Spatial heterogeneous granulation enhance soil nitrogen supply potential via regulating dissolved organic nitrogen

Xinyi Yang, Kun Zhu, Xiaohong Jia, Bo Li, Guitong Li, Xiaorong Zhao, Qimei Lin, Changhua Fan

Department of Soil and Water Science, College of Land Science and Technology, China Agricultural University, No. 2 West Road of Yuanmingyuan, Haidian, Beijing 100193, PR China

College of Natural Resources and Environment, South China Agricultural University, Guangzhou 510642, PR China

Beijing Soil & Fertilizer Extension Service Center, No. 6 Yumin Zhong Road, Xicheng, Beijing 100029, PR China

Environment and Plant Protection Institute, Chinese Academy of Tropical Agricultural Sciences, Haikou 571101, PR China

HIGHLIGHTS

- In SG granules stored more CF-N and mineralized more N from manure.
- Mineral N in SG treated soil was twice as much as HG fertilizer did on day 80.
- SG granules could prolong N supply and improve N supply ability of manure.

GRAPHICAL ABSTRACT

Abstract

Combined application of organic fertilizer (OF) and chemical nitrogen (N) fertilizer (CF) is a common fertilization practice, providing better N supply pattern for crop growth. However, few studies focused on the effect of granulation method of these two fertilizers on N supply to soil. To validate this effect, we mixed the CF (15N–(NH4)2SO4) into cow manure powders with maize straw powder at rate of 2% or 8% (dry weight), respectively, in two forms, homogeneous granulation (HG) and spatial heterogeneous granulation (SG), and applied them to soil to investigate their difference in N transformations during an 80-day incubation. Results showed that there were more NH4+ and NO3− in HG granules and the surrounding soil, while more dissolved organic N (DON) in the SG granules and the corresponding soil after day 30. At day 80, compared to HG, SG released less CF–N into the surrounding soil, but primed more organic N into mineral N. Structural equation model (SEM) revealed that DON was the main form of N transported from fertilizer granules to the surrounding soil, and then drove the changes of soil microbial activity, which determined the amount and dynamic of mineral N in the surrounding soil. These results indicated that, in heterogeneous granulation, the spatial separation between OF and CF slow down, but more importantly enhanced up, the microbial transformation of CF in the granules. This demonstrated that the spatial heterogeneous granulation of OF and CF could change the pattern of N release from fertilizer to soil and offer a potential way to optimize N fertilizer management strategies in the future.

© 2020 Elsevier B.V. All rights reserved.
1. Introduction

The combined use of organic fertilizer (OF) and chemical nitrogen (N) fertilizer (CF) has the potential to optimize agricultural N management by enhancing the microbial link between organic carbon (C) and N processing (Drinkwater et al., 1998; Nosengo, 2003) and resulting in greater N retention capacity (Vanlauwe et al., 2001; Chivengwe et al., 2011). The reason for the above benefits exits in the fact that chemical N controls the OF’s decomposition process (amount and timing), which largely explained by the C/N ratio theory (FOG, 1988; Mary et al., 1996; Knorr et al., 2005). Besides the C/N ratio, the physical contact between OF and CF material is also important to the release of CF–N (Yang et al., 2020), due to its regulating effect of substrate accessibility on soil microbes (Singh et al., 2007).

Mixing CF and OF materials homogeneously as granule, pellet, or tablet, the so-called homogeneous granulation (HG), can improve the contact level greatly between these two components, consequently change the immobilization–mineralization turnover (MIT) of N (Yang et al., 2020; Antille et al., 2013, 2014). In these granules, the two components existed in a more concentrated pattern and inter–contacted easily, reached a real C/N ratio for the OF’s decomposition, and improved their N availability (Antille et al., 2013, 2014).

Contrast to HG, we designed a new method of fertilizer granulation, where the CF as a core was wrapped in a OF layer, called spatial heterogeneous granulation (SG). In these SG granules, CF–N was concentrated in the core and OF coated over the core, making spatial separation between the N and C sources and an uneven distribution of N source within the granule; then a new story of the MIT of N would occurred. In this approach, the inorganic N will be immobilized firstly by the microorganisms in OF to form MBN, then go through mineralization to form available N released into the surrounding soil (Liang et al., 2011; Yu et al., 2016), there-in OF to form MBN, then go through mineralization to form available N released into the surrounding soil (Liang et al., 2011; Yu et al., 2016), therefore the N releasing pattern could be regulated in a controllable way.

