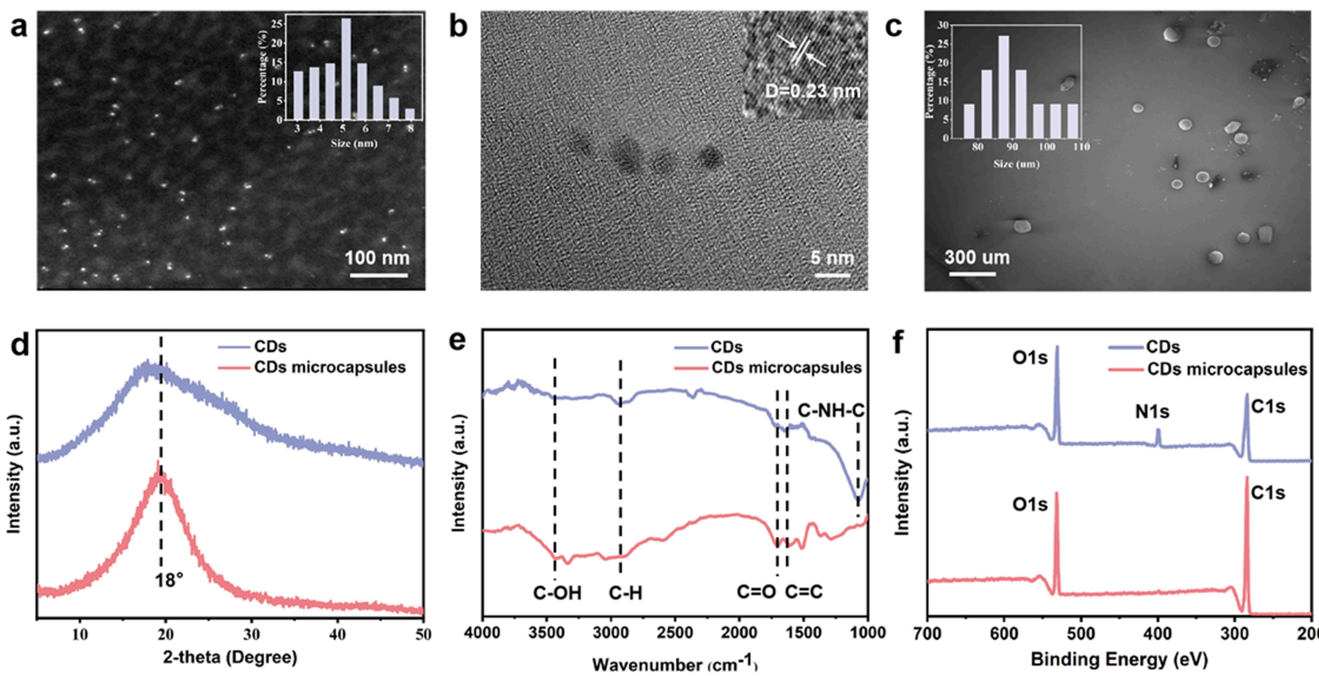


Fig. 1. (a) HAADF-STEM of CDs [the illustration is shown the particle size of CDs]; (b) TEM image of CDs [the illustration is shown the HRTEM of CDs]; (c) SEM of CDs microcapsule [the illustration is shown the particle size of CDs microcapsules]; (d) XRD spectra of CDs and CDs microcapsules; (e) FT-IR spectrum of CDs and CDs microcapsules; (f) XPS spectrum of CDs and CDs microcapsules.

