SCREENING AND OPTIMIZATION OF PELLETING FORMULATIONS FOR *LEYMUS CHINENSIS* SEEDS

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羊草种子丸粒化配方优化研究

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ABSTRACT

To optimize the pelleting formulation of Leymus chinensis seeds for mechanized precision sowing, single-factor and three-factor, three-level orthogonal experiments were conducted using CMC as binder and diatomite and talcum powder as fillers. An integrated evaluation system covering pellet uniformity, seed-bearing rate, compressive strength, cracking time, germination rate, and emergence rate was established. Results showed that CMC concentration, filler ratio, and seed-to-powder ratio all affected pelleting performance. The optimal tested formulation was 1.25% CMC, an 8:2 filler ratio, and a 1:4 seed-to-powder ratio, providing a basis for pelleting and mechanized sowing of small forage seeds.

摘要

为优化羊草种子丸粒化配方并提高其机械化精量播种适应性，以羧甲基纤维素钠（CMC）为黏结剂、硅藻土和滑石粉为填充材料，采用单因素试验结合三因素三水平正交试验，构建兼顾加工性能与生物学表现的综合评价体系，对丸粒化均匀率、有籽率、抗压强度、裂解时间、发芽率和出苗率进行评价。结果表明，CMC 浓度、填充剂配比和种粉比均影响羊草种子丸粒化效果，配方优化本质上是对丸粒质量、结构稳定性、裂解性能与幼苗表现之间平衡关系的调控。在所试组合中，1.25% CMC、填充剂配比 8：2、种粉比 1：4 综合表现最佳，可为小粒牧草种子丸粒化加工及机械化精量播种提供依据。

INTRODUCTION

Leymus chinensis is an important perennial forage grass in the grassland regions of northern China and a typical constructive species in steppe ecosystems. It plays a key role in degraded grassland restoration, artificial pasture establishment, and ecosystem stability. However, its seeds are small, light, awned, slender, and highly irregular, and they are prone to interlocking and entanglement. These traits reduce flowability and dispersibility and often cause unstable seed delivery, missed seeding, reseeding, and uneven seed distribution during mechanized sowing. For such small and irregular forage seeds, pelleting is an effective way to increase seed size, improve shape regularity, and enhance flowability and sowing precision. Its effectiveness depends on the interaction among binder properties, filler composition, coating structure, and hydration behavior. Sodium carboxymethyl cellulose (CMC) can improve coating adhesion and integrity, diatomite contributes to coating skeleton formation and water uptake, talcum powder improves pellet smoothness and flowability, and the seed-to-powder ratio further affects coating thickness, compactness, and disintegration behavior. Thus, pelleting formulation optimization is essentially a process of balancing pellet quality, mechanical stability, cracking behavior, and subsequent germination and emergence (*Bozdar et al., 2026; Chandrika et al., 2025; Pedrini et al., 2023*).

Previous studies have shown that pelleting formulation markedly affects seed performance, but the optimal materials and ratios are species-dependent (*Bai et al., 2025; Muhammad et al., 2025; Pedrini et al., 2023*). *Bai et al. (2025)* reported that 80% talcum powder, 20% bentonite, and 2% CMC improved seed-bearing rate, disintegration rate, compressive strength, germination, and field performance in quinoa.

Yang et al. (2019) showed that pellet quality, splitting rate, water-holding capacity, seed vigor, and seedling growth of Caragana korshinskii varied with binder, filler, and water-retaining agent combinations. *Yang et al. (2020)* further found that different material ratios significantly affected the physical properties, germination traits, and seedling growth of pelleted sorghum-sudangrass hybrid seeds. Likewise, *Muhammad et al. (2025)* demonstrated that filler composition and binder type jointly influenced pellet physical traits, germination, seedling emergence, and vigor in red clover, while *Pedrini et al. (2023)* showed that pelleting improved the handling and precision-seeding performance of small-seeded species used for ecological restoration.

