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Article

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

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ABSTRACT: The utilization of microencapsulated soil conditioner (MSC) with a water-soluble core and natural polymer shell offers a potential solution to address the issues of over-fertilization and low efficiency in soil. Fulvic acid (FA), a refined form of humic acid, possesses desirable characteristics such as water solubility, fertilizer retention, and convenient monitoring. Urea, a neutral fertilizer, is beneficial for plant growth, easy to store and apply, and causes minimal harm to the soil. Sodium alginate, as a type of natural polymer, has great potential for use in the agricultural sector due to its biocompatibility, environmental safety, and water-holding abilities. The preparation of MSC incorporating FA and urea involved the employment of double emulsion and ion crosslinking mechanism utilizing the sharp-hole coagulation bath method. Structural analysis confirmed the presence of core materials within the MSC. The analysis of the structure indicated that the MSC possessed a particle size about 200 μm, displaying a uniform spherical shape. Subsequent sustained release and biodegradation tests demonstrated the MSC's ability to significantly enhance both fertilizer retention and water retention capacities. In addition, a planting experiment involving cabbages was conducted employing these microcapsules. The growth status of the cabbages, their physiological activities, nitrogen balance index value, and photosynthesis rate were thoroughly examined. The statistical analysis findings indicated that the MSC possessed the capability to enhance cabbage yield, rendering it a highly promising sustained-release fertilizer.

Key words: soil conditioner; microcapsules; structure and properties; planting experiment; sustained-release fertilizer.

INTRODUCTION

China, being a prominent agricultural nation, exhibits substantial usage of fertilizers. However, the current utilization rate of these fertilizers is suboptimal, leading to significant wastage of resources. Furthermore, this inefficiency in fertilizer usage can result in environmental pollution. Notably, fulvic acid (FA) is a natural substance that belongs to the humic substance family. It is derived from organic matter such as decomposing plants and minerals found in soil. Known for its dark brown to black color, FA plays a vital role in soil fertility and plant growth. In addition, nitrogen fertilizer, urea, plays a pivotal role in determining the yield of grain crops. Apart from being absorbed by plant roots, FA and urea are also lost through various mechanisms, including denitrification, leaching, evaporation, precipitation, and biodegradation. Consequently, these losses can contribute to water pollution. Moreover, excessive fertilization practices may further diminish the efficiency of fertilizer utilization. The best way to apply fertilizer is to reduce the amount of fertilizer, but keep the yield of crops (Zhou et al. 2017).

In order to achieve the desired effect, the following requirements are needed for the new fertilizer. First, it cannot be evaporated and may be degraded by microorganisms in the soil environment. Second, it can be slowly released and provide enough nutrients during the plant growth period (Ali et al. 2018, Ke et al. 2023, Nuttida et al. 2018). Kavitha et al. (2018) investigated the application effect of activated carbon in agriculture. Biological activated carbon 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.

(2015) 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. Lerma et al. (2018) prepared a novel type of polymer soil conditioner in which polyacrylic acid was used to modify montmorillonite. However, the application of the mentioned fertilizer 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 cited materials was not obvious, which was not beneficial for the growth of plant.

Microencapsulation technology is mainly used in food, medicine, textile and other fields. Different from described applications, microencapsulated materials used in the agriculture not only require non-toxicity and harmlessness, but also solubility, slow release, and biodegradability features in the environment (Sun et al. 2018, Maestrelli et al. 2015). 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 efficient utilization of fertilizer (Yue et al. 2016, An et al. 2019, Ji et al. 2019). 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 (Yang et al. 2014, Haghighi et al. 2019, Liu et al. 2019).

Based on these requirements, our laboratory has made some innovations in sustained-release fertilizers (Yang et al. 2020, Wang et al. 2020, Zuo et al. 2020). The form of sustained-release fertilizer was innovated, and the microencapsulation model was selected to encapsulate the nutrients. This can not only improve the proportion of nutrients in microcapsules, own targeted period, prevention of salt injury and improve its practicability, but also increase nutrient holding capacity and the sustained release time of the microcapsules.

In this work, a water/oil/water (W/O/W) model and the sharp-hole coagulation bath method (Wan et al. 2012) was used to prepare a type of sustained-release fertilizer, that is, microencapsulated soil conditioner (MSC). Both FA and urea were used as the core materials, and the natural polymer sodium alginate (SA) was used as the shell material. The structure and performance of MSC were characterized, and they were applied to 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. The application results showed that the MSC prepared in our study owned good nutrient holding capacity and prolonged released time, which are beneficial for the actual planting.

MATERIALS AND METHODS

Materials

SA (viscosity: 500–1,000 ma·s), liquid paraffin (CP), sodium chloride (AR) and potassium chloride (AR) were provided by Shanghai Titan Company (Shanghai, China). Calcium chloride anhydrous ($CaCl_2$), sodium dodecylbenzensulfonate (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. FA (90% pure) was obtained from Cool Chemistry (Beijing, China).

