Novel microencapsulated soil conditioner: improving utilization efficiency of core materials and yield of cabbages

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Research Article

Keywords: microencapsulated soil conditioner, structure and properties, planting experiment, cabbages, sustained-release fertilizer

Posted Date: March 13th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2663030/v1

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Abstract

Microencapsulated soil conditioner (MSC) with water-soluble core and natural polymer shell can be used to solve the problems of soil about over-fertilization and low efficiency. Fulvic acid (FA) is a kind of purified humic acid, which possesses the characteristics of water-solubility, fertilizer maintenance and expedient monitoring. The MSC containing FA was prepared by double emulsion and ion crosslinking methods. Structure analysis revealed that the MSC owned a particle size between 1.58 and 2.14 mm with a similar round shape. Sustained release and biodegradation tests exhibited that MSC can effectively improve the fertilizer-retaining and water-retaining capacities. In addition, a massive amount of these microcapsules were prepared using sharp-hole coagulation bath method. As a type of neutral fertilizer, urea is useful to plant, easy to preserve and use, and has little damage to soil. The two materials, FA and urea, were typical and useful as core materials of MSC for actual applications. The planting experiment of cabbages was carried out using these microcapsules. The growth status of cabbages, physiological activities, nitrogen balance index (NBI) value and photosynthesis rate were investigated. Results demonstrated that the MSC owned the ability of improving the yield of cabbages, and it was a very promising sustained-release fertilizer.

1. Introduction

As a large agricultural nation, China has high fertilizer applications. The utilization rate of current fertilizer is low and results in a lot of resources waste. The loss of fertilizer may also cause pollution to the environment. Nitrogen fertilizer is the main fertilizer that determining the yield of grain crops. Besides being absorbed by plant roots, nitrogen fertilizer also loses in three forms such as evaporation, precipitation and biodegradation. This may cause water environment pollution. Moreover, over fertilization may even reduce the nitrogen utilization efficiency. The best way to apply fertilizer is to reduce the amount of nitrogen fertilizer but keep the yield of crops [1–3].

In order to achieve the desired effect, following requirements are needed for the new fertilizer. First, it cannot be evaporated and may be degraded by microorganisms in the soil environment along with water loss. Second, it can be slowly released and provide enough nutrients during the plant growth period [4–6]. Kavitha et al. [7] investigated the application effect of activated carbon in agriculture. Biological activated carbon (BAC) can improve the water and fertilizer conservation effect of the substrate, the soil structure, and the utilization rate of nutrients and crop yield. Jiang et al. [8] used attapulgite, sodium polyacrylate and desulfurization gypsum to prepare different types of soil conditioners, and they were effectively used to regulate the ion exchange capacity, pH value and water and fertilizer retention capacity of soil. Combatt et al. [9] prepared a novel type of polymer soil conditioner in which polyacrylic acid was used to modify montmorillonite. However, the application of above soil conditioner in soil was affected by environmental temperatures, soil types and biological interactions, which may lead to the final disadvantage of soil cultivation. In addition, the sustained release behavior of above materials was not very obvious, which was not beneficial for the growth of plant.
Microencapsulation technology is mainly used in food, medicine, textile and other fields. Different from above applications, microencapsulated materials used in the agriculture not only require non-toxicity and harmlessness, but also require solubility, slow release and biodegradability features in the environment [10–12]. These microcapsules are mainly composed of the core materials for crop growth and the shell materials for covering the core. Its slow and sensitive release properties can improve the utilization efficiency of fertilizer [13–15]. Natural polymers are widely used in drug delivery, food flavor improvement and cosmetics due to their wide sources, affordable price, non-biological toxicity and biodegradability. It is a feasible and effective method to use natural polymer as the shell materials for microcapsules [16–18].

Based on above requirements, our laboratory has made some innovations in sustained-release fertilizers [19–22]. The form of sustained-release fertilizer was innovated, and the microencapsulation model was selected to encapsulate the nutrients. The W/O/W (water/oil/water) model was used to prepare a novel type of sustained-release fertilizer, that is, microencapsulated soil conditioner (MSC) [22]. To better illustrate the release behavior of the core material, FA was selected and applied as the core material of MSC. The quickly crosslinking capability of sodium alginate in calcium chloride solution can preserve the hypothetical model of microcapsules. Results demonstrated that the MSC exhibited sustained release behavior, owned good biodegradation performance and possessed saline-alkali soil remediation ability. This can not only improve the proportion of nutrients in microcapsules and improve its practicability, but also increase the sustained release time of the microcapsules.