Despite these advances, these findings cannot be directly transferred to *L. chinensis*. Compared with the seeds examined in previous studies, *L. chinensis* seeds are awned, slender, and highly irregular, traits that may markedly affect binder wetting, powder adhesion, coating formation, and pellet flowability. In addition, many previous studies focused mainly on one or several indicators, such as germination, pellet quality, or seedling growth, whereas integrated evaluations combining pellet uniformity, seed-bearing rate, compressive strength, cracking time, germination, and emergence remain limited, especially for *L. chinensis*. Therefore, a formulation specifically designed for *L. chinensis* is still needed to address both its special seed morphology and its requirement for mechanized precision sowing.

Accordingly, CMC was selected as the binder and diatomite and talcum powder as the filler materials, considering their applicability, availability, and practical suitability for seed pelleting. It was hypothesized that the pelleting performance of *L. chinensis* seeds is jointly regulated by binder concentration, filler composition, and seed-to-powder ratio, and that an optimal formulation exists to balance pellet uniformity, structural stability, cracking behavior, and seedling emergence. Therefore, single-factor experiments were conducted to screen suitable ranges of CMC concentration, filler ratio, and seed-to-powder ratio, followed by a three-factor, three-level orthogonal experiment to optimize the formulation. Pellet uniformity, seed-bearing rate, compressive strength, cracking time, germination rate, and emergence rate were used as evaluation indices. The results are expected to provide a theoretical basis and practical reference for pelleting formulation design and mechanized precision sowing of *L. chinensis* seeds.

MATERIALS AND METHODS

Experimental materials

Leymus chinensis seeds (cultivar Zhongcao 27) were purchased from Suqian Lvqin Landscape Engineering Co., Ltd. on October 25, 2025. According to the supplier specifications, seed purity was ≥85%, initial germination was ≥65%, moisture content was ≤13%, and the 1000-seed weight was 1.8 g. The initial germination rate of the unpelleted seeds measured in this study was 70.0%. The pelleting materials included talcum powder (400 mesh), diatomite (500 mesh), and sodium carboxymethyl cellulose (CMC), all purchased from Henan Changyu Chemical Products Co., Ltd. The main instruments used in this study included a seed pelleting machine, an electronic balance, an NDJ-8S digital rotational viscometer, a texture analyzer, a YT-100L intelligent electric thermostatic incubator, and a Runfeng R-2000 suspension dryer.

Experimental methods

Pelleting procedure

Well-filled, uniformly sized *Leymus chinensis* seeds were cleaned and weighed for each treatment, then pelleted in a rotary small-scale seed pelleting machine at 720 r·min^{-1}. The filler amount was determined by the preset seed-to-powder ratio, and diatomite and talcum powder were premixed at the designated ratio. During pelleting, CMC solution was first sprayed onto the seeds for wetting, followed by gradual addition of the filler in portions. Binder and filler were applied alternately until the predetermined amount of filler had been fully incorporated. The pellets were then rotated without further material addition for 5 min to improve compactness, followed by a small amount of binder for surface fixation. Finally, the pelleted seeds were dried at 50 °C for 5 min and cooled before use. Except for the tested factors, all other conditions were kept constant. Pelleting was conducted indoors in winter at an ambient temperature above 15 °C.

Determination of CMC solution viscosity and torque

With reference to published studies and the viscosity requirements for *L. chinensis* seed pelleting, CMC solutions with mass concentrations of 0.75%, 1.00%, 1.25%, 1.50%, 1.75%, and 2.00% were prepared for measurement. The solutions were fully dissolved at room temperature and left to stand for deaeration before testing (*Guo et al., 2023*). Viscosity was measured using an NDJ-8S digital rotational viscometer with spindle No. 3 at 60 r·min^{-1}. The viscosity and corresponding torque of each treatment were recorded three times, and the average value was taken as the final result.

