A nanocarrier pesticide delivery system with promising benefits in the case of dinotefuran: strikingly enhanced bioactivity and reduced pesticide residue†

Qinhong Jiang,‡a Yonghui Xie,‡b Min Peng, c Zhijiang Wang, b Tianjiao Li, d Meizhen Yin, c Jie Shen* a and Shuo Yan* a

There is a growing demand for reducing pesticide application to minimize their potential threats to food/environmental safety. Herein, a star polymer (SPc) with low production cost was synthesized using two reactions, and it could be applied as an efficient pesticide nanocarrier/adjuvant. SPc could be spontaneously conjugated with dinotefuran through hydrogen bonding and van der Waals forces with a pesticide loading content (PLC) of 17.41%. The complexation of dinotefuran with SPc reduced the dinotefuran size from 269.28 to 29.43 nm and significantly decreased the contact angle of pesticide droplets from 53.4 to 27.9 degrees on plant leaves. The plant uptake of SPc-delivered dinotefuran was increased by 1.45 and 1.53 times those of dinotefuran alone at 6 and 12 h after treatment. As envisioned, in the dose-dependent experiments, the corrected mortality of aphids treated with the dinotefuran/SPc complex was finally increased by 18.4% (100 mg L⁻¹), 15.0% (50 mg L⁻¹) and 10.7% (25 mg L⁻¹) compared to dinotefuran alone. Interestingly, the residue of dinotefuran delivered by SPc was decreased to 1.21, 1.37 and 2.30 times 3, 5 and 7 d after the treatment, respectively. Meanwhile, the dinotefuran/SPc complex showed no negative effects on agronomic traits (fresh weight, plant height, and leaf length and width) of oilseed rape; however it had a slight synergistic effect on non-target lady beetles due to the enhancement of broad-spectrum bioactivity. SPc is a promising pesticide adjuvant to improve the bioactivity of synthetic pesticides and decrease the pesticide residue, showing great potential for green pest management.

Introduction

As the basic technology of modern science, nanotechnology has been successfully applied in many fields such as material preparation, microelectronics, biomedicine, etc.1 In recent years, nanotechnology has also provided strong technical support and innovative ideas for agricultural development.2,3 Nanotechnology can be applied to optimize the physical and chemical properties of pesticides, enhance pesticide delivery and promote sustained pesticide release.4–8 Recently, a series of nanomaterials have been developed as carriers of synthetic/botanical pesticides and fertilizers.9–12 The active
ingredients (AIs) of most traditional pesticides are hydrophobic and can be encapsulated in or attached to the peripheral groups of nanoparticles, increasing the dispersion and affinity of pesticides and expanding the contact area of targets.13–15 Thus, nanocarriers can reduce pesticide application, which is beneficial for reducing environmental pollution and negative effects on human health. Therefore, it is one of the main aspects of plant protection research to explore efficient nanocarriers and use them to improve the effective utilization of pesticides.

Employing polymeric nanomaterials for agrochemical delivery is a recently developed approach. Our group has constructed a cationic star polymer (SPc) that can assemble with pesticides to reduce their particle size and increase their dispersity and plant uptake, thus improving their bioactivity.16,17 For instance, the complexation of thiamethoxam with SPc through electrostatic interaction decreases the particle size to 116.16 nm and increases the contact and stomach toxicity of thiamethoxam against aphids by about 20%.18 The SPc-delivered osthole was also nanosized to 17.66 nm to increase the control efficacy of strawberry pests and disease.19 The SPc–chitosan complex (17.4 nm) activates the endocytosis pathway of plants to amplify the defence responses to control potato late blight.20 Therefore, SPc is a suitable adjuvant to deliver various synthetic/botanical pesticides or plant elicitors to improve their bioactivity, exhibiting good potential for field application.