Preparation of microencapsulated soil conditioner

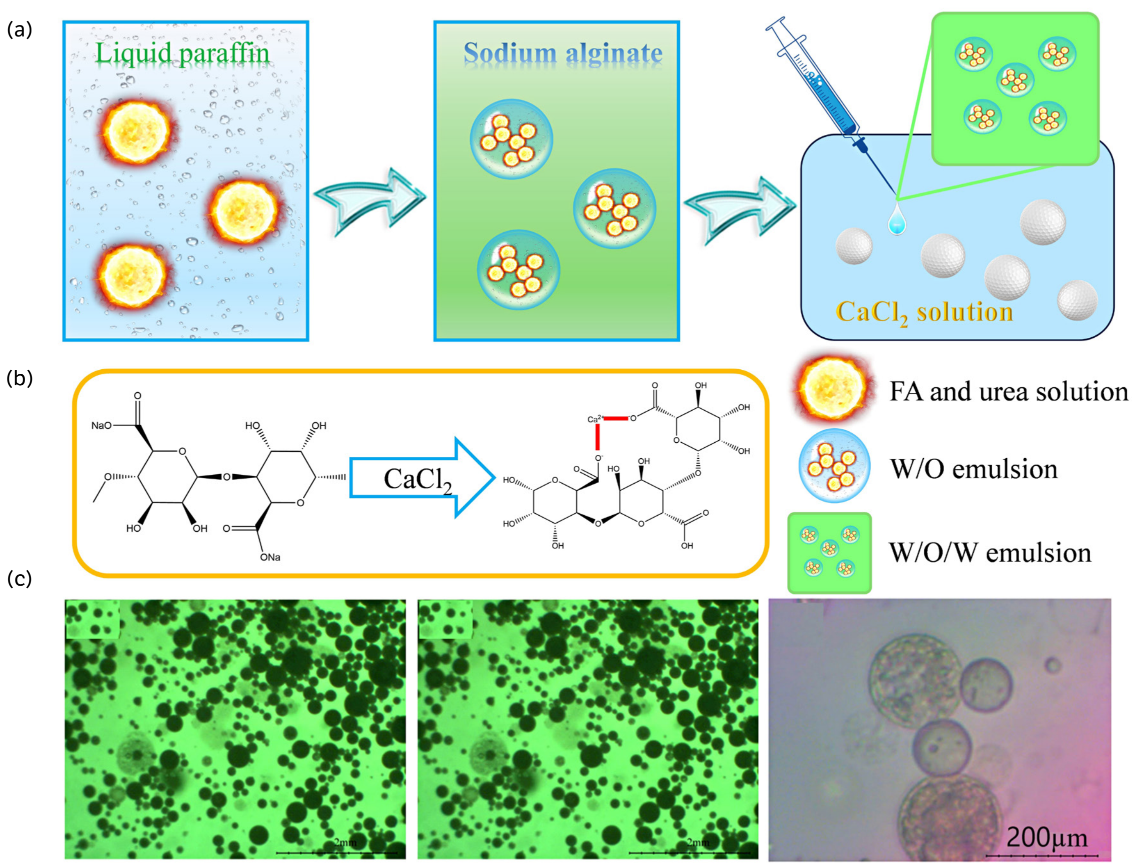
The MSC was prepared using the sharp-hole coagulation bath method. Different amounts of FA, urea and liquid paraffin were added to 1 L of purified water, and the mixture was stirred under an 80°C-water bath until it was completely dissolved, forming a uniform emulsion. Then, some amount of SA was added under intensive stirring. The resulting emulsion was added to the sharp-hole coagulation bath with varying concentrations of $CaCl_2$. The formulation of MSC and the samples used in the planting experiment are listed in Table 1.

In this method, the equipment parameters were set as follows: 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. A total of 5 L of deionized water was poured into the equipment through the upper water inlet. The height of the forming tank was adjusted using the lifting button to facilitate the formation of microcapsules. $CaCl_2$ powder was added to adjust the concentration of the coagulation bath, while the emulsion was added to the storage tank. By properly rotating the ball valve, the flow rate of the emulsion was controlled to form an independent microsphere structure without adhesion. These steps were repeated until all the samples were completely prepared.

Table 1. Formulation of different microencapsulated soil conditioner and the samples used in planting experiment.

Samples	Sodium alginate/g	Paraffin/g	Fulvic acid/g	Urea/g	$CaCl_2$/g
Blank control group	-	-	-	-	-
W1			5	40	
W2	0.8	150	5	40	20
W3	0.8	150	5	40	40
W4	0.8	150	10	40	20

Figure 1a presents the preparation process of MSC. In this process, SA was utilized as a shell material to prepare the microcapsules, while FA and urea were used as water-soluble core materials. A homogeneous emulsion was formed by stirring a W/O emulsion of FA, urea, and liquid paraffin, which was then homogenated with SA solution to create the W/O/W structure. The surfactant characteristics and stirring rate played important roles in achieving a successful emulsion. The MSC were prepared using the sharp-hole coagulation bath method due to the large quantity requirement. The emulsifying emulsion was transformed into liquid drops through a sharp-hole device and dropped into the coagulation bath. The wall material of the liquid drop reacted with the coagulation bath, resulting in the formation of water-insoluble microcapsules. To complete the MSC formation, $CaCl_2$ was used for ionic crosslinking mechanism, as shown in Fig. 1b (Neilson et al. 2015, Altuntas et al. 2016, Toledo-Madrid et al. 2018, Zheng et al. 2019).



FA: fulvic acid; W/O: water/oil; W/O/W: water/oil/water.
Figure 1. Microencapsulated soil conditioner: (a) preparation process, (b) crosslinking mechanism, (c) actual size and photos.

Characterization of microencapsulated soil conditioner

Morphology observation

The microcapsules were observed using transmitted and reflected polarizing microscope (PLM, XPF-300) from Shanghai Tianxing Instrument Co. The eyepiece has a magnification of 10X, while the objectives have specifications of 10X, 40X, and 80X, resulting in total magnifications of 100X, 400X, and 800X, respectively.

Encapsulation efficiency

Different types of MSC, each weighing 1 g, were placed in centrifuge tubes containing 50 mL of deionized water. The system was then placed in a constant temperature water bath at 30°C. Initially, the content of FA in the sustained-release solution was measured using a ultraviolet (UV) spectrophotometer every 30 min. Two g of MCS was soaked in 50 mL of deionized water for 24 h. Afterwards, it was completely crushed using a cell disruptor, and the content of FA was determined using a UV spectrophotometer to calculate its encapsulation efficiency.

Water leaching resistance

Thirty g of dry sand soaked in 5 mL of deionized water was placed in a centrifuge tube with a bottom opening of 50 mL. Then, 2 g of MSC was evenly spread on top, followed by covering it with dry sand. The samples were divided into four groups based on the type, with two experimental groups and one control group for each. The system was subjected to simulated rainfall using a 50 mL solution of 3.3 $g \cdot L^{-1}$ FA, and the leachate was collected for performance characterization.

Sustained-release capacity

The concentration of FA was measured at 423 nm using the Shimadzu UV-visible spectrophotometer, model UV3600. First, a standard curve was established by using gradient concentrations of FA standard solutions ranging from 0.2 to 0.8 $g \cdot L^{-1}$ and detecting them with the UV-visible spectrophotometer. Then, each sample obtained during the experiment was diluted 50 times and tested, and the obtained absorbance was compared with the standard curve to calculate the concentration of FA.

Biodegradability performance

Fifty g of soil for plant cultivation was dispersed in 500 mL of deionized water to prepare a soil solution. Two g of MSC was soaked in 50 mL of the soil solution and placed in a constant temperature water bath at 50°C. After 12 h of treatment, it was dried overnight. After completing the characterization of mass and particle size, the MSC was returned to the same conditions, and the process was continued until degradation was complete.

