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Slow-release fertilisers increased microflora and nitrogen use efficiency and thus promoted peanut growth and yield

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Abstract: The effects of large granular slow-controlled release fertiliser prepared by a double coating of sulfur and sodium alginate on peanut growth, nitrogen fertiliser utilisation, and soil microbial community were investigated through peanut pot experiments, with a view to providing a theoretical and practical basis for the development of large granular slow-controlled release fertiliser. The results showed that the homemade large granular fertiliser could promote the root development of peanuts, and the root volume increased by 45.10% compared with the uncoated fertiliser at the fruiting stage. At the same time, the soil NH_4^+-N and NO_3^--N content were reduced at the seedling stage and increased at the fruiting stage to achieve the fertiliser's slow and controlled release effect. A significant contribution to the net photosynthetic rate was made for growth development and yield in the middle and late stages. Pod dry weight was significantly higher at the blooming stage than uncoated fertiliser, 4.8% higher at the fruiting stage, and 22.9% higher in nitrogen use efficiency (NUE). In terms of microbial bacterial communities, the large granular slow-release fertiliser promoted the diversity of the treated bacterial communities to some extent, with little difference in the relative abundance of soil bacterial communities. These results showed that a one-time application of homemade large granular slow-release fertiliser positively affected peanuts in terms of yield increase, promotion of nitrogen uptake and improved nitrogen utilisation under nitrogen application with urea equivalent, but the overall effect on soil microbial community was small.

Keywords: photosynthetic characteristics; root morphology; nitrogen content; microbial relative abundance; oil crop

Peanut is an important economic oil crop, with China is one of the world's largest peanut producers (Zhang et al. 2019). Although the peanut planting area is not as much as rape, its total production accounts for 50% of oil crops. In addition, peanut yields, total production and exports have always ranked first in the country's oilseed crops (Wan et al. 2005, Wan 2009, Dong et al. 2012, Zhang et al. 2016, Liu et al. 2017), with a national peanut planting area of 4 730 000 ha in 2020, with a yield of 3.8 t/ha and a total production of 17 992 700 t. In recent years, peanut yields have been increasing, and this is mainly due to the application of mineral fertilisers. Nitrogen (N) is the main nutrient necessary for plant growth, and

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traditionally, it is believed that 70–80% of the N required for peanut growth is provided through N fixation by peanut root nodules. However, recent studies have shown that fixation of atmospheric N_2 by peanut rhizomes can only provide 40–50% of the N required for peanut growth, suggesting that more than half of the N required by peanut must be taken from soil and fertiliser (Chen et al. 2015). Jiang et al. (2020) found that the yield of peanuts treated with 75 kg/ha N fertiliser was significantly higher compared with no N fertiliser, and N application significantly impacted peanut production. Wen et al. (2001) found that 120 kg/ha mulch N fertiliser obtained the highest N recovery compared to equal amounts of common fertiliser on sandy soil in Japan, but different applications of N fertiliser at different times are poorly known.

The world population continues to grow, so searching for new methods to improve crop yield and quality through sustainable agriculture has become one of agriculture's major challenges. In the past decades, conventional peanut fertilisation has mainly been divided into 3–4 applications, including basal and follow-up fertilisers, a demanding, time-consuming, and labour-intensive method. This method may result in nutrient losses, which can lead to several environmental problems, such as eutrophication and the greenhouse effect (Zhang et al. 2012). The N requirement of peanuts is mainly concentrated in the podding stage, and less N is required in the seedling stage. While the N release rate provided by fertiliser is fast, it can easily cause N deficiency and poor pod development in the later stage. The emergence of slow-release fertilisers provides a new option for efficient fertilisation of peanuts. Compared with urea, slow-release N fertiliser is a new mineral fertiliser with a longer fertiliser release period and less susceptible to nutrient loss, which can be absorbed and degraded by microorganisms when applied to the soil, increasing the effectiveness of nutrients and making the release of soil nutrients at the same pace as plant demand and less likely to cause harm to the soil environment (Jia et al. 2021). Previous studies have found that the application of slow-release N fertiliser can delay the release of N fertiliser, improve soil water holding capacity, nitrification and N adsorption, increase crop N recovery, and also reduce N_2O and CH_4 emissions, ammonia volatilisation and N leaching losses, and the application of slow-release N fertiliser has become a new trend to save fertiliser consumption and is an environmentally friendly method of N fertiliser application (Wang et al. 2015, Yang et al. 2016). Studies conducted by Sun et al. (2023) proved that using the slow-release mixed fertiliser improved the grain number and yield of corn, which increased by 12.6–20.0%. Wang et al. (2023) applied the new fertiliser to the rice, and the results showed that the rice yield of the new fertiliser increased by 7.51% to 11.59% compared with that of the local rice formula fertiliser, respectively, using two different slow-release fertilisers compared to urea application. However, the poor slow-release effect of natural substances has led to the fact that most slow-release fertilisers are manufactured from plastic polymers, which are virtually non-degradable and expensive to produce (Naz and Sulaiman 2016).

In this experiment, two natural materials, sulfur and sodium alginate, were used to prepare large particle double-coated slow-release fertilisers, and the release characteristics were studied. Pot experiments were carried out on peanuts under the condition of equal N with urea to investigate their effects on peanut growth and N utilisation and soil microbial community, to provide further theoretical and practical basis for the development of large particle slow-release fertilisers.