Nanotechnology has the potential to overcome agricultural, forestry, and environmental challenges. However, new environmental and human health hazards may emerge from nanotechnology applications.21–25 There are several important issues related to the safe application of nanopesticides in the environment, such as (1) whether the nanocarrier increases the pesticide residue in plants and the environment, (2) whether the application of nanopesticides affects non-target predators, pollinators and environmental microbiota while enhancing the bioactivity, and (3) whether the surface adhesion of nanopesticides can be improved to avoid surface runoff and spray drift, causing severe environmental pollution.14,26,27 Dinotefuran is characterized by its strong contact and stomach toxicity, fast-acting property and wide insecticidal spectrum, and it has been widely used to control insect pests with piercing–sucking mouth parts in wheat, rice, cotton, vegetable, tobacco and other crops.28,29 However, residual levels of neonicotinoid insecticides, including dinotefuran, are relatively high in the environment.30–33 In addition, dinotefuran exhibits toxicity effects on bees, earthworms and other organisms to some extent.34–36 Some nanocarriers have been applied for dinotefuran-controlled release, improving its utilization efficiency, decreasing leaching loss, and promoting ecological safety.37–39

Our previous studies have focused on the enhanced bioactivity of SPc-delivered pesticides. However, the potential negative effects of the pesticide/SPc complex such as residue and safety toward natural enemies and plants should be evaluated before large-scale application. In the current study, SPc was used to prepare the dinotefuran/SPc complex that was taken as an example to evaluate the residue of SPc-delivered pesticide and its toxicity against predators and plants. We determined the pesticide loading content of SPc toward dinotefuran, the particle size and morphology of the dinotefuran/SPc complex, and the interaction between SPc and dinotefuran to illustrate the self-assembly mechanism. Then, we tested the contact angle and plant uptake of the dinotefuran/SPc complex and determined the toxicity of the dinotefuran/SPc complex against green peach aphids to elucidate the mechanism of improved bioactivity. Finally, we tested the toxicity of the dinotefuran/SPc complex against predatory lady beetles, determined its residue in plants, and examined its potential impacts on plant agronomic traits to evaluate its environmental safety. Our study demonstrated that the benefits of nanocarrier-delivered pesticides were enhanced bioactivity and reduced pesticide residue.

Methods

SPc synthesis

SPc was synthesized following the method described by Li et al.16 In brief, 2-bromo-2-methylpropionyl bromide (253 mg, 1.11 mmol) was added dropwise to pentaerythritol solution (25 mg, 0.18 mmol) in dry tetrahydrofuran (THF, 20 mL) and triethylamine (111.3 mg, 1.11 mmol) at 0 °C. The reaction was then quenched with methanol after stirring for 24 h. The residue recrystallized in cold ether to afford the star initiator (Pt–Br, 50 mg, 40%) following solvent removal. A flask equipped with a magnetic stirrer was charged with Pt–Br (40 mg, 0.055 mmol), 2-(dimethyl amino)ethyl methacrylate (2.2 g, 7.7 mmol) and dry THF (8 mL). The mixture was degassed by nitrogen for 30 min, and CuBr (46 mg, 0.22 mmol) and N, N,N′,N″,N‴-pentamethyl diethylenetriamine (110 mg, 0.44 mmol) were added. Polymerization was conducted at 60 °C for 7 h. The reaction was quenched by cooling and air exposure, and SPc was finally obtained as a white powder.

Preparation of the dinotefuran/SPc complex

Pure dinotefuran was purchased from Tianmen Hengchang Chemical Co. (China). SPc and dinotefuran were dissolved in ddH2O solution. SPc was mixed with dinotefuran, and the mixture was incubated for 15 min at room temperature to prepare the dinotefuran/SPc complex. In aqueous solution, the dinotefuran could spontaneously combine with SPc into the dinotefuran/SPc complex.