Applicability performance of microencapsulated soil conditioner

Cultivation experiment of cabbages

As shown in Table 1, the cultivation experiment involved three groups of MSC with different component proportions (W2, W3, and W4), one group using the traditional fertilization method (W1), and one control group (CK). Each group consisted of 10 cabbages with similar growth statuses, which were planted in pots (20 cm × 18.5 cm) filled with soil (3 L, pH = 7.2–7.6) in a greenhouse. The burial depth of the MSC at the time of planting was 2 and 5 cm from the soil surface, and it was recorded as W1H2, W1H5, W2H2, W2H5, W3H2, W3H5, W4H2, and W4H5, respectively. Prior to seeding, cabbage seeds were soaked at room temperature for 4 h. Then, the seeds were sown in 36 holes, with five seeds per hole according to the recommended breeding method. After covering the seeds with nutrient soil (approximately 1-mm thick), thorough watering was applied to maintain soil moisture.

Physiological growth curves

The plant height, crown width, number of leaves and planting site were recorded for each group of cabbages at around 12 p.m. every day with a mm-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. Additionally, a plant phenotype experiment was conducted by selecting specific plants. These selected cabbages were placed in a test room every other week to determine their parameters.

Nitrogen content of plant leaves and photosynthesis

The second leaf of the plant closest to the core of vegetables was measured for chlorophyll and flavonoids using plant polyphenol-chlorophyll meter (Dualex Scientific+, Focele-A, France), and the nitrogen balance index (NBI) was obtained. The physiological parameters were measured and recorded every three days after their seeding. The photosynthesis, transpiration, and respiration of cabbages were tested using portable photosynthetic-fluorescence measurement system (GFS-3,000, WALZ, Germany). The photosynthesis of plant leaves was measured under conditions of weak plant transpiration and sustained photosynthesis.

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 five days to attain the dry weight.

Measurement of total nitrogen content and organic content

The semimicro Kjeldahl method was used to detect total nitrogen in soil. Ten g of the soil sample was digested with 100 mL of concentrated sulfuric acid. The nitrogen-containing organic compounds were converted into ammonium nitrogen through a complex high-temperature and chemical decomposition. The resulting ammonia, after alkalization, was absorbed using 50 mL of boric acid. It was then titrated with a 20-mL standard acid solution, and the total nitrogen content in the soil (excluding nitrate nitrogen) was calculated.

The potassium dichromate sulfuric acid method is commonly used to determine organic matter in soil. Under heating conditions, an excess of potassium dichromate sulfuric acid ($K_2Cr_2O_7$-H_2SO_4) solution was used to oxidize the carbon present in soil organic matter. The remaining potassium dichromate ($K_2Cr_2O_7$) was then titrated with a standard iron (II) sulfate ($FeSO_4$) solution. The amount of organic carbon was calculated based on the amount of potassium dichromate consumed. This value was multiplied by the constant 1.724 to obtain the organic matter content in the soil.

Statistical analysis of data

Statistical Package for the Social Sciences 19 software was used for variance analysis and significance testing of the experiment results.

RESULTS AND DISCUSSION

Preparation and properties analysis of microencapsulated soil conditioner

The particle size of the MSC ranged between 20 and 200 μm, as depicted in Fig. 1c. This size range was consistent with the particle size of urea used in actual agricultural production. Additionally, the microcapsules exhibited a spherical shape. The test results of encapsulation efficiency of different MSC are shown in Fig. 2a. The use of a dual-layer membrane material in this product helps to improve the encapsulation efficiency of the water-soluble core, resulting in a significant ratio, 85.02%, compared to single-layer membrane microcapsules and adsorbent microspheres.

The particle size range of the MSC was about 200 μm, which is consistent with the size of urea granules used in agricultural production. The particle size of the microcapsules prepared in the experiment mainly depends on the concentration of liquid paraffin and the cross-linking interaction between the shell material and the $CaCl_2$ solution. The ability of microencapsulated materials to control leaching loss reflects their ability to preserve nutrients for MSC.

Relevant experimental data are presented in Fig. 2b, showing that all four experimental groups effectively improved water resistance compared to the control group. This could be attributed to two reasons. First, the natural polymer of the microcapsule shell has some water absorption ability, allowing it to retain nutrients; second, the relatively dense spatial structure of the microcapsules prevents leaching. The sustained release curves of MSC with different core materials are shown in Fig. 2c, demonstrating good sustained-release behavior.

The sustained-release time was at least 800 h (about 34 days), which covers the growth period of most horticultural crops. The biodegradation curves of MSC are illustrated in Fig. 2d. A significant mass loss occurred in the first 50 h, indicating the degradation of the outer shell of sodium alginate. The initial mass reduction resulted from the degradation of the outer layer, which caused the destruction of the protective structure of the core. This may have led to the loss of core materials along with the degradation of the outer shell. As demonstrated by the data presented in Table 2, the superiority of our work lies in its comparison with analogous products.

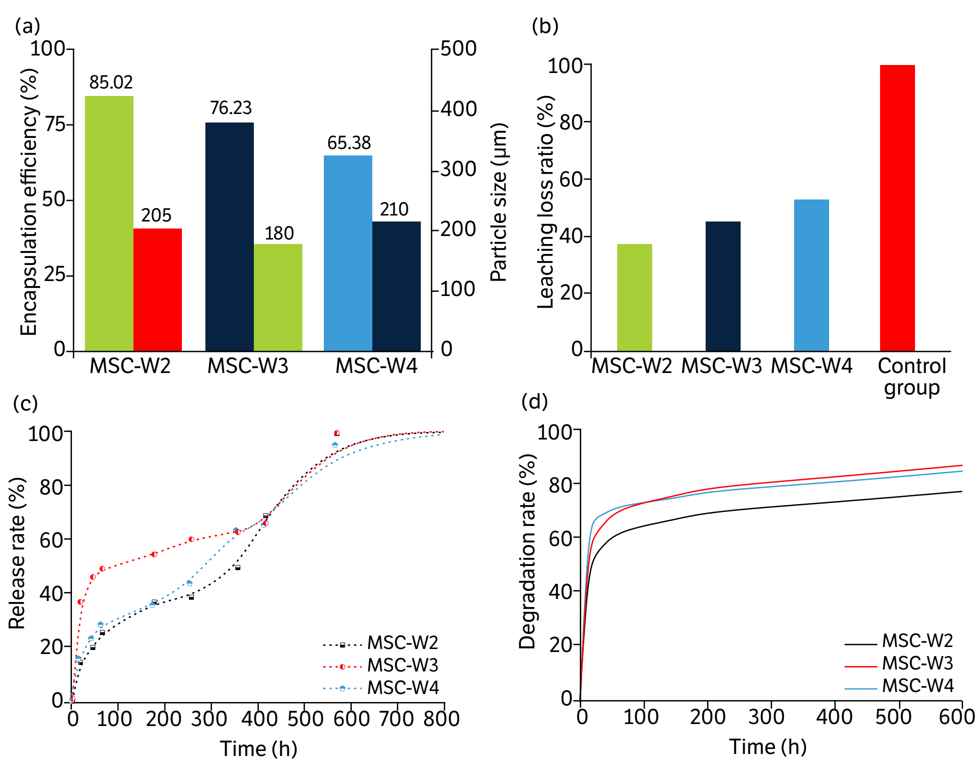


Figure 2. Properties of microencapsulated soil conditioner: (a) encapsulation efficiency, (b) leaching loss ratio, (c) sustained release ratio, (d) biodegradation rate.