et al., 2022) The UV spectrophotometer was used to probe the electron leap of CDs. Fig. S3a shows the UV absorption spectra of CDs. The UV absorption peak of CDs is located around 350 nm and corresponds to the $n \rightarrow \pi^*$ electron jump of the oxygen-containing functional group. (Feng et al., 2017) Fig. S3b shows the fluorescence spectra of the CDs solution under the excitation of different wavelengths, and its emission peak is located at 460 nm, which indicates that the CDs can absorb light from 360 to 430 nm wavelengths, and it can convert UV light into blue light with good light conversion effect. Fig. 2a shows the fluorescence spectra of CDs and CDs microcapsules under wavelength excitation at 365 nm, both of which show very similar fluorescence emission behaviour, with their emission peaks located at 460 nm. The inset of Fig. 2a shows that the CDs solution and the CDs microcapsules can emit similar intense blue light under UV irradiation, suggesting that the fluorescence emission centre of the CDs microcapsules originates from the CDs. In order to further prove that the fluorescence of the CDs microcapsules comes from the CDs, the fluorescence lifetimes of the two microcapsules were tested. Fig. 2b shows the fluorescence decay curves of the CDs with a fluorescence lifetime of 0.46 ns, and Fig. 2d shows the fluorescence decay curves of the CDs microcapsules with a fluorescence lifetime of 0.10 ns. The fluorescence decay curves of the two microcapsules are similar, and both of them show the double-exponential function, which proves that the fluorescence of the two microcapsules is from the same. The two fluorescence decay curves are similar and both show double exponential function, which proves that the fluorescence of them come from the same luminous centre. The quantum yield of CDs is 14.7 %. The fluorescence intensity of CDs was explored at different concentrations, and as shown in Fig. S3d, the fluorescence intensity reached its strongest at a concentration of 0.05 mg/mL. However, since the CDs solution concentration will be diluted by other reagents during the preparation of