Single-factor experimental design

To identify the key factors affecting the pelleting performance of *L. chinensis* seeds, single-factor experiments were conducted using CMC concentration, filler ratio (diatomite:talcum powder), and seed-to-powder ratio as the test factors. The factor ranges were determined by synthesizing those reported in representative studies on seed pelleting formulations for Caragana, wheatgrass, sorghum-sudangrass hybrid, Seriphidium borotalense, quinoa, and Rheum tanguticum, so as to cover both feasible and potentially unsuitable levels for *L. chinensis* seed pelleting (*Hossaini et al., 2025*). In each experiment, only one factor was varied while the others were kept constant. The fixed conditions and factor levels are shown in Table 1. For all treatments, pelleting was carried out with a constant seed mass, and filler amount was determined according to the preset seed-to-powder ratio. Treatments that failed to form complete and stable pellets were used only for feasible-range screening and were excluded from subsequent statistical analysis (*Li et al., 2023*).

Table 1

Factors and levels of the single-factor experiment

Factor	Fixed condition 1	Fixed condition 2	Levels
CMC concentration	Filler ratio 8:2	Seed-to-powder ratio 1:5	0.75%, 1.00%, 1.25%, 1.50%, 1.75%, 2.00%
Filler ratio (diatomite:talcum powder)	CMC concentration 1.25%	Seed-to-powder ratio 1:5	10:0, 9:1, 8:2, 7:3, 6:4, 5:5, 4:6, 3:7, 2:8, 1:9, 0:10
Seed-to-powder ratio	CMC concentration 1.25%	Filler ratio 7:3	1:1, 1:2, 1:3, 1:4, 1:5, 1:6

Orthogonal experimental design

Based on the feasible ranges identified in the single-factor experiments, CMC concentration, filler ratio, and seed-to-powder ratio were selected as the factors in the orthogonal experiment. Each factor had three levels, and an L9 (3^3) orthogonal array was used to optimize the pelleting formulation for *L. chinensis* seeds. The factors and levels are shown in Table 2. Nine treatments were arranged according to the orthogonal design. Pelleting was performed as described above, and the relevant indices were then measured. Range analysis and a comprehensive scoring method were used to determine the optimal formulation (*Moses et al., 2025*).

Table 2

Factors and levels of the orthogonal experiment

Factor	Level 1	Level 2	Level 3
A CMC concentration	1.00%	1.25%	1.50%
B Filler ratio (diatomite:talcum powder)	7:3	6:4	8:2
C Seed-to-powder ratio	1:4	1:6	1:5

Determination of evaluation indices

Pelleted seeds from each treatment were randomly sampled to determine seed-bearing rate, pellet uniformity, compressive strength, and cracking time. All treatments were conducted with three independent replicates. In each replicate, 100 pellets were used for seed-bearing rate after manually removing the coating layer and counting valid pellets, and another 100 pellets were used for pellet uniformity; pellets with mass within ±10% of the target pellet mass were regarded as qualified. Compressive strength was measured on 10 pellets per replicate using a texture analyzer, and cracking time was determined on 20 pellets per replicate by recording the time from immersion in water to obvious cracking or complete disintegration (*Zubaidah et al., 2022*). In the single-factor experiment, 20 pelleted seeds per replicate were incubated for 7 d at 20–25 °C under a 12 h light/12 h dark photoperiod, with relative humidity of approximately 85% and light intensity of 200–300 μmol m^{-2} s^{-1}. Germination was defined as radicle emergence exceeding one-half of the seed length. In the orthogonal experiment, 20 pelleted seeds per replicate were sown in soil-filled foam boxes and cultured for 15 d at 20–25 °C and 80%–90% relative humidity. The substrate was garden soil containing humus, and water was supplied twice daily using a fine mist sprayer (*Palani-Vasantha et al., 2024*). Emergence rate was then recorded. The formulas used to calculate these indices were as follows:

$$S = \frac{N_s}{N_1} \times 100\% \tag{1}$$

$$U = \frac{N_q}{N_2} \times 100\% \tag{2}$$

$$P = \frac{\sum_{i=1}^{n} P_i}{n} \tag{3}$$

$$T = \frac{\sum_{i=1}^{n} T_i}{n} \tag{4}$$

$$G = \frac{N_g}{N_3} \times 100\% \tag{5}$$

$$E = \frac{N_e}{N_4} \times 100\% \tag{6}$$

where S is the seed-bearing rate (%); N_s is the number of valid pellets; N_1 is the total number of pellets examined for seed-bearing rate; U is the pellet uniformity (%); N_q is the number of qualified pellets; N_2 is the total number of pellets examined for pellet uniformity; P is the mean compressive strength (*N*); P_i is the first rupture force of the i-th pellet; T is the mean cracking time (s); T_i is the cracking time of the i-th pellet; n is the number of tested pellets; G is the germination rate (%); N_g is the number of germinated seeds; N_3 is the total number of seeds tested in the germination test; E is the emergence rate (%); N_e is the number of emerged seedlings; and N_4 is the total number of seeds tested in the emergence test.

Data processing and statistical analysis

Experimental data were organized and analyzed using Excel and SPSS software, and the results are presented as mean ± standard deviation. In the single-factor experiments, one-way analysis of variance (ANOVA) was used to test the significance of differences among treatments. When the assumption of homogeneity of variance was met, Duncan's multiple range test was applied for multiple comparisons; otherwise, the Games–Howell test was used (*Patyal et al., 2025; Pedrini et al., 2020*). In the orthogonal experiment, range analysis and a comprehensive scoring method were employed to evaluate the effects of different factors on pelleting performance (*Sohail et al., 2022*). The significance level was set at $P < 0.05$.

RESULTS AND ANALYSIS

Results and analysis of the single-factor experiments

Single-factor experiments were conducted to determine suitable ranges of CMC concentration, filler ratio, and seed-to-powder ratio for *L. chinensis* seed pelleting. Pellet uniformity, seed-bearing rate, cracking time, compressive strength, and germination rate were used as evaluation indices, and treatments that failed to form stable pellets were excluded from statistical analysis (*Sprey et al., 2025*).

Effect of CMC concentration on the pelleting performance of Leymus chinensis seeds

To further characterize the adhesive properties at different CMC concentrations, the viscosity and torque of CMC solutions were measured, and the results are shown in Fig. 1.