Table 2. Comparison with other soil conditioners of urea based on polysaccharides.

Soil conditioners	Encapsulation efficiency (%)	Sustained release ratio (%)	Degradability	References
PZ(Fe)/GL-SA-Urea	37.63	68% within 100 h	degradable	Lu et al. (2023)
GL/CS/MAP-FA	not mentioned	85% within 100 h	degradable	Youzhi et al. (2020)
CS–P(NIPAM-co-MAA)-urea	10.2	80% within 100 h	degradable	Yang et al. (2020)
AG-GL/CQAS/β-CD-FS	15	70–85% within 250 h	not mentioned	Li et al. (2021)
MSC	65–85%	30–40% within 100 h	80%	This work

PZ(Fe)/GL-SA-Urea: pickling zeolite (FeOOH)/gelatin-sodium alginate-urea; GL/CS/MAP-FA: gelatin/chitosan/magnesium ammonium phosphate-fulvic acid; CS–P(NIPAM-co-MAA)-urea: chitosan-poly(N-isopropyl acrylamide-co-methacrylic acid)-urea; AG-GL/CQAS/β-CD-FS: arabic gum–gelatin/chitosan quaternary ammonium salt/β-cyclodextrin-ferrous sulfate; MSC: microencapsulated soil conditioner.

Physiological growth curves

High-throughput plant phenotype technology can track and measure physiological parameters such as plant height and leaf width without causing physical damage (Parent et al. 2015). This technology offers advantages in terms of accuracy, objectivity, and efficiency, and can provide strong support for related research. However, there are not many reports currently available on the use of plant phenotype equipment to study physiological growth performance. In this experiment, plant phenotypic equipment was used to continuously track and measure the growth process of cabbages, as shown in Figs.3a and 3b. These photos were taken from 0 and 90° angles, respectively. In Fig. 3, the plant height and leaf width of cabbages exhibit a significant increasing trend. This provides a relatively objective basis for the relevant data on crop growth performance (Tschiersch et al. 2017).

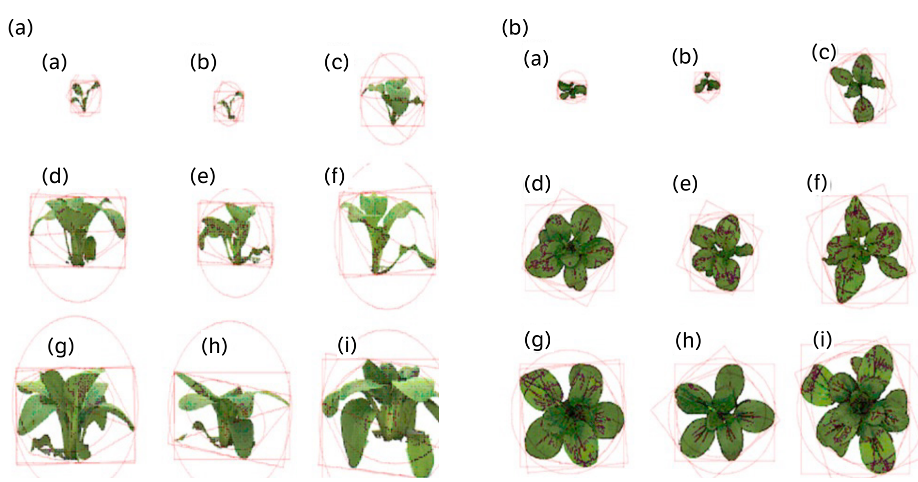


Figure 3. W4H5 growth duration measurement chart: (a) 0° direction, (b) 90° direction (time interval from a to b, b to c, etc. was about one week).

Figure 4 presented the data on leaf width and plant height of the control and experimental groups, which reflected the growth trend of cabbages (Jeon et al. 2018). In Fig. 4a, it can be observed that there was no significant difference in leaf width during the first seven days. This could be because the embryo of the seed itself provided enough nutrients for the initial growth of cabbages, resulting in a plant height of about 6–8 cm (Fig. 4b) (Godlewska et al. 2019).

Comparing the experimental groups with the control group, both the sustained-release fertilizer and traditional fertilizer groups showed better growth trends. After 14 days, it was found that the plant height of the traditional fertilization group (about 14 cm) was better than that of the sustained-release fertilizer group (about 13 cm) and the control group (about 12 cm). However, the leaf width of the sustained-release fertilizer group (about 25–27 cm) was better than that of the traditional fertilizer group (about 25 cm) and the control group (about 23 cm). Under conditions of insufficient seed nutrition, the nitrogen content in the fertilizer directly affected the physiological growth performance of cabbages. From days 15 to 25, it was observed that the cabbages in the sustained-release fertilizer group continued to grow rapidly, with the leaf width increasing from about 27–30 cm to 37–44 cm. In contrast, the traditional fertilizer group grew from 25 to 31 cm, while the control group grew from 24 to 31 cm.