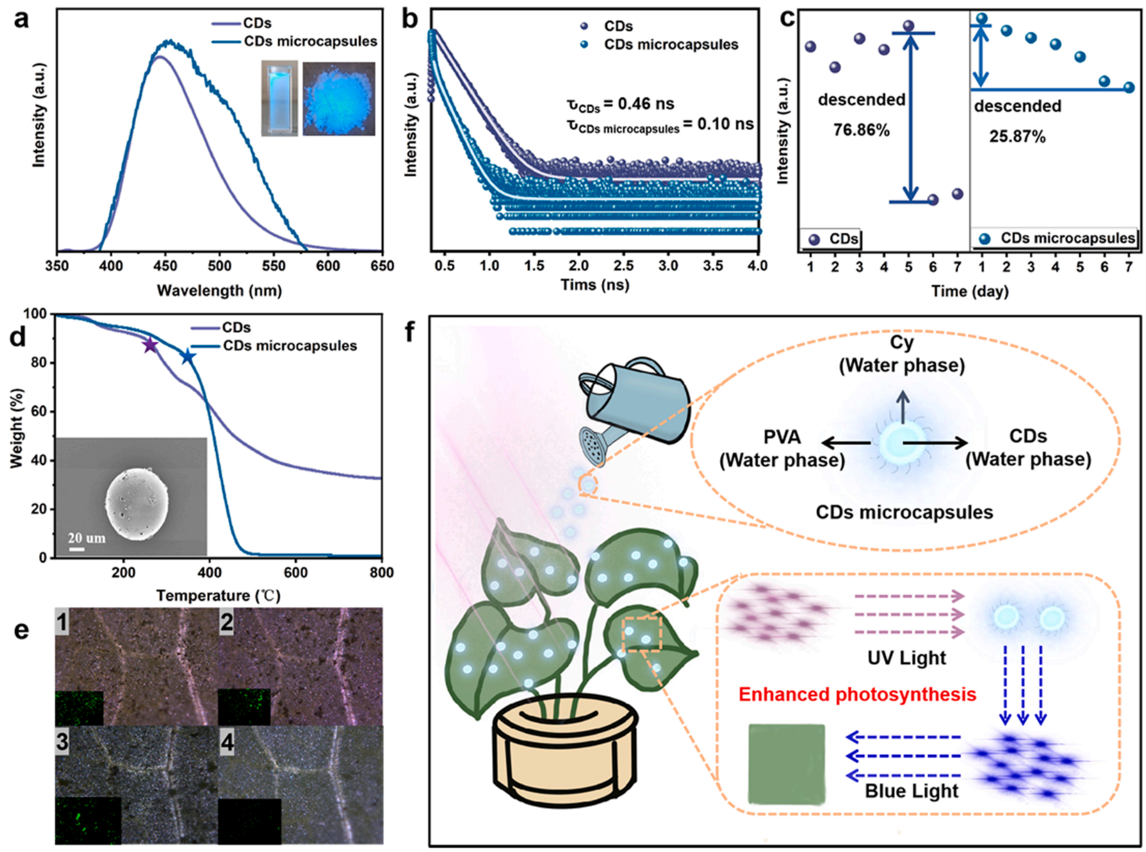


Fig. 2. (a) The PL of CDs and CDs microcapsules at the excitation wavelength of 365 nm [the illustration is CDs and CDs microcapsules under UV light]; (b) The fluorescence decay curve of CDs and CDs microcapsules; (c) Fluorescence intensity of CDs and CDs microcapsule over time; (d) TG of CDs and CDs microcapsules [the illustration is shown the SEM of CDs microcapsules]; (e) Leaf surface under microscope: (1) Sprayed with CDs microcapsules; (2) The first simulated rain wash; (3) The second simulated rain wash; (4) The third simulated rain wash.

CDs microcapsules, the optimal fluorescence intensity for the preparation of CDs microcapsules corresponds to CDs concentration of 0.5 mg/mL (Fig. S3e). The above results demonstrated that the CDs microcapsules can overcome the fluorescence quenching and have good light conversion performance in the solid state, which is the basis for their application in the regulation of plant light environment.

CDs microcapsules can be used on plant foliage as light-converting materials to promote plant growth, and must also have good slow-release and adhesion properties, so the slow-release and adhesion properties of CDs microcapsules were verified. Fig. 2c shows the fluorescence intensity changes of CDs and CDs microcapsules over 7 days. The fluorescence intensity of CDs fluctuates slightly in the first five days, but due to the fluorescence quenching and photobleaching properties of CDs, its fluorescence intensity decreases greatly on the sixth day, and its fluorescence intensity decreases by 76.86 % compared with that on the fifth day. The PVA-coated CDs microcapsules could not only overcome the solid-state fluorescence quenching of CDs, but also had a good slow-release effect, and the fluorescence intensity on the seventh day decreased by only 25.87 % compared with the first day, and still showed fluorescence performance even after 15 days, which was conducive to long-term photoconversion and proved that the CDs microcapsules had a good slow-release performance. The slow-release performance of CDs microcapsules is closely related to their surface pores. The inset of Fig. 2d shows the SEM image of a single CDs microcapsule, from which it can be seen that the surface of the CDs microcapsule has a lot of pores with different sizes, and these pores provide excellent conditions for the slow release of CDs. Fig. 2d shows the thermal weight loss analysis of CDs and CDs microcapsules. CDs started to degrade substantially at 250 °C, whereas the temperature reached 400 °C before substantial degradation after using PVA-coated CDs, which indicates the enhanced thermal stability of CDs microcapsules. All these results indicate that the CDs microcapsules have good slow release properties.

To verify the adhesion of CDs microcapsules, CDs and CDs microcapsules were sprayed on plant foliage after simulating rainwater rinsing, and they were placed under a microscope for observation. Fig. 2e shows pictures of foliage after spraying CDs microcapsules under microscope, and its inset shows pictures of the same area under UV irradiation using a microscope (1, 2, 3, and 4 are freshly sprayed with carbon spot microcapsules, simulated rain wash for the first time, simulated rain wash for the second time, and simulated rain wash for the third time, respectively). When the CDs microcapsules were sprayed onto the leaves, a large number of CDs microcapsules were evenly dispersed and adhered to the leaf surface. After the first simulated rain washing, there were still a large number of CDs microcapsules adhering to the leaf surface; when simulated rain washing for the second time, some CDs microcapsules could still be seen adhering to the leaf surface; and when simulated rain washing was performed for the third time, there were almost no CDs microcapsules left on the leaf surface. Fig. S4a shows the picture of the leaf surface after spraying CDs under the microscope, when CDs were just sprayed onto the leaf surface, the stems along the leaf surface showed the phenomenon of agglomeration, and the CDs could be washed off after only simulating the rainwater rinsing once, which indicated that the adhesion of the CDs were greatly enhanced after the CDs were prepared into CDs microcapsules, which was attributed to the presence of a large number of –OH on the surface of PVA, (Aslam et al., 2018) which could enhance the surface bonding of the CDs microcapsules in the leaf surface of the plant.