Loading capacity measurement

Pure dinotefuran was dissolved in ddH2O solution to prepare 15, 20, 22, 25 and 30 μg mL⁻¹ dinotefuran solution. The ultraviolet absorption of the above samples was measured using a UV-vis spectrophotometer (Thermo Genesys180, USA), and each concentration was done in triplicate. The
standard calibration curve of dinotefuran was constructed from a series of dinotefuran dilutions with the absorbance at 251 nm. 2 mL of dinotefuran solution (2 mg mL\(^{-1}\)) was mixed with 1 mL of SPc solution (1.51 mg mL\(^{-1}\)) and then dialyzed using regenerated cellulose with a molecular weight cutoff of 1000 Da (Shanghai Yuanye Bio-Technology Co., China) for 15 h. The absorbance at 251 nm was measured to determine dinotefuran concentration. The pesticide loading content (PLC) was calculated using the following formula.

\[
\text{PLC (\%)} = \frac{\text{weight of dinotefuran loaded in complex}}{\text{weight of dinotefuran loaded complex}} \times 100\%
\]

### Particle size measurement and complex morphology characterization

The particle sizes of dinotefuran (1 mg mL\(^{-1}\)) and the dinotefuran/SPc complex (1 mg mL\(^{-1}\)) with mass ratios of 1 : 1, 1 : 2 and 1 : 3 were measured using a Particle Sizer and Zeta Potential Analyzer (Brookhaven NanoBrook Omni, USA) at 25 °C. Each treatment included 3 independent samples. The morphological characteristics of dinotefuran and the dinotefuran/SPc complex with a mass ratio of 1 : 1 were further examined using a transmission electron microscope (TEM) (JEOL-1200, Japan). A few microliters of each sample were dropped on the microgrid, treated with 2% phosphotungstic acid, and air-dried before the observation.

### Isothermal titration calorimetry (ITC) assay

To determine the interaction of dinotefuran with SPc, 2 mL of pure dinotefuran solution (0.138 \(\mu\)mol L\(^{-1}\)) was titrated with 250 \(\mu\)L of SPc solution (1 \(\mu\)mol L\(^{-1}\)) in Nano ITC (TA Instruments Waters, USA). The heats of interaction during each injection were calculated by integrating each titration peak using Origin7 software (OriginLab Co., USA). The test temperature was 25 °C, and \(\Delta G\) was calculated using the formula \(\Delta G = \Delta H - T \Delta S\). The ITC assay was done in triplicate.

### Contact angle analysis

According to the method described by Zhu et al., the contact angles of the dinotefuran/SPc complex and dinotefuran on oilseed rape leaves were measured using an Optical Contact Angle Meter (Date Physics Corporation OCA25, Germany). \(d\)dH\(_2\)O was used as the control. Fresh leaves with similar thickness and size were chosen to perform the test. At room temperature, 5 \(\mu\)L of samples (1 mg mL\(^{-1}\)) was dripped onto the same leaf area for measurement. When the droplet on the leaf becomes stable for approximately 10 s, the image of the contact angle between the liquid and the leaf was collected. The contact angle was analyzed using the ellipse fitting algorithm. The algorithm assumes that the water drop profile is part of an ellipse. Each treatment contained 3 independent samples.

### Plant uptake analysis of dinotefuran delivered by SPc

A commercial formulation of dinotefuran (Mitsui Chemicals, Japan) was used to determine the plant uptake of the dinotefuran/SPc complex in plants. Dinotefuran (effective content: 20%) was mixed with SPc at a mass ratio of 1 : 1 to obtain the dinotefuran/SPc complex. Four-leaf stage oilseed rape plants were immersed in dinotefuran (200 mg L\(^{-1}\)) or the dinotefuran/SPc complex solution (200 mg L\(^{-1}\)) for 1 min and then air-dried. The plant uptake of SPc-delivered pesticide should be examined in a relatively short time; thus, the plants were washed with ddH\(_2\)O at 6 or 12 h after the treatment and stored at -20 °C for liquid chromatography-tandem mass spectrometry (LC-MS/MS) analysis. ddH\(_2\)O was used as the control.