The small soil body surrounding the fertilizer granules can be called fertilizer sphere, which is hot spot of N transformation process like rhizosphere or charosphere, within which microbial colonization enhanced fertilizer sphere, which is hot spot of N transformation process like rhizosphere or charosphere, within which microbial colonization enhanced the N releasing pattern could be regulated in a controllable way. The soil used in the experiment was collected from the 0–15 cm layers of a pH 8.02 (soil–to–water ratio of 1–to–5, w/v) arable soil at the Shangzhuang Experimental Station of China Agricultural University in Beijing, China (40°08′21″N, 116°10′52″E). The soil is fluvial in FAO system and its properties were shown in Table 1. Soil was sieved to 2 mm mesh size and pre-incubated at 25°C in the dark for 7 days to stabilize the microbial activity.

Biochar balls were made by hardwood material under 500°C for 3 h. The organic C content was 62.3%, total N content was 0.58%, NH₄⁺–N content was 5.3 mg kg⁻¹, NO₃⁻–N content was 8.4 mg kg⁻¹, available phosphorus content was 156 mg kg⁻¹, and available phosphorus content was 532 mg kg⁻¹. The C content of modified starch was only about 0.34%.

2. Materials and methods

2.1. Granulation method

Homogeneous granulation (HG): The Powders of ammonium sulfate and air–dry cow manure (CM) and maize straw (MS) were evenly mixed in the corresponding proportion. Modified starch solution (1.5%, W/V) was used as a binging material to improve the granulation. The gravimetric water content of the mixture was adjusted to 30%, then the mixture was kneaded into granules with a diameter of 1.0 cm. In order to maintain the same size of fertilizer granule, we also wrapped the biochar balls into the mixture of ammonium sulfate and organic material.

Spatial heterogeneous granulation (SG): In order to enhance the physical stability of the CF core, we used biochar balls as the supporting material. Briefly, ammonium sulfate solution was sprayed onto the biochar balls (about 2–3 mm in diameter), making the biochar balls reach a gravimetric water content of 30%. The CM and MS mixture was moistened with the above–mentioned starch solution to the water content of 30%, and then manually coated onto the biochar balls to form the SG granules in diameter of 1.0 cm.

2.2. Laboratory incubation

Soil microcosm experiment consisted 5 treatments with 3 replicates: CK (control, only soil), 2HG and 8HG (HG granule with 2% or 8% of MS in the total dry weight of OF mixture), 2SC and 8SC (SG granule with 2% or 8% of MS in the total dry weight of OF mixture). Each treatment was applied at an equivalent total N rate of 225 kg N ha⁻¹ (100 mg N kg⁻¹ soil). The proportion of the three materials was calculated based on total N content, with 50% of N from ammonium sulfate (([NH⁴]₂SO₄, atom = 9.865%) and another 50% of N from CM and MS. The specific information is shown in Table 2. Each replicate was applied with 14 granules and the schematic experimental set up was shown in Fig. S1.

Before the onset of the experiment, the soil, which had been stored in dark for 7 days, was pre-incubated at 50% WHC (water holding capacity) for 10 days in dark at 25°C to activate soil microbes and stabilize soil respiration (Marschner et al., 2015). The amount of the added water was the difference between the target WHC and the initial water

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>The basic properties of the soil and organic material.</td>
</tr>
<tr>
<td>Items</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Sand (&gt;-0.05 mm), g kg⁻¹</td>
</tr>
<tr>
<td>Silt (0.05-0.02 mm), g kg⁻¹</td>
</tr>
<tr>
<td>Clay (&lt;0.02 mm), g kg⁻¹</td>
</tr>
<tr>
<td>Organic C, g kg⁻¹</td>
</tr>
<tr>
<td>Total N, g kg⁻¹</td>
</tr>
<tr>
<td>¹⁵N, atom %</td>
</tr>
<tr>
<td>NH₄⁺–N, mg kg⁻¹</td>
</tr>
<tr>
<td>NO₃⁻–N, mg kg⁻¹</td>
</tr>
</tbody>
</table>
content. Following pre-incubation, 1500 g soil (dry weight equivalent) was packed in a 3000 mL plastic jar (10 cm length × 10 cm width × 30 cm height) with a bulk density of 1.0 g cm−3. The mixture of soil and fertilizer granules occupied 1/2 the volume of the plastic jar. The 1500 g soil consisted three layers: 800 g soil as the bottom, 400 g soil as the top layer, and the middle layer of 300 g soil was used as the sampling layer, which was divided into 28 small grids (4 × 7 array, Fig. S1). Such grids were designed to assist the sampling of granules and their surrounding soils. To allow aeration of soil, the boxes were opened for 2 h every 3 days, and water was replenished according to the weight loss.