Previously, the low toxicity of CDs has been reported in several literatures, and we verified its biocompatibility. CDs microcapsules were configured into solutions of different concentrations, and oocysts were selected as experimental objects to observe the survival quantity of oocysts under different concentrations of CDs microcapsules solutions. At high concentrations, the survival rate of oocysts was still greater than 80 % (Fig. S5), indicating low toxicity of CDs microcapsules.

Combined with the above data and analyses, the CDs microcapsules have good slow-release properties and adhesion, and have the potential to promote plant growth. Fig. 2f shows the schematic diagram of CDs microcapsules for promoting plant growth, spraying CDs microcapsules on the plant leaf surface, due to the good adhesion of CDs microcapsules, it can be well adhered to the plant leaf surface, the CDs microcapsules absorb UV rays from sunlight and convert them into blue fluorescence, improving the light environment of the plant growth, and achieving the purpose of promoting the growth of plants.

2.3. Preparation and characterization of CDs microcapsules polyurethane film

Polyurethanes prepared by integrating physical cross-linking due to high-density hydrogen bonding in isophthalic dihydrate and dynamic covalent cross-linking by D-A bonding into the same polymer structure. And the synergistic enhancement effect produced by the introduced dual-cross-linking network made the macromolecule a self-healing and tough copolymerised polyurethane, and finally CMPF was prepared using polyurethane-coated CDs microcapsules.

Fourier Infrared spectroscopy as well as Raman tests were first carried out to prove the successful preparation of the polyurethane. Fig. 3a shows the infrared spectra, the stretching vibration peak of –NH- at 3323 cm^{-1} and the out-of-plane bending vibration peak at 1543 cm^{-1}, and the stretching vibration peak of –CN- at 1333 cm^{-1}, and the stretching vibration peak of –CN- at 1660 cm^{-1} attributed to the stretching vibration peak of C = O in the urethane ester, which is attributed to the influence of amino group and the formation of hydrogen bond between hydroxyl and carbonyl, which increases the polarization strength of the chemical bond, and shifts the original absorption band of C = O group to the low frequency region. O group shifted to the low-frequency region due to the influence of the amino group and the formation of hydrogen bond between the hydroxyl group and the carbonyl group, which increased the polarization strength of the chemical bond and shifted the original absorption band of the C = O group to the low-frequency region, which indicated that the –NCO group in the raw material, isophorone diisocyanate (IPDI), had reacted with –OH completely to form the urethane group (–NH(CO)O-). In addition, the stretching vibration peaks of –NH- all appeared near 3323 cm^{-1} instead of 3440 cm^{-1}, indicating that the –NH- groups are almost always conjugated with the carbonyl groups in the polymer to form hydrogen bonds, forming the microcrystalline regions of the hard segments. The characteristic peak of -C = C- at 1510 cm^{-1} indicated that the cross-linker 4,4-diphenylmethane bismaleamide (BMI) was successfully introduced into the prepolymer capped by aromatic isophthalic acid dihydrazide/2,5-furandimethanol (ID/BHMF). In addition, there was a small fluctuation in the infrared spectrum at 1760 cm^{-1} after curing of the material and a weak vibration peak of the furan group of the raw material at 775 cm^{-1}, which indicated that the furan ring group was consumed, and the bismaleimide and the linear urethane containing the furan ring generated a D-A bond through a cycloaddition reaction, and the self-repairing urethane with a bis-crosslinked network structure was successfully prepared. To further demonstrate the successful generation of D-A bonds, tests were carried out using Raman spectroscopy, and the characteristic absorption peak of the D-A bond located at 1760 cm^{-1} can be seen in the Raman spectrum in Fig. 3b. The XRD graph of the polyurethane film was tested (Fig. S6) and a clear diffraction peak located at 20° was seen, proving that the material has an amorphous structure.