MATERIAL AND METHODS

Experimental design

The experiment was conducted in the greenhouse of Shandong Peanut Research Institute (36°48'N, 120°29'E) on June 24, 2022, with the following basic soil physical and chemical properties: organic carbon was 9.7 g/kg, total N 0.9 g/kg, available phosphorus 96.7 mg/kg, available potassium 79.0 mg/kg, pH 5.9. Two peanut seeds were planted in each plastic pot with 3 kg of soil, and one seed was left after germination. The trial was divided into control (T0), evaluation of N fertilisation (T1), and recommended N fertilisation (T2), with three replications in each group. The trial period was about 4 months. T0 treatment with no fertiliser; T1 was common commercially available urea (120 mg N per pot), and T2 was homemade large granular slow-release fertiliser (LSRF) with the structure of 2/3 urea inner core wrapped with sulfur-coated urea, the other 1/3 urea and bentonite and modified starch as the pre-nutrient layer, and the outermost layer wrapped with sodium alginate slow-release layer with larger granules and 120 mg

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of N per grain, and a uniform fertiliser with a particle size of about 0.6–0.8 cm. The total N content of both T1 and T2 treatment was 120 mg per pot. In the T1 treatment, peanut seeds and commercially available urea were applied in a plastic pot. In the T2 treatment, the fertilisation method was that peanut seeds were applied together with a large-particle slow-release fertiliser in a plastic pot. After sowing, water management was carried out according to plant growth and soil moisture content.

Determination methods

Peanut agronomic traits. The effects of different treatments on peanut agronomic traits were measured at 1, 2, and 4 months after application, respectively. Growth parameters included plant height, relative value of chlorophyll content (SPAD) value of leaves, photosynthetic characteristics and plant dry weight. Functional leaves (inverted trifoliate leaves) facing the sun were selected from each plant, and leaf greenness was measured in triplicate from 9:00 to 11:00 a.m. using a SPAD chlorophyll meter (chlorophyll meter model SPAD-502, Konica Minolta, Japan). Similarly, the CIRAS-3 portable photosynthetic system (Amesbury, USA) was used to determine photosynthetic characteristics, including stomatal conductance, net photosynthetic rate, transpiration rate, and intercellular CO_2 concentration under ambient CO_2. The aboveground plant parts, roots and pods were also dried to constant weight in an oven at 80 °C and weighed to obtain the dry weight of each part.

Root morphological indexes. Root morphology was scanned by a scanner and analysed using the WinRHIZO root analysis system, including total root length, root surface area, root volume, and root tip number.

Total N content in plants and soils. Plant samples were dried in an oven at 70 °C to determine total N using the Kjeldahl method and to calculate N use efficiency. The soil samples were mixed well and stored at 4 °C after sieving, and soil available N content (NH_4^+-N and NO_3^--N) was extracted with 1 mol/L KCl and analysed using a flow injection analyser.

The formula for the nitrogen use efficiency (NUE) of peanuts is as follows:

$$\text{NUE (\%)} = \frac{\text{(N uptake of crops in N application area)} - \text{(N uptake of crops in control area)}}{\text{(nitrogen application rate)}}$$

Soil bacterial community determination. Total soil DNA was extracted using a DNA extraction kit, and PCR amplification was performed using bacterial 16S rRNA region primers F: ACTCCTACGGGAGGCAGCA and R: GGACTACHVGGGTWTCTAAT for target gene amplification. The PCR-amplified products were purified, and the purified samples were sent to the Illumina NovaSeq sequencing platform of Beijing Biomarker Biotechnology Co. By splicing and filtering the reads, clustering or denoising, and performing species annotation and abundance analysis, the species composition of the samples can be revealed; furthermore, alpha diversity, significant species difference, correlation analysis and functional prediction analysis can be performed for statistical analysis of the bacterial community structure.

Data analysis

SPSS 22.0 data statistical software (IBM Co., Armonk, USA) was used for analysis. Duncan's method was used to discriminate statistically significant differences between treatments ($P < 0.05$). Plotting was performed using Origin 8.5. For microbiology, the community composition of peanut inter-rhizosphere soils was analysed for species abundance at the genus level and alpha diversity by Shannon's index.

RESULTS

Fertiliser appearance and release rate. Using hydrostatic incubation at 25 °C, Figure 1 showed the nutrient release of LSRF; it can be seen that LSRF showed good slow and controlled release; its N release rate was 61% at 28 days and reached more than 80% at 42 days, which met the requirements of slow and controlled release fertiliser. This was mainly due to its double-layer envelope structure; although the membranes were all-natural substances, the double-layer structure made it control the slow dissolution of urea and had a more excellent performance in nutrient control and released with a view to having a positive effect on plant production.

Effect on photosynthesis of peanut. The effects on the photosynthetic parameters of peanuts are shown in Figure 2, and overall, it seems that the values of the indices are higher at the blooming stage. Specifically, in terms of net photosynthetic rate (Figure 2A), a representative parameter of photosynthesis, differences between treatments started to appear at the blooming stage and persisted until fruiting. The