2.3. Samplings and measurement

The fertilizer sphere soils (0–0.5 cm away from the outer surface of the fertilizer granule) were taken at day 5, 15, 30, 50 and 80. In each sampling event, we took the soil and fertilizer granules separately from the sampling grid. The following parameters were analyzed: mineral N (NH₄⁺ and NO₃⁻), dissolved organic C (DOC) and N (DON), and microbial biomass C (MB) and N (MBN) and ¹⁵N enrichment of the NH₄⁺, NO₃⁻ and MBN pool (stored at −20 °C) and phosphor lipid fatty acid (PLFA) analyses (stored at −80 °C). Soil samples were extracted for mineral N analysis using 2 M KCl (soil: extractant = 1:5), and the extracts were centrifuged for 10 min at 2000 × g and filtered using 0.45 μm polytetrafluoroethylene filters, and analyzed for DON and MBN concentration with the TON analyzer (Liqui TOCII, Elementar, Germany). MBN and MB were estimated by the chloroform fumigation extraction method (Brookes et al., 1985). We used the NH₄⁺–diffusion technique to determine the ¹⁵N abundance of extracted NH₄⁺ and NO₃⁻ (Sebillo et al., 2004). The extracts of fumigated and non–fumigated were freeze-dried to obtain samples for analysis of ¹⁵N in MBN. The ¹⁵N signals were analyzed using a stable isotope ratio mass spectrometer (Isoprime 100) linked to a CN analyzer (elemental analyzer via PYRO cube).

Extracellular enzyme activities (β-glucosidase, protease and dehydrogenase) were determined using the following methods. Dehydrogenase activity was assayed through colorimetric determination of triphenyl formazan formed when soils were incubated with 2, 3, 5-triphenyltetrazolium chloride at 37 °C for 24 h (Moldenke, 1994). β-Glucosidase activity was measured according to Ekenler and Tabatabai (2003) and protease activity was analyzed following the method of Geissler and Horwath (2008).

All measurements were undertaken in triplicate from the independent replications. The net N mineralization rate (Nmin, mg N kg⁻¹ day⁻¹) was calculated as the daily difference of mineral N between start and end of each period.

The mass of (NH₄)₂SO₄–derived N in different N pools was calculated according to Dawson et al. (2002). We also determined microbial N and carbon (C) use efficiency (NUE and CUE) using a widely accepted stoichiometric method (Sinsabaugh et al., 2016). Phospholipid fatty acid (PLFA) analysis was used to determine a profile of active microbial communities (Bossio et al., 2006). Details of these methods were given in the supporting material.

2.4. Statistical analysis

The effects of different treatments on the N and C components, soil properties and the soil N pools were analyzed using one–way and repeated–measures ANOVA followed by Tukey’s HSD as a post hoc test using SPSS 20.0 (IBM Co., Armonk, NY, USA). We used SEM approach to disentangle the regulation mechanism of two granulation methods on soil N supply potential using AMOS P software (IBM SPSS AMOS 20.0.0). To evaluate the influence of soil biological and chemical properties on soil Nmin and N availability, we ran a SEM model to elaborate the transformation process. We assessed the conceptual model by the goodness–of–fit statistics and used the lowest AIC value to select the optimal model.

3. Results

3.1. N dynamics in fertilizer granules and outer soil

In fertilizer granules, NH₄⁺ decreased more rapidly in HG than in SG during the first 15 days, and about 2 to 4 times higher in SG than that in HG at the end of incubation (Fig. 1a). NO₃⁻ increased gradually both in HG and SG, and the NO₃⁻ in SG was about 2 times as high as that in HG at day 80 (Fig. 1b). Similarly, MBN increased continuously through the 80–day incubation in SG, and ending at about 500 mg kg⁻¹, which was about 90% higher than those in HG (Fig. 1c). The differences of DON contents between HG and SG were not significant until 30 days later (Fig. 1d).

In the outer soils, NH₄⁺ increased rapidly (peaked at day 15th) in HG, whereas slowly in SGs (peaked at day 30th) with a significantly higher contents at the end of incubation (Fig. 1e), meaning more NH₄⁺ was released from fertilizer granules to the outer soil. At the same time, NO₃⁻ increased continuously through the 80–day incubation in SG, ending at about 110 mg kg⁻¹, which was 100% higher than those in HGS (Fig. 1f). Both HGs and SGs significantly increased DON in the surrounding soils and HGs provided more DON than SGs at the end of incubation (Fig. 1h).