In this work, both urea and FA were used as the core materials of MSC, which was used to carry out experiments on the actual planting of vegetables. The relevant properties of vegetables were monitored and characterized with high-tech technologies, and the actual impact of MSC on vegetables was studied. It was demonstrated that MSC owned better promoting effect on the growth of Chinese cabbage’s root and greatly improved the practicability of sustained-release fertilizers.

2. Experimental

2.1 Materials

Sodium alginate (SA, viscosity: 500–1000 ma·s), liquid paraffin (CP), sodium chloride (AR) and potassium chloride (AR) were provided by Shanghai Titan Company (Shanghai, China). Calcium chloride anhydrous (CaCl₂), sodium dodecylbenzenesulfonate (CP), sorbitan monooleate (CP) and urea (AR) were purchased from Aladdin Industrial Corporation (Shanghai, China), Lingfeng Chemical (Shanghai, China), Macklin Chemical (Shanghai, China) and Sinopharm Chemical (Shanghai, China), respectively. Fulvic acid (FA, 90% pure) was obtained from Cool Chemistry (Beijing, China).

2.2 Preparation of microencapsulated soil conditioner

The microencapsulated soil conditioner (MSC) was fabricated according to the method presented in Fig. 1(A). First, under ultrasonic treatment, 5 mL of FA solution (120 g/L) was added into 15 mL of liquid
paraffin, and the primary emulsion was prepared. Then, this emulsion was dropwise poured to 0.08 g/L of SA aqueous solution, and homogenized for 5 min. The mixture was transferred into injection syringe (with 1 mm needle), and was then dripped into 10 wt.% CaCl$_2$ solution. Thus, the microcapsules were prepared, and the outer layer was made up of calcium alginate. These microcapsules were named SA8P15, and the other samples, SA6P15, SA8P25, SA8P10, were obtained using the same process. The structure and properties such as sustained release behavior, biodegradation performance and water retention properties were investigated in detail [22].

Furthermore, due to the need of a massive amount of MSC, the sharp-hole coagulation bath method was used and the preparation process owned some difference from above. Here, urea and FA were used as the core materials of MSC. 8 g of SA was added in 1 L of purified water, and the mixture was stirred under 80°C water bath until it was completely dissolved to form a uniform solution. Then, 30 g of urea and 10 g of FA were added under intensive stirring. The above solution was added to the sharp-hole coagulation bath. The parameters of this equipment were set as following: the rotating rate was 200 r/min, the temperature was 40°C, the dropping rate was 25 mL/min, and the rate of circulating water was 10 mL/min. 5 L of deionized water was poured from the upper water inlet into the equipment. The height of the forming tank was adjusted through the lifting button to facilitate the formation of microcapsules. The CaCl$_2$ powder was added to adjust the coagulation bath concentration, and the emulsion was added to the storage tank. Then, the ball valve was properly rotated to control the flow rate of the emulsion to form an independent microsphere structure without adhesion. The above steps were repeated until the samples were completely prepared. The formulation of MSC and the samples used in the planting experiment were listed in Table 1.

<table>
<thead>
<tr>
<th>Samples</th>
<th>SA/g/L</th>
<th>FA/g/L</th>
<th>Urea/kg/mu</th>
<th>CaCl$_2$/g/L</th>
</tr>
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<tbody>
<tr>
<td>CK</td>
<td>-</td>
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<tr>
<td>W1</td>
<td>-</td>
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<td>40</td>
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<tr>
<td>W2</td>
<td>8</td>
<td>5</td>
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<tr>
<td>W3</td>
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<td>20</td>
</tr>
<tr>
<td>W4</td>
<td>8</td>
<td>5</td>
<td>40</td>
<td>20</td>
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</table>

2.3 Planting experiment of cabbages

As shown in Table 1, three groups of MSC with different proportions of components (W2, W3 and W4), one group of traditional fertilization method (W1), and one group of control group (CK) were used for the planting experiment. In each group, ten cabbages with the same growth status were selected and planted. According to the burial degree of MSC at the time of planting, it was 2 and 5 cm away from the soil surface, and was recorded as W1H2, W1H5, W2H2, W2H5, W3H2, W3H5, W4H2 and W4H5, respectively.
The seeds of cabbage were soaked for 4 h at room temperature, and then the seeds were seeded in thirty-six holes according to the breeding method of five seeds per hole. The seeds were covered with nutrient soil (about 1 mm thick), and then they were watered thoroughly to keep the soil’s moisture.