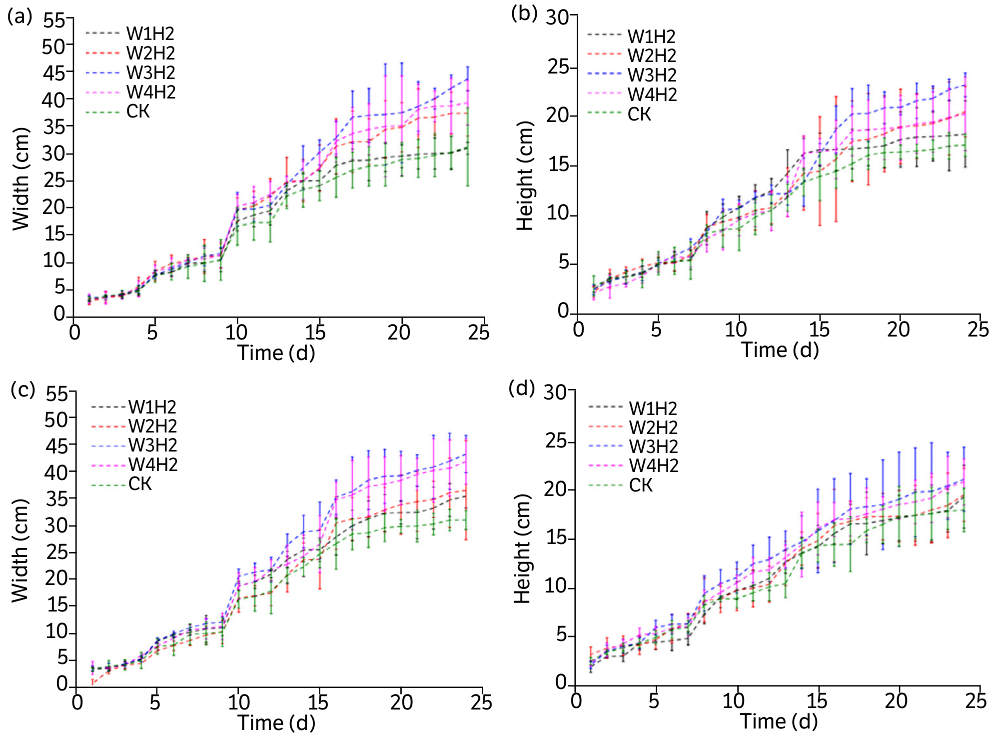


Figure 4. Continuous growth curves of cabbages: (a) leaf width of plant treated with fertilizer buried at 2 cm; (b) height of plant treated with fertilizer buried 2 cm; (c) leaf width of plant treated with fertilizer buried at 5 cm; (d) height of plant treated with fertilizer buried 5 cm.

These results demonstrate that the sustained-release fertilizer provided continuous fertility for cabbage growth compared to traditional fertilization. The use of FA promotes root growth and protects soil microorganisms involved in the decomposition of nitrogen fertilizer, thus prolonging the presence of nitrogen in the soil. Calcium ions activate the cell walls of plant roots, enhancing their ability to absorb nutrients and water.

As a result, the final growth trend showed that W3Hn was greater than W4Hn, and W4Hn was greater than W2Hn, as well as the traditional group and the control group (Cordeiro et al. 2018). These findings indicate that, with the same urea concentration, the effect of sustained-release microcapsules was beneficial for cabbage growth, while the presence of FA and calcium ions improved the utilization rate of urea. Comparing Figs. 4a and 4c and 4b and 4d, it can be observed that the growth of cabbages buried at 2-cm depth was better than those buried at 5-cm depth. This may be attributed to the shallower root system and better lateral root development, which limited the ability to absorb nutrients from deeper layers. The analysis of variance for experimental data was presented in Table 3.

Table 3. Significance analysis of leaf width and plant height of fertilizer treatment buried at 2 and 5 cm.

Samples	Leaf width (2 cm)	Plant height (2 cm)	Leaf width (5 cm)	Plant height (5 cm)
W1	0.022	0.087	0.017	0.004
W2	0.001	0.017	0.022	0.016
W3	0.061	0.031	0.025	0.039
W4	0.005	0.020	0.027	0.073
Blank control group	0.047	0.011	0.073	0.028

Most of the significance values were less than 0.05, indicating that the experimental data were representative. Moreover, some individual data points had significance values even lower than 0.01, suggesting an extremely significant effect. Therefore, the use of sustained-release fertilizer and a shallower planting depth is advantageous for cabbage growth.

Nitrogen content of plant leaves and photosynthesis

The NBI is a key indicator of cabbage growth, representing the ratio of chlorophyll to flavonoid (Agati et al. 2016, Mattila et al. 2018, Sahin et al. 2018). Flavonoids possess antioxidant properties and can scavenge active hydrogen, while chlorophyll is crucial for photosynthesis. Initially, NBI values were similar as the cabbage growth relied on nutrient reserves within the embryo and was independent of external fertilization. NBI was associated with the germination cycle of plants (Fig. 5).

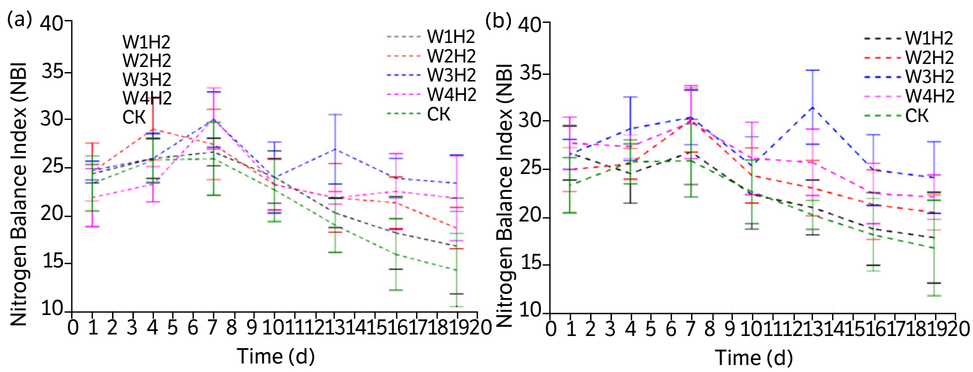


Figure 5. Nitrogen balance index curves of leaves during the growth of cabbages: (a) nitrogen balance index curves of fertilizer buried at 2 cm during growth; (b) nitrogen balance index curves of fertilizer buried at 5 cm during growth.

On the fourth day, NBI values reached their peak for all cabbages due to fewer leaves and an abundant nutrient supply in the plant. From the fourth to the seventh day, cabbage growth was promoted, leading to increased chlorophyll content in the leaves due to external nitrogen supply. During the growth process from the seventh to the 20th day, the NBI of the sustained-release fertilizer group exceeded that of the traditional fertilizer and control groups. The NBI of the traditional fertilizer and control groups exhibited a continuous decline, whereas the sustained-release fertilizer group maintained a higher NBI with occasional fluctuations.

The analysis of variance for experimental data is presented in Table 4. For the NBI values of fertilizer buried at 2 and 5 cm, W1H2, W2H2, and W2H5 demonstrated the lowest significance with $p = 0.004$ ($p < 0.01$), which was significantly below the specified confidence level of 0.05. This indicated a significant correlation between the composition of W1 and W2 and the absorption and utilization of fertilizer. The NBI of the sustained-release fertilizer group consistently surpassed that of the traditional fertilizer and control groups, highlighting its superior ability to provide nitrogen fertilizer compared to traditional fertilization methods. Traditional fertilization only supplied nutrients for a short period of time and lacked sustainable fertilization capabilities, while sustained-release fertilizer continuously met the nitrogen fertilizer requirements throughout the cabbage growth process.

Table 4. Nitrogen balance index (NBI) significance data of fertilizers buried at 2 and 5 cm.