Dinotefuran was extracted from homogenized leaves (5 g) using 20 mL acetonitrile acetate (1%) for 10 min. After centrifugation at 5000 r min\(^{-1}\) for 5 min, 20 mL of supernatant was evaporated using a gentle stream of nitrogen (40 °C) until the volume was reduced to 1 mL. Each sample was purified using a polytetrafluoroethylene membrane filter (Haiming Zhongli Filtering Equipment Factory, China). Residues were dissolved in 1 mL acetonitrile/water (2 : 8 v/v) for LC-MS/MS analysis, which was performed on an ACCOUTY UPLC-TQD system with an ACQUITY UPLC BEH C18 column (Waters Co., USA). The two analytes were separated using a mobile phase consisting of acetonitrile-ammonium acetate (3 : 7 v/v) solution. The injection volume was 20 \(\mu\)L, and the column temperature was 40 °C. Other operating conditions were as follows: interface voltage: 4000 V, flow rate of mobile phase: 400 \(\mu\)L min\(^{-1}\), heating block temperature: 400 °C; and interface temperature: 300 °C. Each treatment contained 3 independent samples.

### Bioactivity of the dinotefuran/SPc complex against green peach aphids

Pure dinotefuran was mixed with SPc at a mass ratio of 1 : 1 to prepare the dinotefuran/SPc complex, which was used for the bioactivity test. Aphids are major agricultural pests causing great economic loss by piercing the phloem and indirectly transmitting plant viruses in many crops, and dinotefuran has been widely used for controlling aphids due to its strong stomach toxicity. Based on plant uptake data, SPc could promote the plant uptake of dinotefuran; thus, root application was performed to determine the bioactivity of the dinotefuran/SPc complex to avoid the interference of contact toxicity similarly to the methods previously reported by Deng et al. and Zhang et al. The roots of 9–10 cm height radish seedlings infested with green peach aphids (about 30 aphids per treatment) were completely immersed in the dinotefuran/SPc complex (100, 50 and 25 mg L\(^{-1}\)), dinotefuran (100, 50 and 25 mg L\(^{-1}\)) and SPc solution with corresponding concentrations. ddH\(_2\)O was used as the control. The current study also tested commercial dinotefuran (Mitsui Chemicals) with the same effective content as SPc-loaded dinotefuran. Aphids were maintained...
in an incubator at 18 ± 1 °C, 60–70% relative humidity, and a 14L:10D photoperiod. The number of dead aphids was recorded 1 and 2 d after the treatment, and the corrected mortality was calculated using the following formula. Each treatment was repeated 4 times.

\[
\text{Corrected mortality (\%)} = \frac{\text{Mortality in treatment} - \text{Mortality in control}}{1 - \text{Mortality in control}} \times 100\%
\]

Safety evaluation of the dinotefuran/SPc complex in sustainable agriculture

Pesticide residue is directly related to food and environmental safety. Neonicotinoid insecticides such as dinotefuran, imidacloprid and thiamethoxam are easily photolyzed with high degradation rates in aqueous and soil environments under natural light conditions. To investigate whether the complexation of dinotefuran with SPc changed the dinotefuran residue, a commercial formulation of dinotefuran (Mitsui Chemicals) was mixed with SPc at a mass ratio of 1:1 to obtain the dinotefuran/SPc complex. Four-leaf stage oilseed rape plants were immersed in 200 mg L\(^{-1}\) solutions of dinotefuran and the dinotefuran/SPc complex for 1 min, and collected 3, 5 and 7 d after the treatment for LC–MS/MS analysis as described above. The degradation rate of dinotefuran was calculated according to the following formula. Each treatment was repeated 3 times.

\[
\text{Degradation rate (\%)} = \frac{\text{Pesticide content in 3 d} - \text{Pesticide content in 5/7 d}}{\text{Pesticide content in 3 d}} \times 100\%
\]

Although dinotefuran is considered as a safe neonicotinoid insecticide for crops, humans and animals, whether the introduction of SPc brings chemical damage to plants is an inevitable issue. The symptom of chemical damage is usually observed 1–5 d after the pesticide application, and the damaged plants can recover in 10–15 d. Thus, the status of the above-treated plants was observed after the application of dinotefuran or the dinotefuran/SPc complex, and the plant weight and height and the length and width of the largest leaf were measured 7 d after the treatment. Each treatment contained 4 oilseed rape plants, which was repeated 4 times.