2.4 Physiological growth curves

The plant height, crown width, number of leaves and planting site were recorded for each group of cabbages at around mid-afternoon every day with a millimetre ruler. Among them, plant height was the distance from the root to the highest point of the leaves, and crown width was the maximum linear distance of top view. In addition, these plants were selected and conducted plant phenotype experiment, and the cabbages were placed in the test room every other week to determine its parameters.

2.5 Nitrogen content of plant leaves and photosynthesis

The second leaf of the plant closest to the core of vegetables was measured for the amount of chlorophyll and flavonoids using plant polyphenol-chlorophyll meter (Dualex Scientific+, Focèle-A, France), and the nitrogen balance index (NBI) was obtained. The physiological parameters were measured and recorded. The photosynthesis, transpiration and respiration of cabbages were tested using portable photosynthetic-fluorescence measurement system (GFS-3000, WALZ, Germany). The photosynthesis of plant leaves was measured under conditions of weak plant transpiration and sustained photosynthesis.

2.6 Root analysis and yield of cabbages

During the process of plant growth, the roots of the cut leaves were washed with deionized water, and then they were analyzed using the root analysis system (WinRHIZO, Regent, Canada). The root length, diameter, area, volume, and root tip count were recorded. The plants were cut from 1 cm below the leaves. They were immediately subjected to mass measurement, and the wet weight was recorded. Then, the same group of plants was placed in an envelope and dried at 70°C for 5 d to attain the dry weight.

3. Results And Discussion

3.1 Preparation and properties analysis of MSC

Figure 1(A) presented the preparation process of MSC. SA was used as a type of shell material to prepare microcapsules. FA and urea were used as water-soluble core materials. A mixture of FA, urea and liquid paraffin was prepared by stirring to form a homogeneous emulsion, and then homogenated with SA solution to form the structure of W/O/W. During this process, the characteristic of surfactant and the use of stirring rate were important to the preparation of the emulsion. In addition, the MSC can be prepared by the method of sharp-hole coagulation bath due to the massive amount requirement. The emulsifying emulsion was made into liquid drops through a sharp-hole device and dropped into the coagulation bath. The wall material of the liquid drop reacts with the coagulation bath to form water-insoluble microcapsules. The MSC was finally formed by CaCl$_2$ through ionic crosslinking mechanism which was
presented in Fig. 1(B) [23–26]. The particle size of the MSC was ranged between 1.58 and 2.14 mm (Fig. 1(C)), which was consistent with the urea particle size used in actual agricultural production. In addition, it can be seen that the microcapsules were spherical in size.

The test results of electrical conductivity for soil treated with different MSC were shown in Fig. 2(A). It was shown that the conductivity of all experimental groups was higher than that of the control group after treatment. This indicated that the concentration of soluble ions in the dry sand was increased with the addition of different MSC. Thus, the conductivity of soil was improved, and the ion exchange capacity and the element diversity of soil can be effectively improved. Ca\(^{2+}\) was used in the preparation of microcapsules, and this may be the reason for the increase of ion concentration in soil. Ion exchange ability is an important parameter for soil, which can be used to regulate soil environment and promote crop growth. When Ca\(^{2+}\) was applied into soil, it was released into the soil to regulate the type and concentration of ions. The ability of controlling leaching loss of microencapsulated materials reflects the ability of preservation the nutrition for MSC. The relevant experimental data were given in Fig. 2(B).

Compared with the control group, four groups of experimental groups can effectively improve the effect of water resistance. This may be ascribed to the following two reasons: (1) the natural polymer of microcapsule shell possesses certain water absorption ability, and thus it may retain some nutrients due to its water absorption features; (2) a relatively dense spatial structure may be existed in the microcapsules, and it can prevent leaching phenomenon. The sustained release curves of MSC with different core materials were presented in Fig. 2(C). It can be seen that the prepared microcapsules owned good sustained-release behavior. Its sustained-release time was at least 600 h (about 25 d), which can cover the growth range of most crops. The biodegradation curves of MSC were illustrated in Fig. 2(D). A large mass loss occurred in the first 50 h, which may be the degradation process of outer shell of sodium alginate. The first mass reduction was resulted from the degradation of its outer layer. With the decrease of the outer shell, the protective structure of the core was destroyed. This may lead to the loss of the core materials along with the degradation of the outer shell.