The mechanical properties of the polyurethane film were tested. The stress–strain curves are shown in Fig. 3d, and there was no yielding,

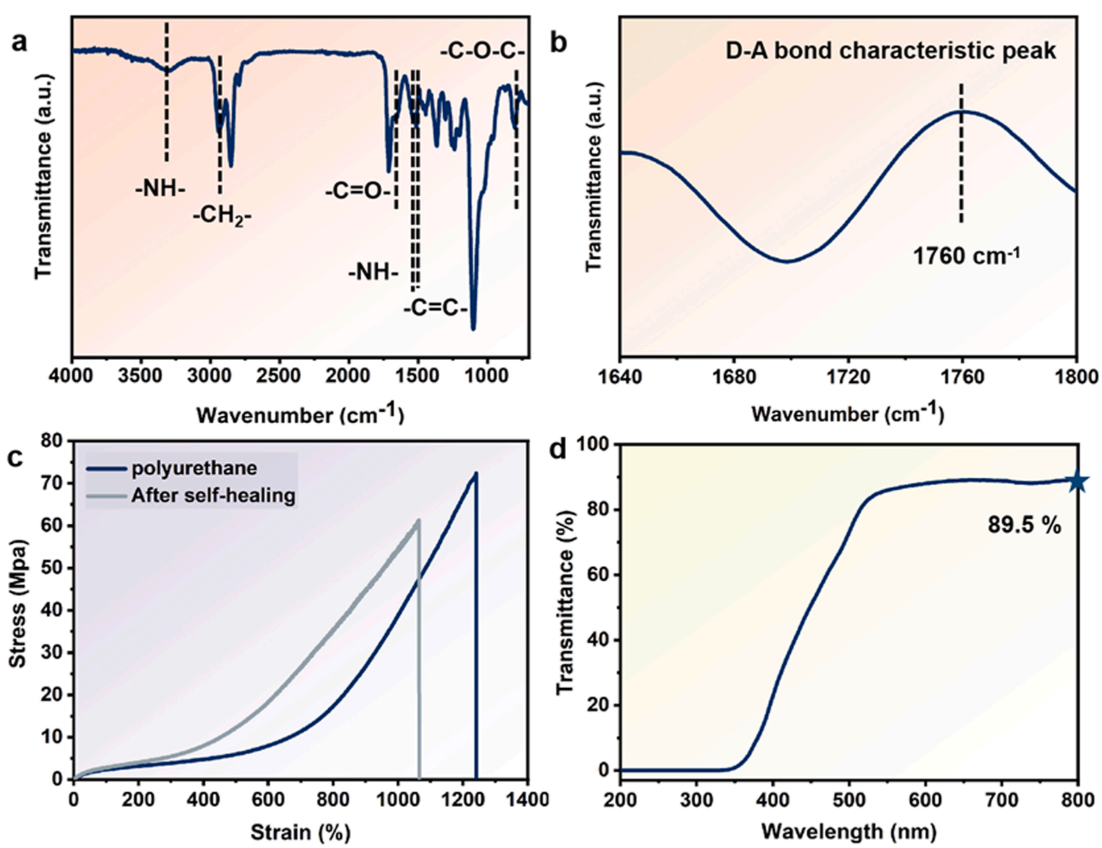


Fig. 3. (a) FT-IR of polyurethane; (b) Raman of polyurethane; (c) Plot of typical stress–strain curves of polyurethane and polyurethane after self-healing; (d) Visible light transmittance of polyurethane.

indicating that the synthesised self-repairing polyurethane material is a typical elastomer. With a tensile strength of up to 72.5 MPa and an elongation at break of 1241.0 %, the final toughness of 235.712 MJ/m^3 was calculated. When deformation occurs during stretching, the hydrogen bond is sacrificed to dissipate energy before the covalent bond (D-A bond) breaks, and the broken –NH- bond also has the opportunity to recombine with other broken –NH- bonds in the neighbouring chain and form a weak temporary hydrogen bond, which increases the intermolecular chain force, and at the same time, the presence of the D-A covalent cross-linking increases the stability of the polymer network, which ensures the intermolecular force, and in addition the effective recombination of the intermolecular hydrogen bonding further improves the material's toughness, which indicates that the material achieves a unity of the mechanical properties and elasticity. Typical stress–strain tests were carried out on the samples after the self-repair treatment (Fig. 3c), and the tensile strength was as high as 60.7 MPa, and the elongation at break was 1064.6 %, which was calculated to be 85 % for the stress repair rate and 86 % for the strain repair rate. These results demonstrate that the polyurethane films continue to exhibit excellent mechanical properties even after self-repair. Finally, the visible light transmittance was tested and showed excellent transparency with a transmittance of 89.5 %. These results show that polyurethane films have great potential for use as greenhouse films for agricultural applications.