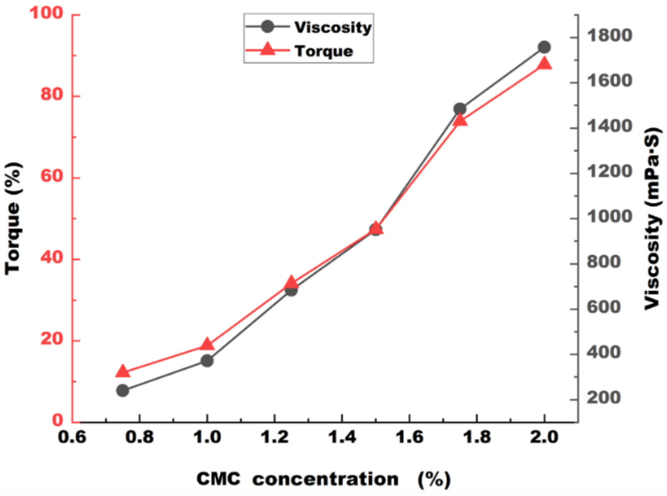


Fig. 1 - Effects of CMC concentration on solution viscosity and torque

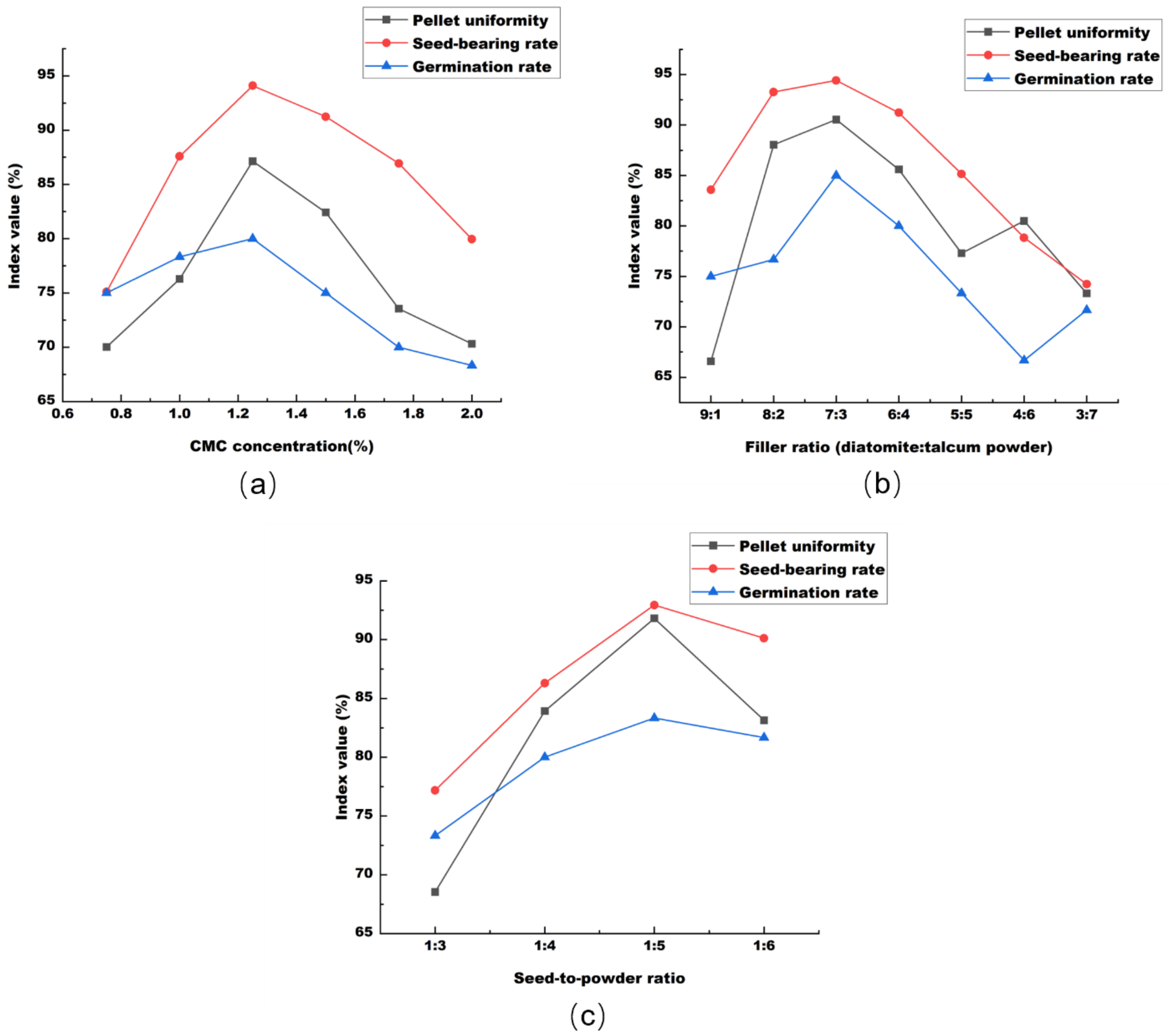
As shown in Fig. 1, both viscosity and torque generally increased with increasing CMC concentration, indicating that the rheological properties of the adhesive were strongly concentration-dependent. The effects of CMC concentration on pelleting-related indices are presented in Table 3, and the corresponding variation trends are shown in Fig. 2(a).