Figure 3 showed the breeding and planting process of cabbages. As shown in Fig. 3(a), after the buds grew in the plug, the seedlings which were far away from each other and owned the same growth vigor were selected as the seedling raising objects. Other buds were cut off for transplanting preparation. In Fig. 3(b), after about two weeks, the seedlings with similar growth vigor were selected and transplanted into the breeding pot, and the water was poured through the breeding basin every afternoon to keep the soil’s moisture. The insects were caught and the physiological status was checked every three days to ensure the normal growth of cabbages. Figure 3(c) and (d) presented the growth status of these cabbages after three and four weeks. Compared with the control group, CK(Fig. 3(A)), the growth status of the four experimental groups, for examples W1H5,W2H5,W3H5,W4H5(Fig. 3(B)-(E)), was significantly improved, which proved that the microencapsulated soil conditioner could improve the soil structure and had the effect of promoting plant growth. During the above four periods, the nitrogen balance index, physical and chemical properties of soil and physiological growth performance were monitored, and the photosynthesis intensity and root growth were measured and analyzed.
3.2 Physiological growth curves

High throughput plant phenotype technology may be used to continuously track and measure physiological parameters such as plant height and leaf width without physical damage [27]. It owned the advantages of accuracy, objectivity and efficiency, and can provide strong support for related research. However, the current reports on the research of plant phenotype equipment in the field of physiological growth performance were not common. In this experiment, the plant phenotypic equipment was used to continuously track and measure the growth process of cabbages, as shown in Fig. 4(A) and (B), which was the photos taken from 0° and 90° direction, respectively. It can be seen from Fig. 4 that the plant height and leaf width of cabbages showed a significant increasing trend, and it may provide relatively objective basis for the relevant data of crop growth performance [28].

Figure 5 presented the data of leaf width and plant height of the control and experimental groups which may express the growth trend of cabbages [29]. It can be seen from Fig. 5(a) that there was no significant difference for leaf width in the first 7 d. This might be due to the fact that the embryo of the seed itself provided enough nutrients for the growth of cabbages, and the plant height was about 6–8 cm (Fig. 5(b)) [30]. Compared with the control group, the growth trend of sustained-release fertilizer and traditional fertilizer groups was better. After 14 d, it was found that the plant height (about 14 cm) of traditional fertilization group was better than that of sustained-release fertilizer group (about 13 cm) and the control group (about 12 cm). However, the leaf width (about 25–27 cm) of the sustained-release fertilizer group was better than that of the traditional fertilizer group (about 25 cm) and the control group (about 23 cm). Under the condition of insufficient seed nutrition, the content of nitrogen fertilizer can directly affect the physiological growth performance of cabbages. However, in 15–25 d, it was found that the cabbages in the sustained-release fertilizer group continued to grow rapidly, and the leaf width increased from about 27–30 to 37–44 cm. In contrast, the traditional fertilizer group grew from 25 to 31 cm, and the control group grew from 24 to 31 cm.

These results showed that sustained-release fertilizer could continuously provide fertility for cabbage growth compared to traditional fertilization. FA could not only promote the growth of roots, but also protect the decomposition of soil microorganisms in the nitrogen fertilizer position, thus prolonging the existence time of nitrogen fertilizer in the soil. Calcium ions may activate the cell wall of plant root and enhance its ability of absorbing nutrients and water. Therefore, the final growth trend was that W3Hn was greater than W4Hn, and W4Hn were greater than that of W2Hn, traditional group and the control group [31]. Results showed that with the same urea concentration, the effect of sustained-release microcapsules was conducive to the growth of cabbages, while FA and calcium ion concentration were conducive to improve the utilization rate of urea. Compared with Fig. 5(a,c) and (b,d), it could be seen that the growth of cabbages buried in 2 cm was better than those buried in 5 cm. This might be related to the shallower root system and better lateral root, which could not extend down to absorb more nutrients. Therefore, sustained-release fertilizer and shallow layer were beneficial to the growth of cabbages.