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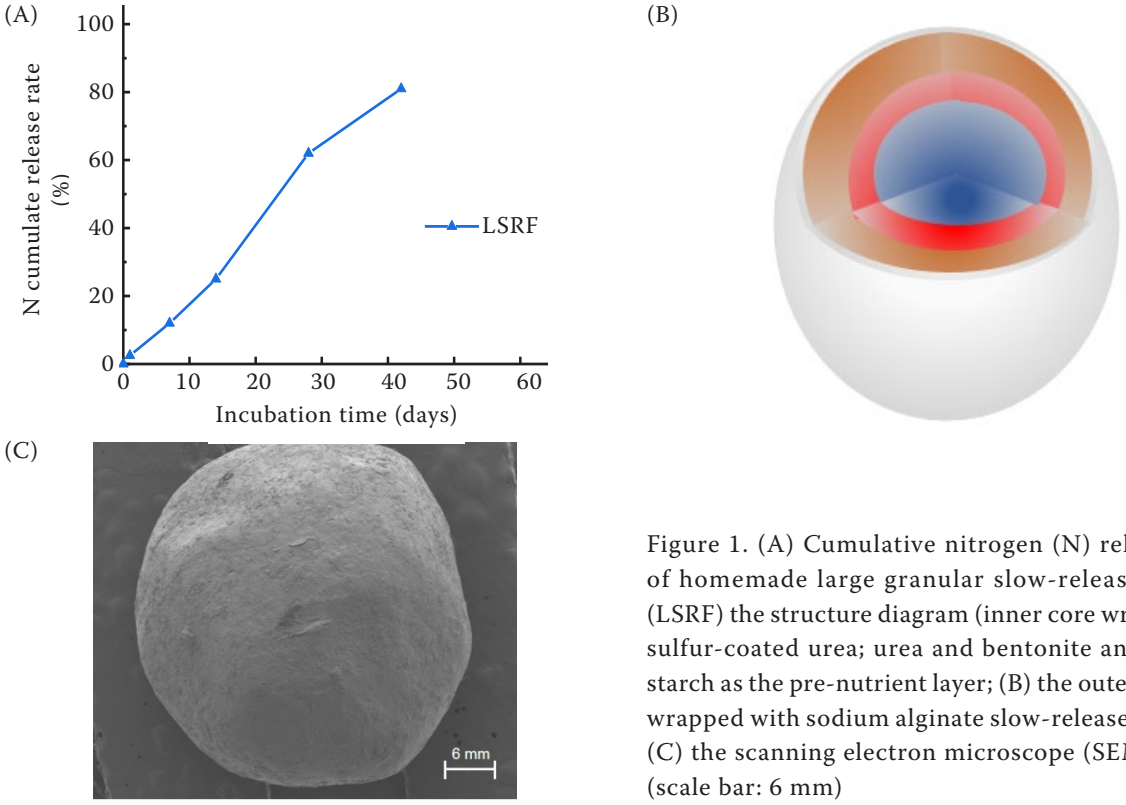

Figure 1. (A) Cumulative nitrogen (N) release curve of homemade large granular slow-release fertiliser (LSRF) the structure diagram (inner core wrapped with sulfur-coated urea; urea and bentonite and modified starch as the pre-nutrient layer; (B) the outermost layer wrapped with sodium alginate slow-release layer), and (C) the scanning electron microscope (SEM) of LSRF (scale bar: 6 mm)

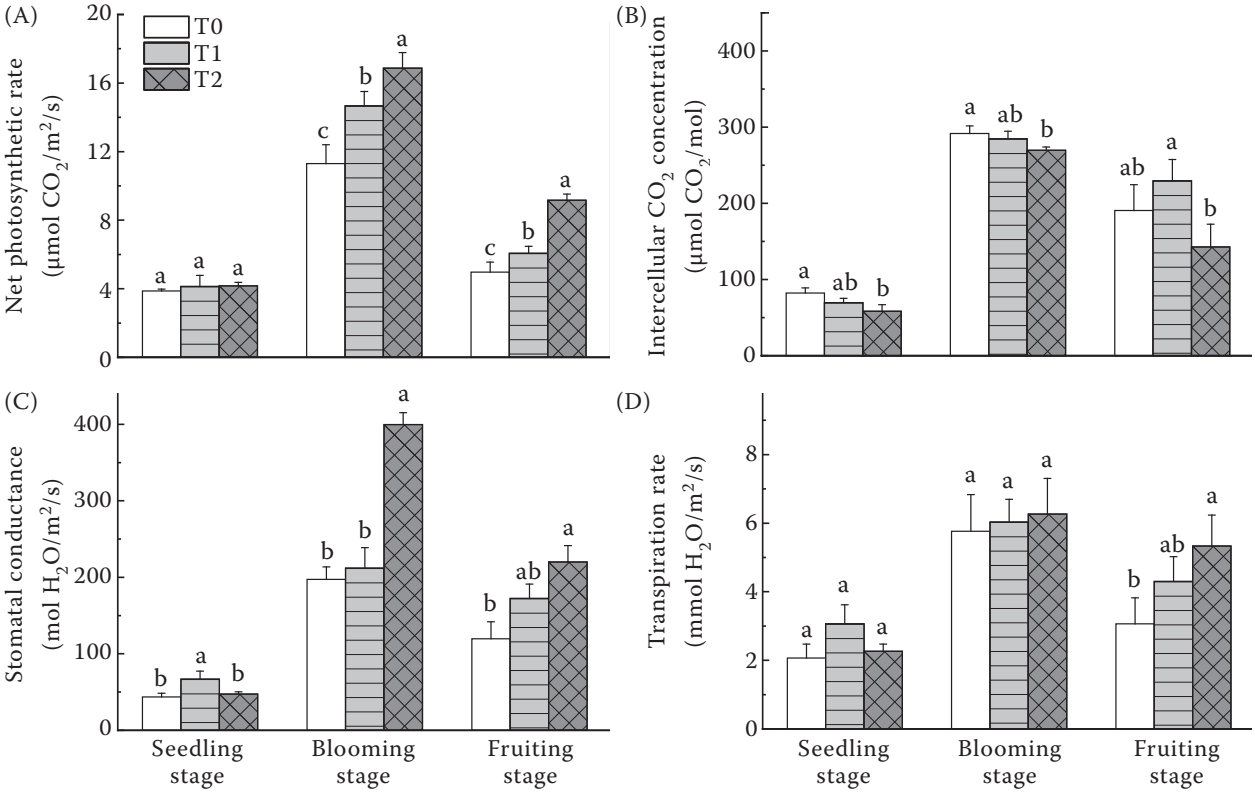

Figure 2. Effects of different treatments on (A) net photosynthetic rate; (B) intercellular CO_2 concentration; (C) stomatal conductance, and (D) transpiration rate at different periods. T0 – no fertiliser; T1 – common urea; T2 – homemade large granular slow-release fertiliser. Different letters above the bars indicate a significant difference at $P < 0.05$ level