Safety evaluation of the dinotefuran/SPc complex against non-target predatory lady beetles

As the major predator of aphids, the lady beetle Harmonia axyridis was selected to evaluate the toxicity of pure dinotefuran delivered by SPc (mass ratio 1:1) toward non-targets. The eggs of lady beetles were immersed in the dinotefuran/SPc complex (200 and 100 mg L\(^{-1}\)), dinotefuran (200 and 100 mg L\(^{-1}\)) and SPc solution (200 and 100 mg L\(^{-1}\)) for 10 s, and the hatching rate was recorded 2 and 3 d after the treatment. Meanwhile, 1st instar larvae were immersed in the dinotefuran/SPc complex (100 and 33 mg L\(^{-1}\)), dinotefuran (100 and 33 mg L\(^{-1}\)) and SPc solution (100 and 33 mg L\(^{-1}\)) for 10 s, and the mortality rate was recorded 1 and 2 d after the treatment. ddH\(_2\)O was used as the control. Each treatment consisted of about 30 eggs or 20 larvae, which was repeated 4 times.

Data analysis

All statistical analyses were conducted using SPSS 19.0 software (SPSS Inc., USA). The descriptive statistics are shown as the mean value and standard errors of the mean, and the data were analyzed using one-way ANOVA with the Tukey HSD test or independent t-test at the \(P < 0.05\) level of significance.

Results and discussion

Loading capacity of SPc and characterization of the dinotefuran/SPc complex

SPc contains a hydrophobic core and a hydrophilic shell with positively charged tertiary amines in the side chain. The hydrophobic core can be used to assemble with hydrophobic AIs, and the hydrophilic shell can improve the water solubility and water dispersion stability of the loaded cargo. Furthermore, the peripheral functional groups can assemble with negatively charged nucleic acids. In the current study, dinotefuran could spontaneously combine with SPc to form the dinotefuran/SPc complex in an aqueous solution. The dinotefuran concentration was proportional to the ultraviolet absorption at 251 nm, and the PLC of dinotefuran was calculated to be 17.41% (Fig. S1†). The PLC of dinotefuran was lower than that of the AIs (20%) of the commercial formulation (Mitsui Chemicals). As shown in Table 1 and Fig. 1B, the combination of dinotefuran with SPc decreased the particle size of dinotefuran from 269.28 to 29.43 nm (mass ratio 1:1). The particle size of the dinotefuran/SPc complex further decreased when the proportion of SPc was increased, but there was no significant difference. Only a small amount of SPc at a mass ratio of 1:1 was enough to reduce the particle size to nanoscale. This property can reduce the application amount of SPc for actual production. Based on representative TEM images (Fig. 1A), it could be concluded that most of the self-aggregated dinotefuran was composed of nearly spherical particles, whereas the particle size of the dinotefuran/SPc complex was relatively stable with smaller sizes.

Interaction of SPc with dinotefuran

The binding ability of SPc with dinotefuran was analyzed by ITC (Fig. 2 and S2†). The high affinity constant \(K_a\) (M\(^{-1}\)) and low dissociation constant \(K_d\) (M) suggested a strong...
interaction between SPc and dinotefuran. The negative ΔG value of −33.38 kJ mol⁻¹ indicated that SPc could spontaneously combine with dinotefuran. The negative ΔH value of −92.94 kJ mol⁻¹ and negative ΔS value of −199.77 J mol⁻¹ K⁻¹ suggested that the interaction of SPc with dinotefuran was through hydrogen bonding and van der Waals forces, and the putative site for hydrogen bonds is shown in Fig. 2A. Consistent with previous studies, SPc can combine with synthetic/botanical pesticides such as thiamethoxam, matrine, osthole and chitosan through various interactions to improve their physical–chemical properties.17–20 Different interaction mechanisms of SPc with pesticides are beneficial for expanding the application area of SPc, and SPc may be a promising adjuvant for pesticide nanometerization.