Samples	NBI (2 cm)	NBI (5 cm)
W1	0.004	0.016
W2	0.003	0.002
W3	0.031	0.031
W4	0.064	0.022
Blank control group	0.048	0.058

The net photosynthetic rate serves as a direct indicator of the conversion of CO_2 to sugar and can effectively reflect cabbage production and growth capacity, which is closely related to the chlorophyll content in cabbage leaves (Fig. 6a). The results demonstrated that the net photosynthetic rate of the sustained-release fertilizer group was significantly higher than that of the traditional fertilizer group. Furthermore, it should be noted that the nitrogen content directly influences the chlorophyll content in the leaves (Gutierrez-Gamboa et al. 2018, Roca et al. 2018, Sunlin et al. 2018, Xiang et al. 2024, Borsuk and Brodersen 2019).

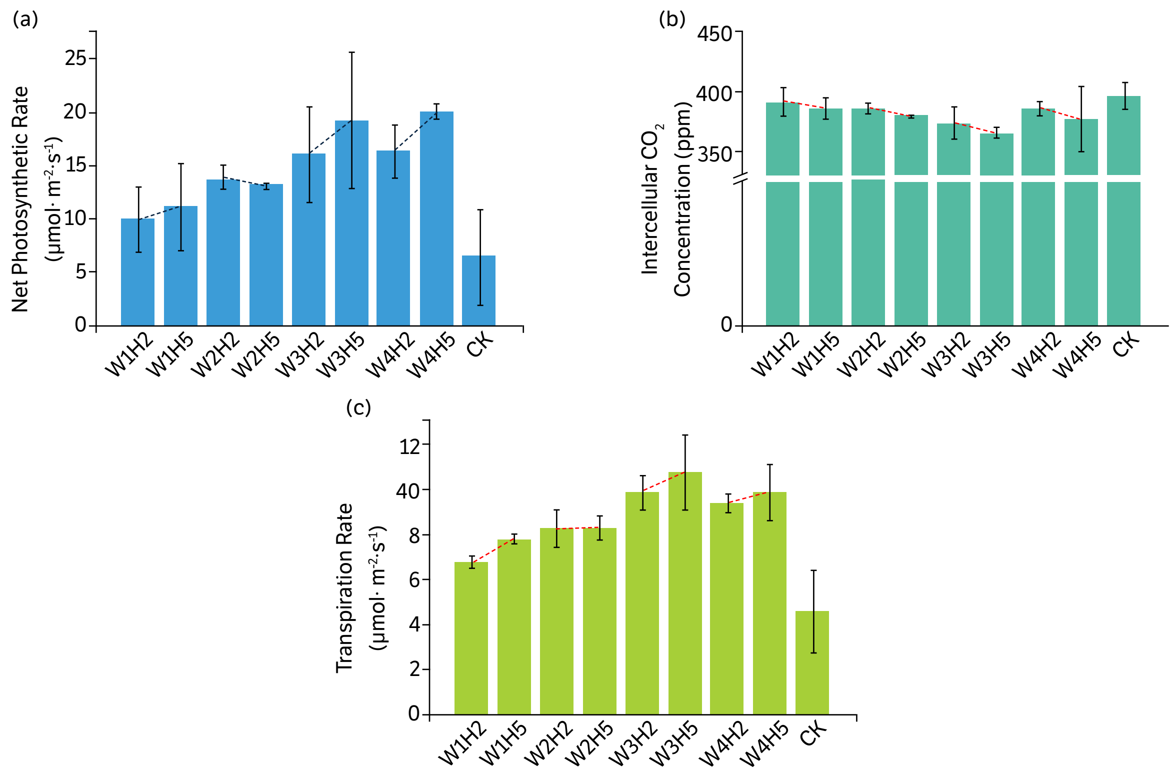


Figure 6. Activity characterization during the growth period of cabbages: (a) net photosynthetic rate of crops; (b) intercellular CO_2 concentration; (c) transpiration rate.

The analysis of variance for the experimental data was presented in Table 4. For the net photosynthetic rate of fertilizer buried at 2 and 5 cm, W3H2, W2H5, and W3H5 exhibited the lowest significance with $p < 0.01$, well below the specified confidence level of 0.05. This indicated that the sustained-release fertilizer possessed the ability to continuously supply nitrogen, which in turn may provide sufficient chlorophyll content in the cabbage leaves, thereby promoting cabbage growth and development.

The intercellular carbon dioxide concentration in the morning or noon can serve as indirect evidence to assess crop photosynthesis (Fig. 6b) (Fujiyama et al. 2019). Under the same light and carbon dioxide concentration, a higher intercellular carbon dioxide concentration corresponds to lower carbon dioxide consumption for photosynthesis. Thus, there is a negative correlation between the intercellular carbon dioxide concentration and the photosynthesis rate (Shen et al. 2019). The analysis of variance for the experimental data is presented in Table 5. For the intercellular CO_2 concentration of fertilizer buried at 2 and 5 cm, W1H2 and W1H5 exhibited the lowest significance, with $p < 0.01$, significantly below the specified confidence level of 0.05. Additionally, both the cured groups and CK group showed lower significance, with $p < 0.05$, indicating no notable difference between CK and the modified groups.

The transpiration rate of crops serves as the driving force for crop water absorption (Fig. 6c) (Wang et al. 2019). Since water is the primary raw material used by cabbage for photosynthesis and nutrient preparation, the transpiration of crops becomes a crucial indicator of cabbage growth (Li et al. 2018). The transpiration rate of the sustained-release fertilizer group was found to be higher than that of the traditional fertilizer group, aligning with the aforementioned trend in photosynthesis rate. The analysis of variance for the experimental data is presented in Table 4. For the transpiration rate of fertilizer buried at 2 and 5 cm, W1H2, W1H5, and W2H5 exhibited the lowest significance with $p < 0.01$, significantly lower than the specified confidence level of 0.05. This indicated that fertilizer groups such as W1 and W2 demonstrated a better fitting relationship with the physiological growth performance compared to the control group.

Table 5. Significance data on net photosynthetic rate, intercellular CO_2 concentration, and transpiration rate.