3.2. Transformation of N from chemical fertilizer

In fertilizer granules, more ¹⁵NH₄⁺ left in SG than in HG at the same time (Fig. 2a), while at the end of the incubation ¹⁵NO₃⁻ produced in SG was about 2 times (~40 vs. ~20 mg kg⁻¹) of that in HG (Fig. 2b). Meanwhile, ¹⁵NO₃⁻ in HG was about 2 times as high as that in HG (Fig. 2c). On the other hand, SG provided less ¹⁵N–DON than HG did, especially at the later period of the incubation (Fig. 2d).

In the surrounding soils, ¹⁵NH₄⁺ was rapidly transported in HGS during the first 15 days, while relatively slow in SGs (Fig. 2e). Meanwhile ¹⁵N–NO₃⁻ was gradually accumulated during the whole incubation (Fig. 2f). At the end of incubation, SGs could sustain about 2 to 3 times ¹⁵N–MBN of what HGs did (Fig. 2g). ¹⁵N–DON in SGs and HGS was 30–50 mg kg⁻¹ at the end of incubation (Fig. 2h).

After 80 days incubation, the total ¹⁵N recovery ratio in the 4 pools (NH₄⁺, NO₃⁻, MBN, and DON) of the fertilizer granules and surrounding soil was 78–81% in SG treatments, and 66–73% in HG treatments. Of the recovery pool, less than 21% moved into the surrounding soils among all treatments (Table S2). In general, the recovery of ¹⁵N–NH₄⁺, ¹⁵N–NO₃⁻ and ¹⁵N–MBN were higher in the SG treatments, and ¹⁵N–DON was higher in the HG treatments.

Table 2
The information for the five treatments used in the study.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Contribution of added N from different amendments (NH₄)₂SO₄</th>
<th>MS</th>
<th>CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>CK</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HG</td>
<td>50%</td>
<td>2%</td>
<td>48%</td>
</tr>
<tr>
<td>SG</td>
<td>50%</td>
<td>2%</td>
<td>48%</td>
</tr>
<tr>
<td>HG</td>
<td>50%</td>
<td>8%</td>
<td>42%</td>
</tr>
<tr>
<td>SG</td>
<td>50%</td>
<td>8%</td>
<td>42%</td>
</tr>
</tbody>
</table>

HG: homogeneous granules; SG: spatial heterogeneous granules; MS: maize straw; CM: cow manure. The nutrient ratio is calculated according to the nitrogen content.
3.3. Factors of soil N transformation

To quantify the relative importance of the influencing factors on soil N supply, we constructed SEM based on the known relationships between soil N transformation and their key drivers in the two granulation methods as well as the effect of MS proportions in the granule. Our model explained 44% of the variance in N conversation from fertilizer to soil (Fig. 3). Regardless of the granulation methods and MS proportions, DON and DOC were gradually released from the fertilizer into the surrounding soil, which as the substrate influenced the soil bacterial community (Table S3). Then soil bacterial community exerted strong indirect effects on soil Nmin through its correlation with soil NUE \( r = -0.37^{***} \), and then controlled the soil Nmin. Moreover, microbial community had a certain regulatory effect on soil enzyme activity (Fig. S3), which can subsequently regulate the Nmin (\( r = -0.32^{***} \)).

Soil N mineralization–immobilization turnover determined the amount of mineral N (\( r = 0.58^{***} \)) in the soil, that is, the soil N supply potential.

4. Discussion

4.1. Spatial heterogeneity generated more labile N inside the fertilizer granules

At the end of incubation, the total and \(^{15}\text{N–NH}_4^+\)–derived \(\text{NO}_3^-\) in SG granules was about 2 times of that in HG granules (Figs. 1b, 2b), meaning more \(\text{NO}_3^-\) was produced in SG granules, and this was in accordance with finding of Paul (2015). It was easy to understand that more \(\text{NH}_4^+\) left in the SG granules, as the added (NH₄)₂SO₄ was absorbed into biochar balls and released slowly (Manirakiza et al., 2019). Under this condition, more added \(\text{NH}_4^+\) nitrified into \(\text{NO}_3^-\) (Fig. 2b) and more \(\text{NO}_3^-\) produced from OF–N via nitrification (Table S3) in the SG granules, which mean more N in manure and maize straw were mineralized and nitrified into \(\text{NO}_3^-\) (Table S3). Meanwhile, the \(\text{NO}_3^-\) accumulated in SG granules on day 80 might also be due to the weaker denitrification (Ge et al., 2012), because the lack of O₂ induced by the strong nitrification and the lower content of DOC (Fig. S2) would inhibit heterotrophic denitrification (Khalil et al., 2004) and reducing \(\text{NO}_3^-\) consumption.