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best results were obtained for T2, with 15.00% and 51.1% increase in pod and fruit set, respectively, compared to T1. In terms of stomatal conductance (Figure 2C), T2 was highly effective at the blooming stage, with 102.5% and 89.5% higher than T0 and T1, respectively, and there were differences between T1 and T2 and T0 in fruiting. The transpiration rate (Figure 2D) only differed between T1 and the other treatments at the seedling stage, but there were no differences among the treatments at the later stage, and the overall effect was small. The differences in intercellular CO_2 concentration (Figure 2B) between treatments were also small, and only at the fruiting stage were differences between treatments, with T2 showing the lowest value. As can be seen in the accompanying figure, leaf greenness content differed among treatments at the seedling stage, and T2 showed an advantage at the fruiting stage, differing from the other two treatments.

Effect on root morphology of peanut. The results of the morphological measurements of the peanut root system are shown in Figure 3. The effects of the different treatments differed in four aspects: root length, root surface area, root volume and root tip number, and overall, the results of T2 were superior in all indicators. There were no significant differences among treatments at the seedling stage. The differences in root length (Figure 3A) began to appear between treatments at the blooming stage and were consistent with those in fruiting. T2 had the best effect, differing from T1 and significantly different from the control; in fruiting, root length reached 3 872 cm, 23.5% and 7.4% higher than T0 and T1, respectively. Differences in root volume (Figure 3C) between treatments were expressed in fruiting. At this time, there was no difference between T1 and T0, and there was a significant promotion effect in T2, where root volume reached 9.5 cm^3, which was 45.10% higher than T1. Regarding root area (Figure 3B) and root tip number (Figure 3D), the differences between treatments were insignificant and did not show statistical differences.

Effects on growth characteristics and dry species of peanut. As shown in Figure 4, the different treatments had different effects on plant height and dry matter weight of peanut at each period. First, the plant height (Figure 4A) of T1 and T2 with fertiliser treatment was significantly different from T0 at the

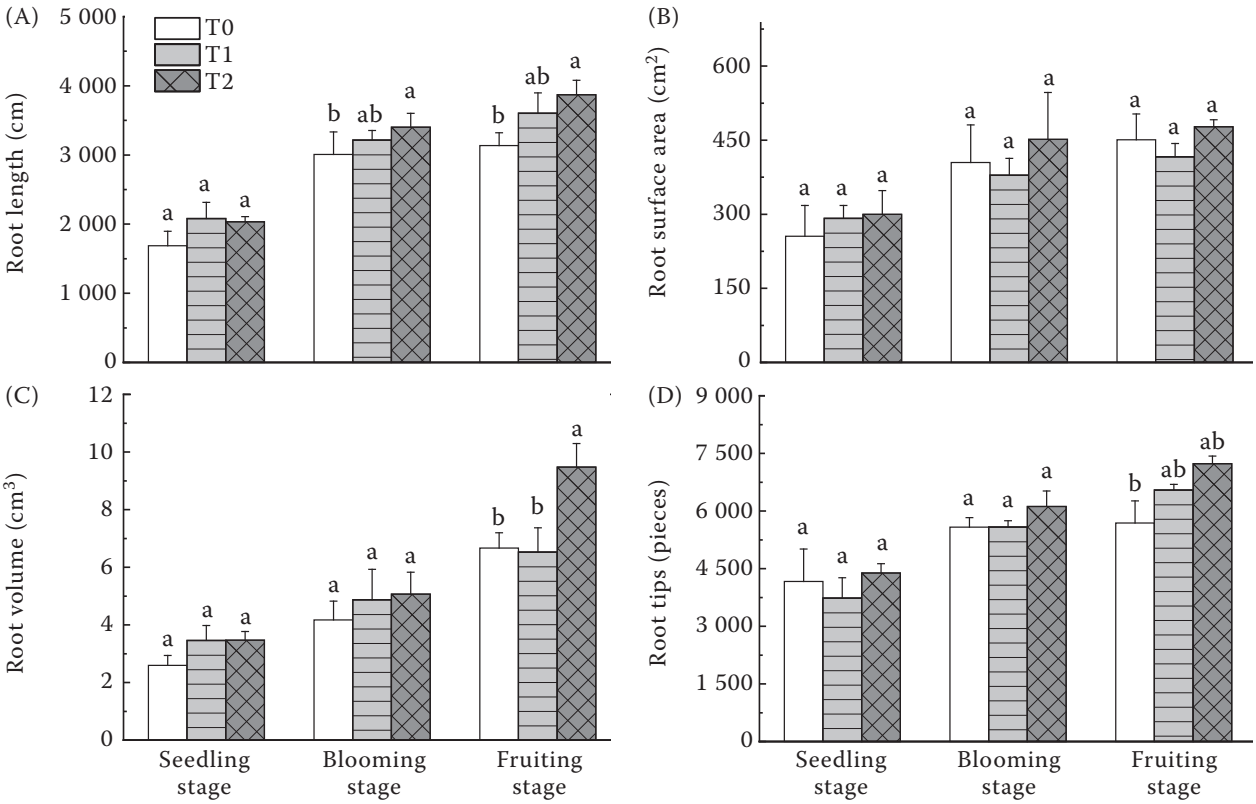

Figure 3. Effects of different treatments on (A) peanut root length; (B) root surface area; (C) root volume, and (D) root tips at different periods. T0 – no fertiliser; T1 – common urea; T2 – homemade large granular slow-release fertiliser. Different letters above the bars indicate a significant difference at $P < 0.05$ level