2.4. CDs microcapsules polyurethane film for greenhouse film to promote vegetable growth

CMPF can be used as greenhouse film for vegetable cultivation to promote the growth of vegetables, and the mechanism diagram is shown in Fig. 4a. When ultraviolet light is irradiated on the greenhouse film, CDs microencapsulated on polyurethane loaded on the polyurethane will convert the ultraviolet light into blue light, which can promote the growth of plants. The effect of CDs microencapsulated polyurethane films prepared by adding different CDs microcapsules to polyurethane as greenhouse films on lettuce growing was investigated. Four groups of polyurethane films with different contents of CDs microencapsulated polyurethane films (0 mg/L, 2000 mg/L, 4000 mg/L, 6000 mg/L) were used for growing lettuce in greenhouse films, and the post-growth lettuce was collected after 45 days and tested. As shown in Fig. 4b, lettuce grown with CMPF grew more vigorously than the blank group, and the effect was most pronounced for lettuce grown with greenhouse film prepared with CMPF at a concentration of 4000 mg/L. Fresh weights of lettuce from all four groups were weighed, and the lettuce grown with CMPF at a concentration of 4000 mg/L had a 177 % increase in fresh weight compared to that of the blank group (Fig. 4c), and the water content is shown in Fig. S7. The dry weights of four groups of lettuce were tested (Fig. 4d), and the experimental groups were generally heavier than the blank group, and the dry weight of lettuce grown with CMPF at a concentration of 4000 mg/L was 243.5 % of that of the blank group, which indicates that the accumulation of organic matter in lettuce was increased after the use of CDs microcapsules. Photosynthesis is essential for the accumulation of organic matter in plants. (Wang et al., 2017) Therefore, the content of photosynthetic pigments in lettuce was tested. Fig. 4c shows the pigment content of the lettuce with an increase in chlorophyll *a*, chlorophyll *b* and carotenoids. Lettuce with 4000 mg/L CMPF showed a 14.5 % increase in chlorophyll *a*, 188.5 % increase in chlorophyll *b*, and 43.3 % increase in carotenoids compared to the blank group. In the growth of lettuce, the main role of chlorophyll *b* is to absorb blue light. (Li et al., 2018) Blue light has an impact on chlorophyll synthesis, and light can participate in the regulation of chlorophyll synthesis. Microcapsules convert ultraviolet light into blue light, regulate the growth environment of lettuce, and promote the synthesis of chlorophyll. Secondly, the absorption peak of chlorophyll *a* is mainly 430 nm and 660 nm, and the absorption peak of chlorophyll *b* is mainly 456.9 nm and 643.8 nm. (Liu and Iersel, 2021) The fluorescence emission peak of the capsule is located at 460 nm, which is very close to the absorption peak of chlorophyll *b*, which is the reason why the content of chlorophyll *b* is greatly increased. The increase in blue light leads to the production of more chlorophyll *b* in the body of the lettuce, which accelerates photosynthesis and achieves an increase in the accumulation of organic matter.

Finally, four groups of lettuce were tested for soluble protein content (Fig. 4f). The soluble protein of lettuce also increased after the