3.3 Nitrogen content of plant leaves and photosynthesis
Nitrogen balance index (NBI) was the ratio of chlorophyll (CHL) to flavonoid (flav), which was the main index reflecting the growth of cabbages [32–34]. Flavonoids could resist oxidation and scavenge active hydrogen, while chlorophyll was the main substance for photosynthesis. At the beginning, NBI was similar because the growth of cabbages using the nutrients in the embryo was not related to the external fertilization and NBI was related to the germination cycle of plants (Fig. 6). On the 4th day, NBI value of all cabbages reached the maximum value, and this was ascribed to less leaves and more nutrients in this plant. From the 4th to 7th days, the growth of cabbages was promoted and the chlorophyll content in the leaves was increased because of the external nitrogen supply. The NBI of the sustained-release fertilizer group was higher than that of the traditional fertilization and the control groups, which illustrated that the sustained-release fertilizer groups showed better effect of providing nitrogen fertilizer than that of the traditional fertilization groups. During the growth process from the 7th to 20th days, the NBI of the sustained-release fertilizer group was much higher than that of the traditional fertilizer and the control groups. The NBI of the traditional fertilizer and the control groups showed a continuous downward trend, and on the contrary, the sustained-release fertilizer group remained high and there was an upward fluctuation. The traditional fertilization could only provide nutrients in a short period of time and owned no ability of sustainable fertilization, while sustained-release fertilizer could continuously provide the nitrogen fertilizer needed during the growth process of cabbages.

Net photosynthetic rate could be used as a direct indicator of CO$_2$ to sugar conversion. It can directly reflect the indicators of cabbage production and growth capacity, which were related to the chlorophyll content in cabbage leaves (Fig. 7(a)). Results showed that the net photosynthetic rate of sustained-release fertilizer group was much higher than that of traditional fertilizer group. In addition, the nitrogen content could directly affect the chlorophyll content in the leaves [35–38]. The sustained-release fertilizer had the ability to continuously supply nitrogen, and thus it may maintain sufficient chlorophyll content in the leaves of cabbages and the growth of cabbages was maintained.

Intercellular carbon dioxide concentration in the morning or noon could be used as indirect evidence to reflect crop photosynthesis (Fig. 7(b)) [39]. Under the condition of the same light and carbon dioxide concentration, the higher the intercellular carbon dioxide concentration was, the lower the carbon dioxide consumption for photosynthesis was. Therefore, there was a negative correlation between the intercellular carbon dioxide concentration and the photosynthesis rate [40].

The transpiration rate of crops was the driving force of crop water absorption (Fig. 7(c)) [41]. Water was also the main raw material for photosynthesis of cabbage to prepare nutrients, so the transpiration of crops was also an important index for the growth process of cabbages [42]. The transpiration rate of the sustained-release fertilizer group was higher than that of the traditional fertilizer group, which was consistent with the above trend of photosynthesis rate. It proved that the sustained-release fertilizer group owned better physiological growth performance compared to the traditional fertilizer and the control groups.

3.4 Root analysis and yield of cabbages
As the main part of absorbing soil nutrients and water, root analysis may reflect the growth trend [43–45]. By comparing the total length, total surface area, average root diameter and dry weight of roots in Fig. 8, the roots of the experimental group treated with sustained-release fertilizer were more developed, which proved that it had better physiological performance.

From the order of total root length: W3H2 (182.7 cm) > W3H5 (162.5 cm) > W4H2 (142.2 cm) > W4H5 (130.5 cm) > W2H5 (118.2 cm) > W2H2 (115.7 cm) > W1H5 (87.0 cm) > W1H2 (82.7 cm) > CK (55.6 cm), it can be seen that the traditional fertilization had a promoting effect on root growth, and the length of root was increased by 31.4 cm (W1H5) and 27.1 cm (W1H2), respectively. In addition, compared with CK, the application of sustained-release fertilizer can increase the total length from 60.1 cm (W2H2) to 127.1 cm (W3H2), which had a more obvious effect on the root. In the same way, the trend of total surface area was similar to that of root length, indicating that sustained-release fertilizer may effectively improve the physiological growth performance of the cabbages. This illustrated that this novel soil conditioner presented a good prospect in practical application.

Figure 9 presented the wet (a) and dry (b) weight of mature cabbages after picking and drying. It can be seen that the yield of cabbage treated with nitrogen fertilizer was significantly higher than that of the control group, indicating that nitrogen fertilizer played an extremely important role in the yield of cabbage. Compared to the traditional fertilization group, the sustained-release fertilizer group exhibited higher yield. For example, when the fertilizer was applied at 5 cm, the order of yield for each group was W3H5 (8.01 g) > W4H5 (6.90 g) > W2H5 (5.18 g) > W1H5 (5.07 g) > CK (4.01 g). This illustrated that the sustained-release nitrogen fertilizer may provide more sufficient fertilizer compared to the traditional fertilization method.