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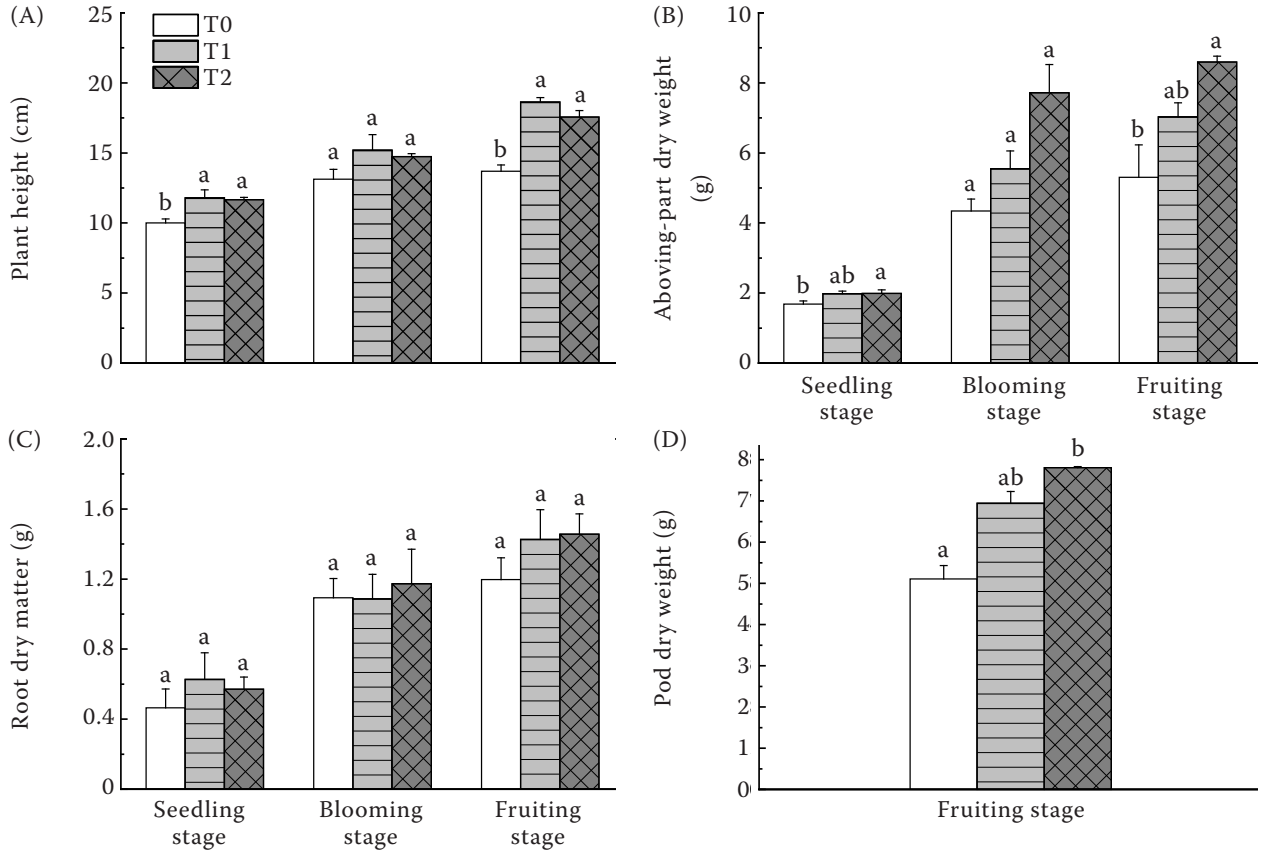

Figure 4. Effects of different treatments on growth characteristics and dry matter weight of (A) peanut plant height; (B) above-part dry weight; (C) root dry weight, and (D) pod dry weight in different periods. T0 – no fertiliser; T1 – common urea; T2 – homemade large granular slow-release fertiliser. Different letters above the bars indicate a significant difference at $P < 0.05$ level

seedling stage, which was consistent with the difference at the fruiting stage, and the difference was greater at the fruiting stage. At this time, the plant height of T1 and T2 increased by 36.0% and 28.2%, respectively, compared to T0. However, the differences between T1 and T2 were not significant, and T1 was slightly higher than T2. The dry weight fraction throughout the cycle showed an increasing trend for all treatments. For the period-specific analysis, there was almost no difference in aboveground dry weight (Figure 4B) between treatments at the seedling stage, with slightly higher results for T1 and T2 than for T0. During the blooming period, they exhibited no differences among treatments. The differences narrowed at the fruiting stage, but T1 and T2 showed significant differences compared to T0. At the fruiting stage, pod dry weight (Figure 4D) was > 5 g for all treatments, and T2 and T1 were significantly different from T0, with T1 increasing 33.3% compared to T0 and T2 increasing 39.7% and 4.8% compared to T0 and T1, respectively. For

Table 1. Effects of different treatments on nitrogen (N) uptake and utilisation of peanut at the fruiting stage