Samples	Net photosynthetic rate (2 cm)	Net photosyntheticrate (5 cm)	Intercellular CO_2 concentration (2 cm)	Intercellular CO_2 concentration (5 cm)	Transpiration Rate (2 cm)	Transpiration rate (5 cm)
W1	0.046	0.029	0.009	0.010	0.009	0.007
W2	0.032	0.000	0.038	0.075	0.045	0.008
W3	0.004	0.004	0.036	0.017	0.025	0.068
W4	0.015	0.036	0.012	0.050	0.011	0.026
Blank control group	0.032	0.032	0.017	0.017	0.045	0.045

Root analysis and yield of cabbages

Root analysis serves as a crucial means of assessing soil nutrient and water absorption, which in turn reflects the growth trend (Mazur et al. 2014, Zhou et al. 2017, Zhao et al. 2019). By comparing the total length, total surface area, and average root diameter depicted in Fig.7, the roots of the experimental group treated with sustained-release fertilizer exhibited more robust development, providing evidence for its superior physiological performance.

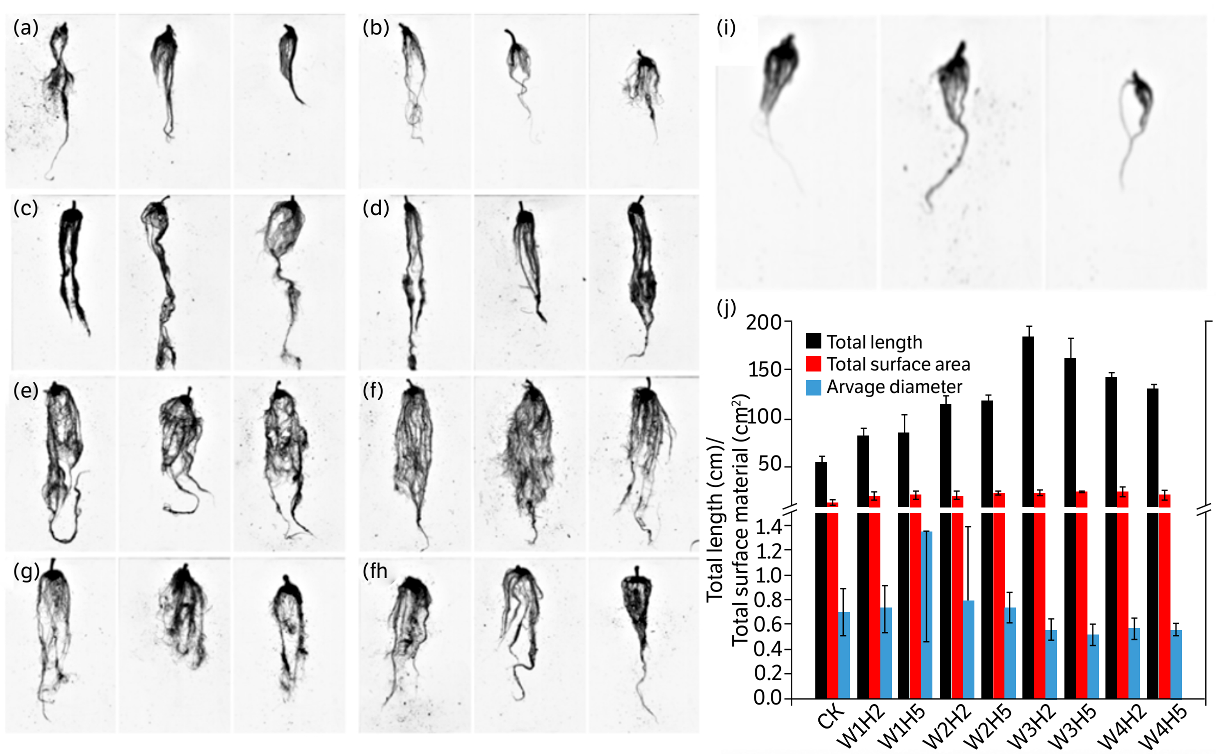


Figure 7. Infrared scanning images of cabbages' root: (a)W1H2; (b) W1H5; (c) W2H2; (d) W2H5; (e) W3H2; (f) W3H5; (g) W4H2; (h) W4H5; (i) CK; (j) distribution of root length, total surface area and average diameter.

Table 6 presents the analysis of variance for the experimental data. For the distribution of root length in fertilizer buried at 2 and 5 cm, W4H5 exhibited the lowest significance with $p < 0.01$, which was below the confidence level of 0.05. This indicated that the sustained-release fertilizer group W4 had a closer relationship to the traditional fertilizer and control groups. For the total surface area in fertilizer buried at 2 and 5 cm, W2H5 demonstrated the lowest significance with $p < 0.01$, indicating that the sustained-release fertilizer group W2 exerted a better promoting effect on growth performance. Lastly, for average diameter in fertilizer buried at 2 and 5 cm, W1H2 and W4H5 exhibited the lowest significance with $p < 0.01$, significantly lower than the specified confidence level of 0.05. This demonstrates that the fertilizer groups W1 and W2 have a close-fitting relationship with growth performance compared to the control group.

Table 6. Significance data for root length, total surface area, and mean distribution.

Samples	Root length (2 cm)	Root length (5 cm)	Total surface area (2 cm)	Total surface area (5 cm)	Mean distribution (2 cm)	Mean distribution (5 cm)
W1	0.042	0.023	0.046	0.051	0.005	0.043
W2	0.032	0.055	0.046	0.008	0.022	0.027
W3	0.014	0.054	0.045	0.021	0.016	0.054
W4	0.045	0.003	0.013	0.033	0.031	0.003
Blank control group	0.042	0.042	0.035	0.035	0.014	0.014