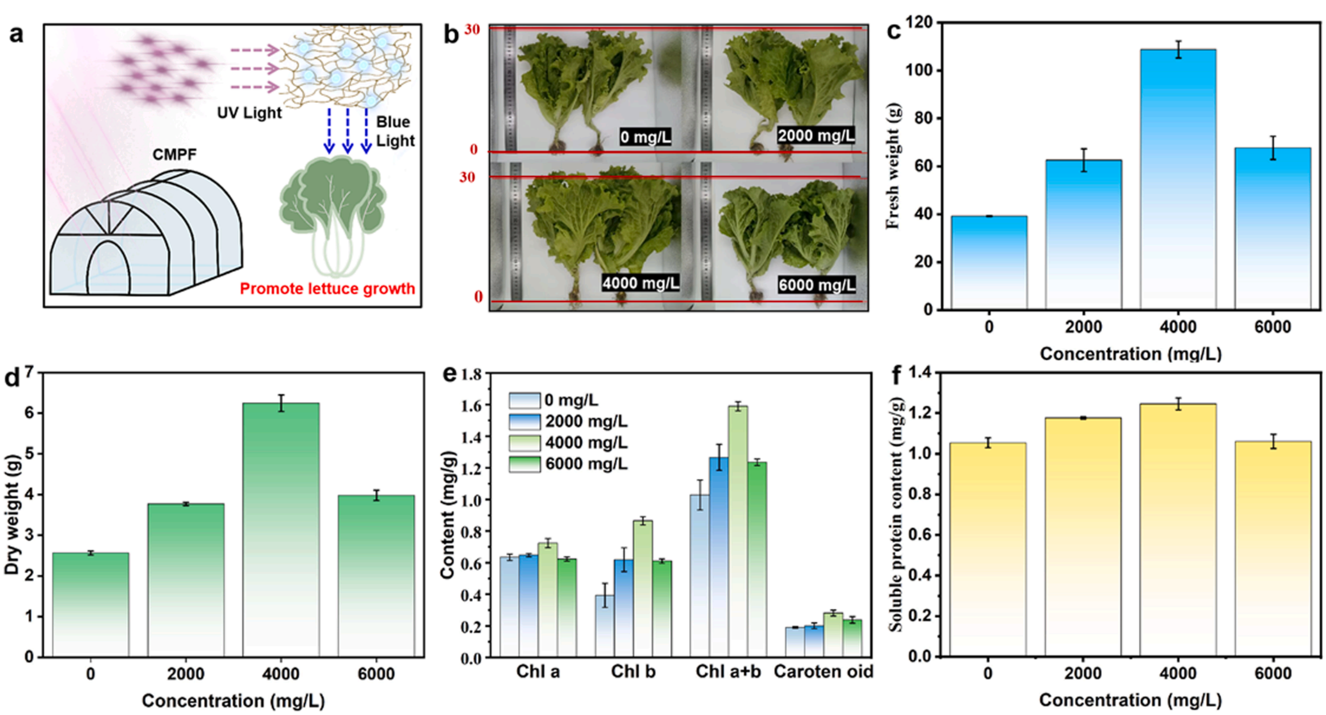


Fig. 4. (a) The diagram of CDs microcapsules polyurethane film as greenhouse film to promote lettuce growth; Effect of CMPF prepared using microcapsules with different levels of CDs on the growth of lettuce: (b) Length and morphology; (c) Fresh weigh; (d) Dry weigh; (e) Pigment Content; (f) Protein content.

application of CMPF, and the soluble protein content of lettuce at 4000 mg/L increased by 17.9 % compared with the blank group. All these results indicated that the CMPF had a significant effect in promoting the growth of lettuce, and the effect was optimal at the concentration of 4000 mg/L.

3. Conclusions

In this work, CDs microcapsules that can overcome the solid-state fluorescence quenching were prepared by using PVA coated with blue fluorescent CDs in a "water/oil/water" manner, and the CDs microcapsules have good slow-release properties, adhesion properties, and have the potential to become foliar fertilizers for green plants. Finally, CDs microcapsules were mixed with self-healing polyurethane to prepare CMPF for greenhouse film for vegetable cultivation, which can improve the light environment for plant growth, promote plant photosynthesis, achieve the purpose of promoting the growth of plants, and improve the utilization rate of sunlight to achieve the effective use of energy. Lettuce grown with a concentration of 4000 mg/L CDs microcapsules had an increase of 177 % and 143.5 % in fresh and dry weights, and 14.5 %, 188.5 %, 43.3 % and 17.9 % in chlorophyll *a*, chlorophyll *b*, carotenoids, and soluble protein contents, respectively, compared with the blank group. At the same time, the film has good mechanical properties and self-repairing properties, which can improve the service life of the greenhouse film and is expected to become a new type of material to improve the light environment of plants.

Author contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.arabjc.2023.105451.

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