Treatment	N uptake in the ground	N uptake by roots	N uptake by a pod	Nitrogen use efficiency (%)
	(mg per pot)			
T0	89.60[b]	23.37[a]	148.49[b]	–
T1	98.42[a]	27.82[a]	188.25[a]	44.2
T2	104.02[a]	26.95[a]	211.02[a]	67.1

Different letters in the same column indicate a significant difference at $P < 0.05$ level among all the treatments. T0 – no fertiliser; T1 – common urea; T2 – homemade large granular slow-release fertiliser

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Table 2. Effects of different treatments on soil available nitrogen (N) content (mg/kg) of peanut in different periods

Treatment	Available N		
	seedling stage	podding stage	mature stage
T0	7.28^{b}	6.53^{b}	6.30^{b}
T1	8.58^{a}	7.23^{ab}	6.49^{b}
T2	7.52^{b}	8.23^{a}	6.89^{a}

Different letters in the same column indicate a significant difference at $P < 0.05$ level among all the treatments. T0 – no fertiliser; T1 – common urea; T2 – homemade large granular slow-release fertiliser

root dry weight (Figure 4C), the difference between treatments was not significant due to small values. Still, at the seedling stage, the rapid release of the available T2 fertiliser had a positive effect. In contrast, in the middle and late stages, the promotion of the slow-release effect of T2 was reflected.

Effect on N uptake and utilisation of peanut and soil N content. Table 1 shows the effects of different treatments on N uptake and utilisation in peanuts at the fruiting stage, from which it can be seen that most of the N was taken up by the pods, followed by the above-ground part, and the roots had the least N uptake due to their small mass. Specifically, N uptake was higher in all treatments with fertilisation than in those without fertilisation and was significantly different from T0 in the above-ground part and pods. T2 was the treatment with the highest N uptake in both the above-ground and pod parts. N uptake in the ground of T2 treatment was 5.6% and 14.4% higher than T1 and T0, respectively, and T1 was the treatment with the highest N uptake in the roots, but the difference with T2 was small. For NUE, T2 reached 67.1%, which was 22.9% higher than T1.

Table 2 shows the effect of different treatments on the change of soil available N content of peanuts in each period. Table 2 shows that the highest soil available N content was found in T1 at the seedling stage, which was significantly different from T0 and T2, 17.8% and 14.1% higher than both, respectively. In the blooming stage, the soil available N content decreased in the T0 and T1 treatments and increased only in the T2 treatment, which was different from both. From the blooming stage to the fruiting stage, soil available N content decreased in both treatments, with little difference between the values of T1 and T0, and T2 was 9.4% higher than T0.

Effects on soil bacterial communities. From the sequencing analysis of the microbial diversity of each treatment soil, it was known that the 16-sequence sequencing data were spliced to produce at least 69 500 clean reads per sample, with an average of 78 827 clean reads per sample. 3 783, 3 606 and 4 219 bacterial OTUs (operational taxonomic units) were obtained for the T0, T1 and T2 treatments at fruiting, and 3 630, 3 970 and 3 828 bacterial OTUs at the fruiting stage. The Shannon index indicates the diversity of bacterial communities, with higher values indicating higher bacterial community diversity. From the results, the Shannon index of T1 was significantly lower than that of T0 at the podding stage and did not show significant differences among treatments at the fruiting stage, but the Shannon index of T2 showed more stable dominant values in both periods. The effects of different treatments on the soil bacterial community's relative abundance are shown in Figures 5A and B. The dominant bacterial genera were the same for the three treatments and did not differ significantly, with vicinamibacterales and gemmatimonadaceae being the dominant groups. Regarding the period, only the bacteria that accounted for the seventh in the podding and fruiting stages differed, subgroup_10 and lysobacter, respectively. Figure 5C and D heatmap aggregated the high and low abundance species in blocks and reflected the similarity and difference of community composition of multiple samples by colour gradient and degree of similarity; it can be seen that the similarity of the same treatment was high. The community composition of different treatments belonged to different branches. As can be seen from Figure 5E and F among the functional bacteria at the genus-based taxonomic level, chemoheterotrophy (35.6–40.3%) and aerobic chemoheterotrophy (26.1–33.6%) were the most abundant genera in both periods. In the podding stage, the following most abundant genera were chitinolysis, predatory_or_exoparasitic, nitrate reduction, methylotrophy, methanol oxidation, phototrophy, photoautotrophy, and the dominant communities in the satiated fruit varied, with chitinolysis, phototrophy, photoautotrophy, oxygenic_photoautotrophy, cyanobacteria, chitinolysis, phototrophy, photoautotrophy, oxygenic_photoautotrophy, cyanobacteria and the percentage of the ten dominant communities in both periods exceeded 85%, and T2 reduced the percentage of the two dominant communities, i.e. chemoheterotrophy and aerobic chemoheterotrophy. Chemo heterotrophy, but increased the proportion