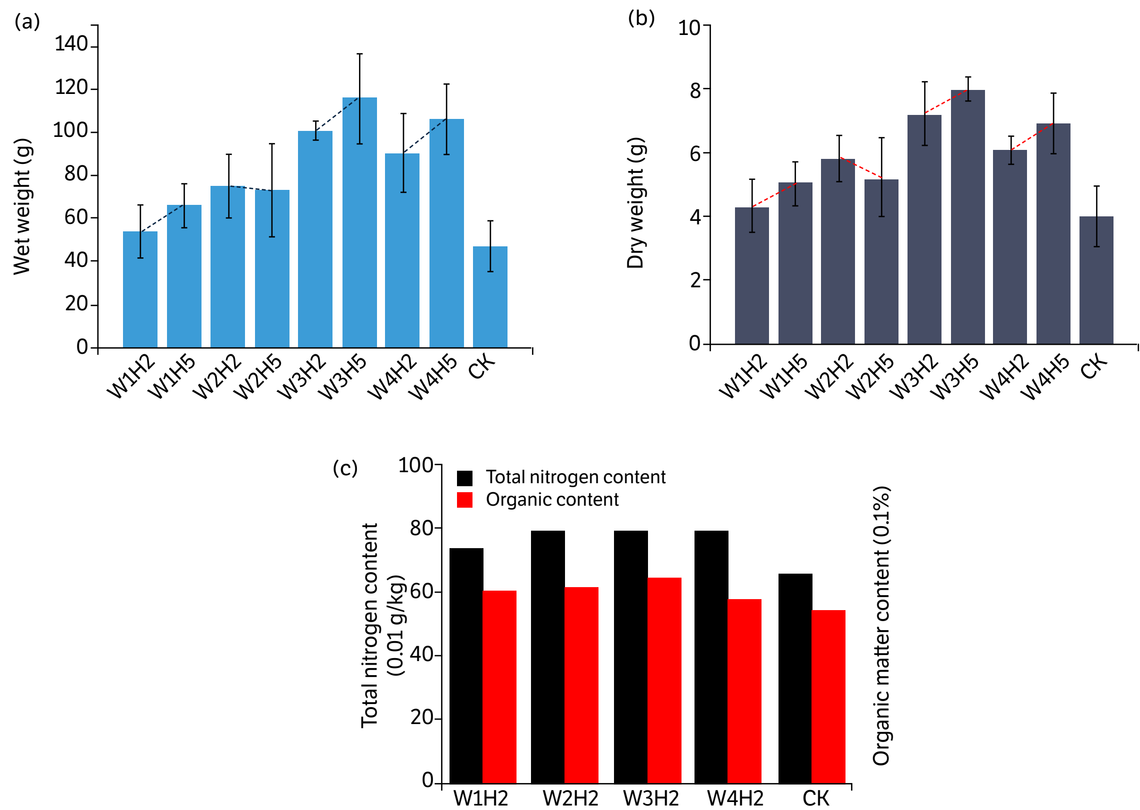
By examining the order of total root length: W3H2 (182.7 cm) > W3H5 (162.5 cm) > W4H2 (142.2 cm) > W4H5 (130.5 cm) > W2H5 (118.2 cm) > W2H2 (115.7 cm) > W1H5 (87.0 cm) > W1H2 (82.7 cm) > CK (55.6 cm), traditional fertilization had a promoting effect on root growth, as reflected by an increase in root length by 31.4 (W1H5) and 27.1 cm (W1H2), respectively. Additionally, compared to CK, the application of sustained-release fertilizer resulted in increased total root length ranging from 60.1 (W2H2) to 127.1 cm (W3H2), indicating a more pronounced effect on root development. Similarly, the trend observed for total surface area follows that of root length, suggesting that sustained-release fertilizer may effectively enhance the physiological growth performance of cabbage plants.

These results highlight the promising practical application prospects of this novel soil conditioner.

Figure 8 presented the wet (Fig. 8a) and dry (Fig. 8b) weight of mature cabbages after picking and drying. The cabbage yielded in the nitrogen fertilizer-treated group was significantly higher than that in the control group, highlighting the crucial role of nitrogen fertilizer in cabbage yield. Moreover, compared to the traditional fertilization group, the sustained-release fertilizer group demonstrated a higher yield. For instance, when the fertilizer was applied at 5 cm, the yield order for each group was W3H5 (8.01 g) > W4H5 (6.90 g) > W2H5 (5.18 g) > W1H5 (5.07 g) > CK (4.01 g).

Table 6 presents the analysis of variance for the experimental data. For the wet weight of fertilizer buried at 2 and 5 cm, W1H2 and W3H2 exhibited the lowest significance. This confirmed an extremely significant correlation between the independent variable (composition of W1 and W3, buried place 2 cm) and the dependent variable (wet weight). Similarly, for the dry weight of fertilizer buried at 2 and 5 cm, W1H2 and W3H5 showed the lowest significance. This illustrated the substantial impact of the composition and formulation of W1 and W3 on the dry weight, confirming the greater usefulness of the fertilizer groups compared to the CK group.

The total nitrogen content and organic content of the soil were measured and analyzed after cabbage planting (Fig. 8c). It was observed that the soil in the fertilizer-treated groups contained significantly higher nitrogen content compared to the control group, which had a nitrogen content of 0.65 g/kg. The order of nitrogen content in the other groups was W3H2 (0.786 g/kg) > W2H2 (0.781 g/kg) > W4H2 (0.735 g/kg) > W1H2 (0.719 g/kg). This indicates that the use of nitrogen fertilizer greatly enhances the nitrogen content in the soil, leading to improved crop yield and related physiological growth performance. Similarly, the analysis of organic matter (Table 7) revealed that the order of organic matter content was W3H2 > W2H2 > W1H2 > W4H2 > CK. This can be attributed primarily to the degradation of MSC capsules, which contribute to the organic matter to the soil and enhance crop yield.



CK: blank control group.
Figure 8. Yield of mature cabbages: (a) wet weight; (b) dry weight; (c) total nitrogen content and organic matter content in soil.

Table 7. Significance data on wet and dry weight.

Samples	Wet weight (2 cm)	Wet weight (5 cm)	Dry weight (2 cm)	Dry weight (5 cm)
W1	0.001	0.014	0.004	0.054
W2	0.049	0.015	0.038	0.044
W3	0.008	0.093	0.040	0.002
W4	0.040	0.018	0.013	0.016
Blank control group	0.008	0.008	0.047	0.047

CONCLUSION

In this study, we successfully prepared a large quantity of MSC using the sharp-hole coagulation bath method. MSC is a type of sustained-release fertilizer that was applied in a planting experiment with cabbages. The growth performance, NBI index, photosynthesis, root status, and yield of the cabbages were tested and evaluated. Physiological growth curves showed an increasing trend in leaf width and height of the cabbages. Additionally, the NBI of the group treated with the sustained-release fertilizer was higher compared to the traditional fertilization and control groups. The net photosynthetic rate demonstrated that MSC continuously supplied nitrogen and maintained sufficient chlorophyll content in the cabbage leaves.

Furthermore, comparing the total length, surface area, average root diameter, and dry weight of roots, it was observed that the roots of the experimental groups treated with MSC were more developed, indicating better physiological performance. These results indicate that MSC, as a sustained-release nitrogen fertilizer, provides more effective fertilization compared to traditional methods. Moreover, this novel soil conditioner has the potential to significantly improve crop yield and can be considered a promising sustained-release fertilizer.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Conceptualization: Lu, W. and Wang, Z.; **Methodology:** Lu, W. and Wang, C.; **Investigation:** Wang, C. and Sun, J.; **Writing – Original Draft:** Lu, W. and He, T.; **Writing – Review and Editing:** Wang, J. and He, T.; **Funding Acquisition:** Lu, W. and Wang, C.; **Supervision:** Sun, J.

DATA AVAILABILITY STATEMENT

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

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Not applicable.

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