The total nitrogen content and organic content of the soil after planting cabbages were detected and analyzed (Fig. 9(c)). It can be found that compared with the nitrogen content of 0.65g/kg in the control group, the soil of other groups using fertilizer contained significantly more nitrogen content. The order of them was W3H2 (0.786g/kg) > W2H2 (0.781g/kg) > W1H2 (0.735g/kg) > W4H2 (0.719g/kg), indicating that the use of nitrogen fertilizer can greatly increase the nitrogen content in soil, which can improve crop yield and related physiological growth performance. Similarly, through the analysis of organic matter, the order of its organic matter content was W3H2 > W2H2 > W1H2 > W4H2 > CK, which was mainly because the microencapsulated soil conditioner capsule can be degraded as organic matter and increase the organic matter content in the soil, so as to improve crop yield.

4. Conclusions

In this study, a massive amount of microencapsulated soil conditioner, MSC, was successfully prepared for actual applications using sharp-hole coagulation bath method. The MSC, a type of sustained-release fertilizer, was applied to the planting experiment of cabbages. The physiological growth performance, NBI index, photosynthesis, root status together with yield were tested and evaluated.

Physiological growth curves revealed that the plant leaf width and height of cabbages exhibited an increasing trend. In addition, the NBI of the sustained-release fertilizer group was higher compared to the
traditional fertilization and the control groups. Net photosynthetic rate illustrated that the sustained-release fertilizer, MSC, owned the ability to continuously supply nitrogen and it may maintain sufficient chlorophyll content in the leaves of cabbage. By comparing the total length, total surface area, average root diameter and dry weight of roots, the roots of the experimental groups treated with MSC were more developed, which proved that it had better physiological performance.

Above results demonstrated that the sustained-release nitrogen fertilizer, MSC, may provide more sufficient fertilizer compared to the traditional fertilization method, and this novel soil conditioner owned the ability of effectively improving crop yield and was a very promising sustained-release fertilizer.

Declarations

Funding

This work was financially supported by “Capacity Building Project of Some Local Colleges and Universities in Shanghai (No.17030501200)“, “National Natural Science Funds (No.51873103)“, “Talent Program of Shanghai University of Engineering Science (No.2017RC422017)“, and “First-rate Discipline Construction of Applied Chemistry (No.2018xk-B-06)“.

Conflicts of Interest

The authors declare no conflict of interest.

Ethics approval and consent to participate

Consent for publication.

Not applicable.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions Statement

Lu Wentong and Wang Caiyan conducted most of the experiments and wrote the main text of the manuscript. Prof. Wang Jincheng designed most of the experimental conditions, including but not limited to experimental environment and experimental equipments. Wang Zuo and Sun Jibo were mainly responsible for drawing pictures and conducted application of the product in the enterprise. All authors reviewed the manuscript.

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Figures
Figure 1

Microencapsulated soil conditioner (MSC): (A) preparation process, (B) crosslinking mechanism, (C) actual size and photos.
Figure 2

Properties of MSC: (A) electrical conductivity, (B) leaching loss ratio, (C) release ratio, (D) biodegradation rate.
Figure 3

Growth photos of cabbages at different planting stages: (A) CK, (B) W1H5, (C) W2H5, (D) W3H5, (E) W4H5; (a) one week, (b) two weeks, (c) three weeks, (d) four weeks.

Figure 4
W4H5 growth duration measurement chart: (A) 0° direction, (B) 90° direction (time interval from (a) to (b), (b) to (c), etc. was about one week).

**Figure 5**

Continuous growth curves of cabbages: (a) leaf width of plant treated with fertilizer buried at 2 cm; (b) height of plant treated with fertilizer buried 2 cm; (c) leaf width of plant treated with fertilizer buried at 5 cm; (d) height of plant treated with fertilizer buried 5 cm.
Figure 6

NBI curves of leaves during the growth of cabbages (a) NBI curves of fertilizer buried at 2 cm during growth; (b) NBI curves of fertilizer buried at 5 cm during growth.
Figure 7

Activity characterization during the growth period of cabbages: (a) net photosynthetic rate of crops; (b) intercellular CO$_2$ concentration; (c) transpiration rate.
Figure 8

Infrared scanning images of cabbages' root: (a) W1H2, (b) W1H5; (c) W2H2, (d) W2H5; (e) W3H2, (f) W3H5; (g) W4H2; (h) W4H5; (i) CK; (j) distribution of root length, total surface area and average diameter.
Figure 9

Yield of mature cabbages: (a) wet weight; (b) dry weight; (c) total nitrogen content and organic matter content.