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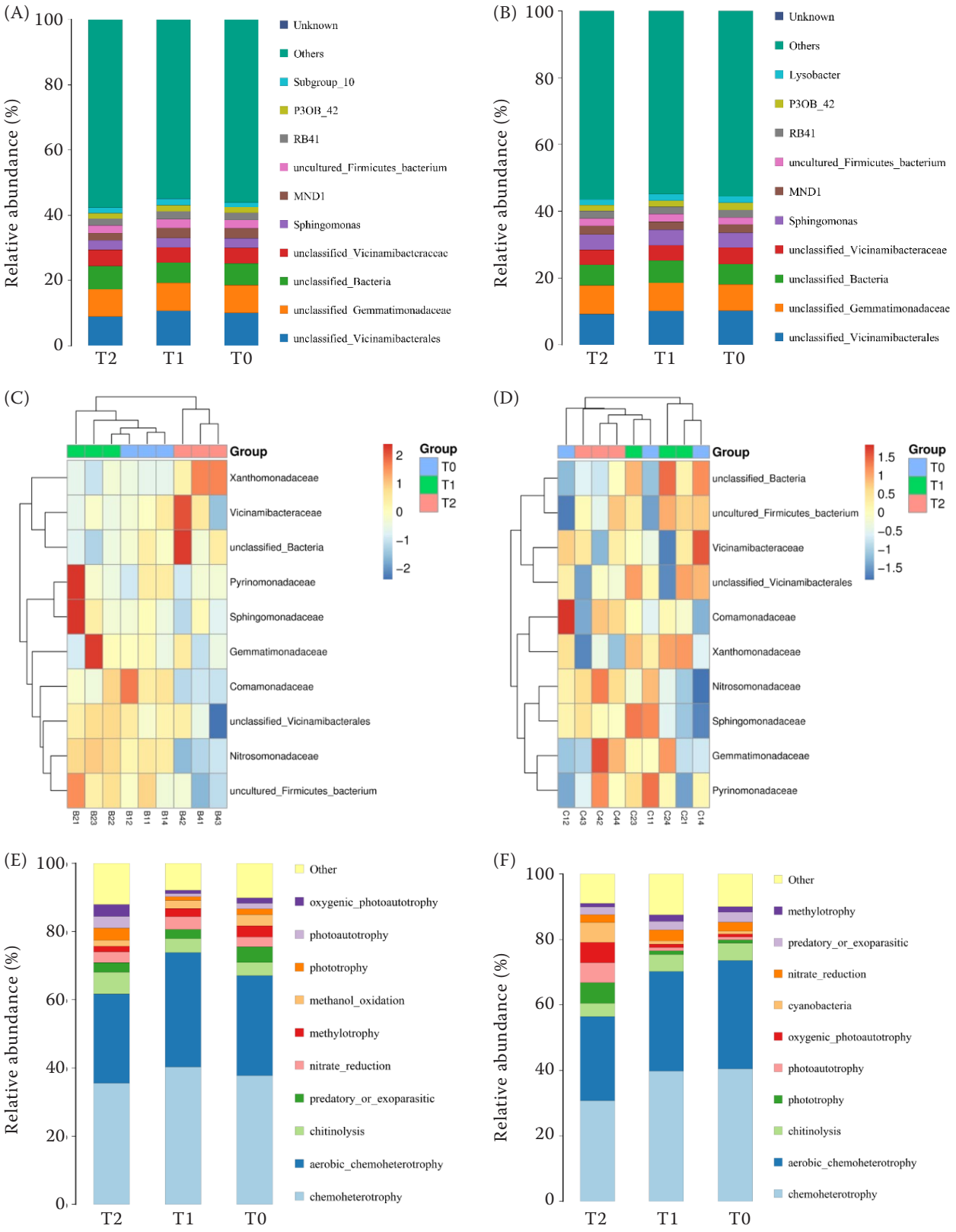

Figure 5. The relative abundance of bacterial community in different treatments at different periods of (A) podding stage; (B) fruiting stage; (C) heat map of soil microbial composition at podding stage and (D) fruiting stage, influence of relative abundance of soil functional bacteria at (E) podding stage and (F) fruiting stage. T0 – no fertiliser; T1 – common urea; T2 – homemade large granular slow-release fertiliser

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of chitinolysis, phototrophy, photoautotrophy and oxygenic_photoautotroph at the podding stage, and phototrophy, photoautotrophy, oxygenic_photoautotroph at the fruiting stage, oxygenic_photoautotrophy, and cyanobacteria in fruiting, but did not produce statistical differences.

DISCUSSION

In this study, we developed a new double-coated controlled-release fertiliser, with natural and easily degradable sulfur and sodium alginate coating materials, which has a slow-release cycle of more than 42 days in water. We compared its fertilisation efficacy with that of uncoated fertiliser in peanuts present in the experiment, and the results showed that affecting root physiology and nutrient uptake, the use of LSRF promoted peanut root development, which increased root volume by 45.10% at fruiting compared to with uncoated fertiliser. At the same time, it reduced the soil's available N content at the seedling stage. It increased the soil's available N content at the fruiting stage, thus achieving the fertiliser's slow and controlled release effect. A significant contribution to the net photosynthetic rate was made for growth development and yield in the middle and late stages. Pod dry weight was significantly higher at the podding stage than uncoated fertiliser, 4.8% higher at the fruiting stage, and 22.9% higher in NUE. In terms of microbial bacterial communities, LSRF promoted the diversity of the treated bacterial communities to some extent, with little difference in the relative abundance of soil bacterial communities. In conclusion, LSRF can control N emissions by applying fertiliser and its biodegradability, achieving fertiliser efficiency and environmental friendliness. It provides a theoretical and practical basis for improving agronomic management of crops and enhancing fertiliser utilisation.