Contact angle and plant uptake of the dinotefuran/SPc complex
In the current study, the contact angle between dinotefuran and the leaf surface was 53.4 degrees, while that of the dinotefuran/SPc complex was decreased to 27.9 degrees (Fig. 3). The contact angle of dinotefuran was significantly decreased with the help of SPc. The outer wall of the leaf epidermis has a keratinized membrane, waxy sheath and trichome to exhibit the hydrophobic characteristic, which

Table 1  Reduced particle sizes of dinotefuran delivered by SPc with various mass ratios

<table>
<thead>
<tr>
<th>Formulation</th>
<th>Mass ratio</th>
<th>Sample number</th>
<th>Size (nm)</th>
<th>Average size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dinotefuran</td>
<td>—</td>
<td>1</td>
<td>340.07</td>
<td>269.28 ± 61.60a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>227.87</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>239.89</td>
<td></td>
</tr>
<tr>
<td>Dinotefuran/SPc complex</td>
<td>1 : 1</td>
<td>1</td>
<td>29.81</td>
<td>29.43 ± 0.91b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>30.09</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>28.39</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 : 2</td>
<td>1</td>
<td>28.53</td>
<td>24.33 ± 6.39b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>16.98</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>27.49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 : 3</td>
<td>1</td>
<td>24.37</td>
<td>22.25 ± 3.22b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>23.84</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>18.54</td>
<td></td>
</tr>
</tbody>
</table>

F₃,₈ = 46.434, P < 0.001. Means ± SE followed by different letters are significantly different (Tukey HSD test, P < 0.05).

Fig. 1  TEM images (A) and particle size distributions (B) of dinotefuran and the dinotefuran/SPc complex.
leads to pesticide drift to pollute the environment. The contact angle between the pesticide solution and the leaf surface can reflect their affinity. The adhesive ability of nanopesticides to plant leaves is an important factor in avoiding pesticide drift and improving the effective utilization of pesticides.\textsuperscript{6,46,47} Santos et al.\textsuperscript{48} evaluated the physical and chemical parameters, the uniformity coefficient of droplets, and the contact angle and surface tension of Bt bioinsecticides and found that the addition of mineral oil and surfactant reduced the contact angle and surface tension of the droplets, leading to greater spreading of droplets on leaves. Pesticide-loaded “hat”-shaped Janus carriers (HJCs) were designed and synthesized, and the pesticide-loaded HJCs can be embedded with the micropapillae and nanosplinters on leaves driven by the “hanger-hat” topology effect, leading to enhanced retention.\textsuperscript{49} In the current study, the contact angle of dinotefuran delivered by SPc was significantly decreased, revealing the easier distribution and spreading of the dinotefuran/SPc complex on plant leaves. The positively charged SPc has both hydrophilic and hydrophobic properties that could reduce the surface tension of the dinotefuran/SPc complex droplet and help the dinotefuran/SPc complex to spread and adhere to leaves, thus decreasing the environmental pollution caused by pesticide drift.

According to LC–MS/MS data, dinotefuran was not detected in the control treatment; the standard calibration curve of dinotefuran is shown in Fig. S3.\textsuperscript{†} The dinotefuran contents in oilseed rape were 15.0 and 19.2 mg kg\textsuperscript{-1} at 6 and 12 h after the dinotefuran treatment, while those increased to 21.7 mg kg\textsuperscript{-1} and 29.4 mg kg\textsuperscript{-1} with the help of SPc (Fig. 4 and S4\textsuperscript{†}). As envisioned, the plant uptake of dinotefuran delivered by SPc was significantly increased 1.45–1.53 times due to the smaller particle size and reduced contact angle of the dinotefuran/SPc complex. The widespread application of systemic insecticides is largely due to their chemical and physical properties, such as the capacity to be systemically translocated over plant vessels and high toxicity toward sap-sucking pests.\textsuperscript{50,51} Plant uptake, bioaccumulation and retention play an important role in the bioactivity of nanopesticides.\textsuperscript{46,49,52} Our previous studies also revealed that SPc could increase the plant uptake of thiamethoxam and osthole by 1.69–1.84 and 1.28 times, respectively.\textsuperscript{18,19}