So why the slow released \(\text{NH}_4^+\), but not the rapid \(\text{NH}_4^+\) (in HG), could produce more \(\text{NO}_3^-\) and MBN, but not DON (Fig. 2b, c, d)? We guessed that the high concentration of \(\text{NH}_4^+\) within the contact thin layer between the biochar balls and the surrounding manure played two roles, substrate of nitrification to provide \(\text{NO}_3^-\) and N source for some slow–growing but long–life soil microorganisms to produce more MBN but less DON, but unfortunately we could not find any proof in the literatures. What we knew was that, in the HG granules, the added \(\text{NH}_4^+\) reacted fast with powders of maize straw and manure to form MBN via immobilization, and then DON formed after the microorganisms fast died (Figs. 1d, 2d). During this process, \(\text{NH}_4^+\) was consumed by microorganisms (Fig. 2c) and less substrate for nitrification and \(\text{NO}_3^-\) concentration was lower in the HG (Figs. 1b, 2b). Therefore, the added \(\text{NH}_4^+\) transformed into DON more and eventually existed in the HG granules (Fig. 2d).

The reason that SG granules produced more mineral N could be attributed to the N mining theory (Craine et al., 2007; Kuzyakov, 2010). In the HG, \(\text{NH}_4^+\) directly contacted with available C (fresh MS) to form MBN and then DON. In this process, less OF–N were assimilated by
microorganisms in the OF granules, so mineral N at the later stage was mainly come from CF–N. While in the SG, due to the CF–N adsorbed by the biochar balls, the probability of contact between the available C and the CF–Na was low. Therefore, in the presence of available C, heterotrophic microorganisms used available C and OF–Nt to synthesize MBN (i.e. N mining), and then these MBN subsequently died and became DON. In this way, the proportion of 15N–DON (Fig. 2d) in the SG was lower than that in HG and then the amounts of non–15N–DON were more than that in HG before day 80 (Table S3), meaning the more DON from OF–N in the SG granules. This further suggested that the spatial heterogeneous granulation could induce more N mining from the stable organic N in the compost and improve the bioavailability of this N.

4.2. Spatial heterogeneous granules provided more available N in the surrounding soil

The spatial heterogeneity of CF and OF in the fertilizer granule shaped the N dynamics in soil, and SG provided more mineral N to the surrounding soil than HGs did (Fig. 1e, f). At the end of the incubation, the amount of mineral N in SG was about 35.9–161.9 mg kg$^{-1}$, 4.5 times higher than that in HG. Of this mineral N pool, only ~2.4% directly came from the added chemical fertilizer ($^{15}$N–(NH$_4$)$_2$SO$_4$), and the others came from organic N in soil, manure and straw, the so called priming effect on N mineralization (PEN) (Moorhead and Sinsabaugh, 2006). This more mineral N provided by granular fertilization was in line with the previous studies, which were homogeneous granulation (Cox, 1995; Wang et al., 2018), and of course was benefit for crop N uptake (Schimel and Chapin, 1996; Pii et al., 2014).

Although only tiny amount (3–7 mg kg$^{-1}$) of $^{15}$N–NH$_4^+$ and $^{15}$N–NO$_3^-$ moved into the surrounding soil at day 15th (Fig. 2e, f), while a large amount of NH$_4^+$ (25 to 70 mg kg$^{-1}$) and NO$_3^-$ (~60 mg kg$^{-1}$) produced in the surrounding soil (Fig. 1e, f), meaning PEN in the surrounding soil was about 8 to 10 times higher than the mineral N directly coming from the chemical N. On the other hand, there was more $^{15}$N–DON (~15 to 75 mg kg$^{-1}$) moved into the surrounding soil at day 15th (Fig. 2h), meaning most of the added CF–N in the fertilizer granules undergo immobilization and released as DON as dead cell material or extracellular polymer substances before it moving out of the granules (Christou et al., 2006; Boddy et al., 2007).