Also, the experimental results showed that fertiliser treatments were mainly different from the control trials in most growth, physiological, and yield parameters. However, the differences between the two fertiliser treatments were mostly not statistically significant; this was expected since they were both urea-based fertilisers. Nevertheless, some results indicated that T2 had slightly higher agronomic efficiency than T1. For example, regarding physiology, the T2 produced differences in leaf greenness levels in peanuts at fruiting compared to urea. Regarding photosynthesis, the T2 produced differences in net photosynthetic rate and stomatal conductance with the other treatments at the podding and fruiting stages, yielding maximum net photosynthetic rate (A) and stomatal conductance (g_s) values. The results of Zhang et al. (2000) showed an interactive effect of reasonable application of controlled-release N fertiliser on the growth and photosynthetic characteristics of cyathea seedlings under certain light conditions, which in turn increased the dry weight of the crop, which is consistent with our experimental results. The reason for this result may be due to the long nutrient release cycle of the slow-release fertiliser, so under the condition of equal N application, it can provide effective N for peanut growth in the middle and late stages, improve the effectiveness of soil nutrients, make the N supply sufficient, enhance the chlorophyll synthesis ability of peanut leaves, increase the chlorophyll content in leaves, and also delay the senescence of leaves, thus improving photosynthetic capacity. In addition, the experiment showed that the application of fertiliser increased the amount of soil available N, but the T1 with urea applied in the middle and late stages had a reduced effect on the increase of soil available N content, while the T3 had an increased effect and showed differences. This may be because slow-release fertiliser may improve soil structure and chemical environment to prolong the presence of N through slow and controlled release of fertiliser, allowing sufficient N uptake by the crop even at mid to late stages, thus improving N uptake by the crop.

At the root level, we observed that the T2 exhibited positive effects in terms of root length and root volume compared with the T1 treatment, most likely due to the long duration of the slow-release fertiliser effect, which improves the nutrient structure of the root microenvironment of peanut, provides good conditions for the life and reproduction of soil microorganisms, and promotes the activity of root organisms, thus facilitating root growth and nutrient accumulation (Nicodemus et al. 2008). This was consistent with the results of Zhang et al. (2011) on barley, whose experimental results showed that roots proliferated around controlled-release urea particles but not around urea particles. Due to root proliferation, shoot N uptake, root dry mass, and N content around urea particles were higher in controlled-release urea than in urea. This means that the root growth around the controlled-release urea granules was enhanced, and that part of the roots around the fertiliser granules played a major role in N uptake.

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In addition, there was a stimulatory relationship between the roots growing around the granules and those growing away from the fertiliser granules.

The main parameters commonly used to evaluate fertiliser efficiency are the biomass produced by the crop and grain yield. Moderate N application promotes more N allocation to reproductive organs, better regulating population quality, and facilitates crop yield formation and N fertiliser efficiency. The percentage of total N on pods is higher when the plant matures. Moreover, slow-release fertiliser is a one-time application and is an effective way to reduce labour costs and improve N fertiliser utilisation efficiency. In this research work, the part with the highest N distribution was the pods, followed by the above-ground part, and the roots were the least abundant, a result consistent with the biomass of peanuts, also known as dry matter weight. Although the treatment of fruiting T2 was not significantly different from T1, the result of N uptake in the aboveground and pod parts of the peanut was optimal, and NUE increased by 23.1% compared to T1 while having the highest pod yield. The reason for this phenomenon may be due to the slow-release fertilisation characteristics of slow-release fertiliser can not only meet the N nutrients required by peanuts in the early stage of growth like urea, but also, as the reproductive period advances, slow-release fertiliser is continuously converted by microorganisms in the soil, thus providing sufficient N sources for peanut growth, thus promoting root uptake, improving photosynthesis, and making the N from nutrient organs continuously transfer to ascending organs. Wu et al. (2022) showed that compared with full N application, slow-release fertiliser compensated for the disadvantages of rapid N release from urea and the need for continuous follow-up in the later stages and also solved the problem of excessive N supply in the first few years of the crop and insufficient in the later stages. Similarly, in the wheat treatment, the N supply from the slow-release fertiliser treatment not only ensured the early fertility differentiation but also provided sufficient soil inorganic N after the nodulation period, thus promoting dry matter accumulation and improving the accumulation of post-opening photosynthetic products and NUE in the seeds. However, the slow-release fertiliser release characteristics are related to various factors such as soil properties, temperature and precipitation, and further research is needed to develop suitable fertiliser formulations for local conditions.

There was an overall linear relationship between soil microbial diversity and the stability of community structure and ecological functions, and in general, the higher the soil microbial abundance and the more complex the community composition, the greater the functional stability of soil microbiology (Balvanera et al. 2010). In this study, comparing the α-diversity of soil microorganisms in different N application treatments, we found that the Shannon index of T1 was significantly lower than that of T0 at podding stage, which was mainly because unbalanced fertilisation would lead to imbalance of effective soil nutrients and decrease in productivity, thus inhibiting soil microbial activity and unfavourable to the reproduction of microorganisms involved in soil nutrient cycling, which in turn led to a decrease in soil microbial diversity (Sun et al. 2015). In addition, no significant differences were shown among treatments at the fruiting stage, but the Shannon index of the T2 exhibited more stable dominant values in both periods, indicating that the application of large-granular slow-release fertilisers could increase the bacterial community richness to some extent. The slow-release fertiliser treatments showed higher soil enzyme activity and microbial population than the pure urea application model. In terms of bacterial community structure, high-throughput sequencing results showed that vicinamibacterales and gemmatimonadaceae were the dominant groups, and each treatment had no significant effect on community structure. However, in contrast to the study of Niu et al. (2022), the experiments showed that applying slow-release fertiliser significantly improved the soil bacterial diversity index and soil microbial community structure compared to conventional fertilisation. Still, the fungal diversity and number of species were reduced. The main reason for this difference was that soil bacterial community structure and diversity are susceptible to various factors such as soil type, soil physicochemical properties, and fertiliser application methods.

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