Bioactivity of the dinotefuran/SPc complex against green peach aphids

The plant uptake of dinotefuran delivered by SPc was significantly improved; thus, the bioactivity of the
The corrected mortality of aphids treated with the dinotefuran/SPc complex exhibited no significant difference from that of dinotefuran alone at 24 h after the treatment. At 48 h after the treatment, the corrected mortality of aphids treated with the dinotefuran/SPc complex (100 mg L$^{-1}$) reached 87.0% compared to 68.6% with dinotefuran alone. In the dose-dependent experiments, the corrected mortality of aphids treated with the dinotefuran/SPc complex was finally increased by 18.4% (100 mg L$^{-1}$), 15.0% (50 mg L$^{-1}$) and 10.7% (25 mg L$^{-1}$). The bioactivity of pure dinotefuran delivered by SPc was comparable to that of commercial dinotefuran, and the corrected mortality of commercial dinotefuran was higher than that of the dinotefuran/SPc complex at the concentration of 100 mg L$^{-1}$ 2 d after the treatment. The potential reasons explaining the improved toxicity may be the pesticide nanometerization by the nano-delivery system, which is beneficial for increasing the contact area of pesticides and improving pesticidal activity. Similar to a previous study, Kumar et al.$^{53}$ constructed nano-sized permethrin, which showed higher toxicity against mosquito ($Aedes aegypti$) than permethrin. In addition, SPc could accelerate the plant uptake of dinotefuran, and the plant uptake and bioaccumulation of insecticides are directly related with the bioactivity of systemic insecticides. For instance, the plant uptake of thiamethoxam delivered by SPc was also enhanced to improve the stomach toxicity against aphids.$^{18}$

**Residue of the dinotefuran/SPc complex and its potential effects on plant agronomic traits**

Although the plant uptake of dinotefuran was significantly improved within 12 h using SPc (Fig. 4B), interestingly, the residue was decreased 1.21, 1.37 and 2.30 times 3, 5 and 7 d after the treatment, respectively (Fig. 6 and S5†). There was nearly no decline of dinotefuran residue for 3–7 d in the dinotefuran alone treatment, and the degradation rate of dinotefuran was less than 1%, whereas the degradation rates of the dinotefuran/SPc complex were 11.7% and 40.5% 5 and 7 d after the treatment, respectively. These results implied that SPc significantly accelerated the degradation of dinotefuran. The potential reason might be that the nanoscale complex was more suitable for biodegradation in plants. As envisioned, dinotefuran was not detected in the control treatment. The widespread residue of dinotefuran in the aquatic environment has been reported in the US, Canada, Japan and China, making dinotefuran a global environmental pollutant.$^{54,55}$ Therefore, the application of SPc is beneficial for controlling dinotefuran residue to mitigate its negative impacts on the environment. As envisioned, we did not observe any chemical damage of dinotefuran delivered by SPc after the immersion, and the status of plant growth was normal. Furthermore, the agronomic traits of oilseed rape such as fresh weight, plant height, and leaf length and width were finally measured 7 d after the treatment, and no significant difference was observed between the dinotefuran/SPc complex and the dinotefuran alone treatment (Fig. S6†), suggesting its safety in sustainable agriculture.
Potential effects of the dinotefuran/SPc complex on predatory lady beetles

As shown in Fig. 7, the eggs and larvae of lady beetles were used to test the potential negative effects of the dinotefuran/SPc complex on non-targets, and neither dinotefuran nor the dinotefuran/SPc complex had significant effects on the hatching rate of lady beetles at the concentration of 100 mg L\(^{-1}\). The hatching rate of lady beetles treated with dinotefuran had no significant difference from that with the dinotefuran/SPc complex when the concentration was increased to 200 mg L\(^{-1}\). Nearly no death of 1st instar larvae was observed in the control and SPc treatment. However, the toxicity of dinotefuran delivered by SPc significantly

Fig. 5 Bioactivity of the dinotefuran/SPc complex against green peach aphids through root application. The corrected mortality was recorded 1 and 2 d after the treatment. ddH\(_2\)O was used as the control. Each treatment contained about 30 aphids, which was repeated 4 times. Different letters above each bar indicate significant differences according to the Tukey HSD test (\(P < 0.05\)).