The more PEN in the surrounding soils could be directly attributed to the results of the high enzyme activities (Fig. S3) and the high level of soil microbial biomass (Figs. 1g, S2c) throughout the whole 80–day incubation. Of course, the high enzyme activities and the high level of soil microbial biomass was provided by the transported DOC, DON and mineral N from the fertilizer granules (Fig. 1a–d).

4.3. Microbial characteristics and N transformation in the surrounding soil

GP (Gram–positive) community preferentially used recalcitrant substances and played a significant role in the decomposition of the SG granules outer layer (Table S4). This phenomenon was attributed to
the fact that more DON (from OF) released from SG granules than the HG granules did (Figs. 1d, 2d), meaning DON stimulated the abundance of GP community and thus enhanced N mineralization in the surrounding soil \( (p < 0.001) \) (Fig. 3). Although we did not measure the DON composition in the current study, but the dissolved organic matter (DOM) from manure is much humified (Lv et al., 2013; W. Zhu et al., 2018), making DON (mostly were proteinaceous compounds and amines) integrate into the fulvic– and humic-like substances and thus more resistant against the biodegradation (He et al., 2015), which is relatively good for GP community (Kramer and Gleixner, 2008; Kamjunke et al., 2017; D’Andrilli et al., 2019).

In the process of N transformation regulated by microorganisms, the microbial NUE also have significant negative correlation with soil Nmin (Fig. 3). The results were in line with previous studies (Sinsabaugh, 1994; Schimel and Weintraub, 2003; Theuerl and Buscot, 2010; Andrensen et al., 2016). There was no significant difference in CUE between all fertilized soils, while NUE in SG treatments were always greater than that in HG treatments (Fig. 4b). Under the premise that the contents of C and N components in soil were not significantly different, the utilization of N by microorganisms was various, which also confirmed the different N sources entering the soil. Fuchslueger et al. (2019) and Zhong et al. (2015) have reported that NUE was sensitive to the changes in N management patterns in ecosystems. In our study, \(^{15}\text{N}-\text{DON} \) (Fig. 2h) was more and NUE (Fig. 4b) was lower in HG treated soil, meaning that NUE increased with the amount of OF–N entering soil. By this way, NUE could be used as a predictor to describe the characteristics of fertilizer granules N supply, this was consistent with other study which NUE is a fundamental parameter to understand and predict ecosystem N dynamics and N sequestration, particularly in response to environmental changes (Mooshammer et al., 2014). The differences in the amount, time scale and pattern of soil N supply regulated by two types of granular organic fertilizers were also compared from the perspective of microbial function.

5. Conclusion

Transformation of N from fertilizer to soil between the HG and SG treatments was significantly different. SG was beneficial for transforming
The chemical fertilizer N to the DON form by immobilization of chemical fertilizer N and mining of native N. Meanwhile, DON was the dominant form in SG treated soil, meaning SG granule could reduce N losses potentially. These results indicated that, in heterogeneous granulation, the spatial separation between OF and CF slow down, but more importantly enhanced up, the microbial transformation of CF – N in the granules. SG offered a more stable and longer releasing of mineral N, through enlarging the DON pool. Soil mineral N content after application of SG fertilizer (170 mg kg$^{-1}$) was 2 times as large as that of HG fertilizer (80 mg kg$^{-1}$) at day 80th. This indicated that coating of stable organic matter (compost) on inorganic N would prolong but enhance the N supply to soil. This study provided clear result on the role of spatial location in granulation of organic material with chemical fertilizer, in that spatial heterogeneous granulation could change the immobilization–mineralization turnover process in the granule and supply more N in amount and longer in time to soil. Although cost would be a little higher, this kind of granulation could change the N supply process, which would be important to improve N use efficiency by crops and decrease negative impact of N fertilizer on environment quality.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.141235.

**CRediT authorship contribution statement**

**Xinyi Yang:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing - original draft. **Kun Zhu:** Supervision, Conceptualization, Funding acquisition, Project administration, Writing - review & editing. **Xiaohong Jia:** Software, Methodology, Writing - review & editing. **Guitong Li:** Investigation, Supervision, Methodology, Writing - review & editing. **Xiaoqiong Zhao:** Investigation, Project administration, Methodology, Writing - review & editing. **Qimei Lin:** Data curation, Project administration, Investigation, Writing - review & editing. **Changhua Fan:** Software, Methodology, Writing - review & editing.

**Declaration of competing interest**

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

**Acknowledgments**

This work was financially supported by the National Key Research and Development Program (2017YFD0200801-02) and the NSFC project (41171211).

**References**