Fig. 6 Residue (A) and degradation rate (B) of dinotefuran delivered by SPc in plants. Four-leaf stage oilseed rape plants treated with the dinotefuran/SPc complex and dinotefuran were collected 3, 5 and 7 d after the treatment. The dinotefuran content was determined using LC–MS/MS analysis. Each treatment contained 3 independent samples. *, **, and *** indicate significant differences according to the independent t test (\(P < 0.05\), \(P < 0.01\) and \(P < 0.001\), respectively).
increased against 1st instar larvae 2 d after the treatment \( (33 \text{ mg L}^{-1}) \). Based on the current data, the toxicity of insecticides delivered by SPc was improved against both target pests and non-target predators due to the enhancement of broad-spectrum bioactivity. Lady beetles have been widely used as a predator to control aphids, and previous studies have demonstrated that the dinotefuran residue could influence the performance of predatory lady beetles.\(^{56,57}\) For instance, dinotefuran is moderately harmful to the predatory lady beetle \( Cryptolaemus \) montrouzieri with 30.67% mortality 24 h after the treatment.\(^ {58}\) Therefore, the application amount of the dinotefuran/SPc complex should be reduced while releasing predatory lady beetles to avoid the negative effects of improved bioactivity. Furthermore, given the negligible toxicity of the dinotefuran/SPc complex against the eggs of lady beetles, the complex can be sprayed when the eggs are released to achieve cooperative pest management.

Extensive studies suggest that SPc is suitable as a pesticide adjuvant for green pest management. (1) The complexation of pesticide with SPc leads to reduction of particle size, enhancement of plant uptake and toxicity, and fast degradation. (2) SPc is synthesized using cheap materials through two reaction steps. The production cost of SPc is US $0.90 per g, which is affordable for field application.\(^ {16}\) (3) The combination of pesticide with SPc can be achieved through a simple mix, which does not change pesticide application habits. (4) SPc has been used to construct a transdermal double-stranded RNA (dsRNA) delivery system, and SPc-delivered dsRNA targeting the key genes of insect pests can penetrate the cuticle of pests for efficient gene silencing and pest management.\(^ {43,45,59,60}\) To further improve the control efficacy, SPc can be applied to deliver dsRNA and pesticide simultaneously to meet the actual demands.

**Conclusions**

Herein, an efficient pesticide delivery system was constructed based on a star polymer that could complex with dinotefuran...
through hydrogen bonding and van der Waals forces. This complexation led to formation of nearly spherical particles of the dinotefuran/SPc complex with the particle size down to the nanoscale. The contact angle of dinotefuran delivered by SPc was decreased, revealing the easier distribution and spreading of the dinotefuran/SPc complex on plant leaves. The plant uptake of dinotefuran delivered by SPc was increased and thus its toxicity was significantly improved against green peach aphids. Interestingly, the residue of dinotefuran was reduced with the help of SPc due to the fast degradation of the nano-sized complex. In addition, the dinotefuran/SPc complex exhibited no negative effects on agronomic traits of oilseed rape but had a slight synergistic effect on lady beetles. Therefore, SPc may be a promising adjuvant to increase pesticide bioactivity and decrease the pesticide residue, showing great potential in sustainable agriculture.

Author contributions

Qinhong Jiang: investigation, writing – original draft. Yonghui Xie: resources, investigation, project administration. Min Peng: investigation. Zhijiang Wang: resources. Tianjiao Li: writing – review and editing. Meizhen Yin: supervision, resources, methodology. Jie Shen: conceptualization, supervision, resources, writing – review and editing. Shuo Yan: conceptualization, supervision, resources, data curation, formal analysis, methodology, writing – review and editing, funding acquisition. Qinhong Jiang and Yonghui Xie have contributed equally to this work.

Conflicts of 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.

Acknowledgements

This work was supported by the Foundation of Yunnan Tobacco Company (No. 2021530000241018).

Notes and references

44 S. Kurwadkar, A. Evans, D. DeWinne, P. White and F. Mitchell, Modeling photodegradation kinetics of three systemic neonicotinoids-dinotefuran, imidacloprid, and