Table 3

Effects of CMC concentration on pelleting-related indices of *L. chinensis* seeds

CMC concentration (%)	Pellet uniformity (%)	Seed-bearing rate (%)	Cracking time (s)	Compressive strength (N)	Germination rate (%)
0.75	70.02±2.04^{d}	75.10±0.46	55.63±8.54^{a}	5.70±0.31	75.00±5.00
1.00	76.29±1.90^{c}	87.59±0.74	54.66±6.33^{a}	5.99±0.17	78.33±2.89
1.25	87.14±1.50^{a}	94.10±1.83	54.13±5.66^{a}	7.55±0.46	80.00±0.00
1.50	82.42±1.22^{b}	91.24±1.34	83.67±23.64^{b}	6.74±1.08	75.00±0.00
1.75	73.55±2.92^{cd}	86.93±1.79	129.21±18.68^{c}	6.75±1.11	70.00±0.00
2.00	70.32±2.52^{d}	79.95±5.26	129.21±17.18^{c}	6.81±1.15	68.33±2.89

Note: *Data in the table are presented as mean ± standard deviation. Duncan's multiple range test was used for pellet uniformity and cracking time, whereas the Games–Howell test was applied to the other indices. Different lowercase letters within the same column indicate significant differences among treatments ($P < 0.05$). No significant differences were observed in the other indices ($P > 0.05$).*



(a) (b)

(c)

Fig. 2 - Effects of CMC concentration, filler ratio, and seed-to-powder ratio on pellet uniformity, seed-bearing rate, and germination rate of pelleted *L. chinensis* seeds

Note: *(a) CMC concentration; (b) Filler ratio; (c) Seed-to-powder ratio*

With increasing CMC concentration, pellet uniformity, seed-bearing rate, and germination rate first increased and then decreased, whereas cracking time generally increased. Among the tested concentrations, 1.25% CMC produced the highest pellet uniformity (87.14%) and seed-bearing rate (94.10%), and also gave the highest germination rate (80.00%) and compressive strength (7.55 N), although the latter two did not differ significantly from several other treatments. In contrast, cracking time remained relatively low at 0.75%–1.25% CMC but increased markedly when the concentration exceeded 1.25%, indicating that excessive binder concentration reduced the disintegration efficiency of the pellets. Overall, 1.25% CMC provided the best balance between pellet formation, structural stability, and biological performance and was therefore considered the most suitable concentration in the single-factor experiment.

Effect of filler ratio on the pelleting performance of Leymus chinensis seeds

The pelleting-related indices obtained under different filler ratios are presented in Table 4, and the corresponding variation trends are shown in Fig. 2(b).

Table 4

Effects of filler ratio on pelleting-related indices of *L. chinensis* seeds

Filler ratio (diatomite:talcum powder)	Pellet uniformity (%)	Seed-bearing rate (%)	Cracking time (s)	Compressive strength (N)	Germination rate (%)
9:1	66.58±1.51^{f}	83.59±0.53^{c}	86.2±31.65	8.24±0.07	75.00±5.00^{bc}
8:2	88.04±0.74^{ab}	93.27±2.09^{a}	72.55±20.55	7.89±0.07	76.67±2.89^{b}
7:3	90.54±1.02^{a}	94.42±2.92^{a}	63.78±10.87	8.5±0.29	85.00±0.00^{a}
6:4	85.60±2.17^{bc}	91.22±1.30^{a}	89.80±10.34	7.76±0.17	80.00±0.00^{ab}
5:5	77.30±1.78^{d}	85.15±3.66^{b}	69.54±17.28	6.53±0.42	73.33±2.89^{bc}
4:6	80.50±0.95^{cd}	78.83±0.49^{d}	102.22±12.58	8.38±0.19	66.67±2.89^{c}
3:7	73.31±2.19^{e}	74.23±2.46^{e}	106.70±13.29	8.07±0.05	71.67±2.89^{bc}

***Note**: Data are presented as mean ± standard deviation. Pellet uniformity, seed-bearing rate, and germination rate were compared using Duncan's multiple range test, whereas compressive strength was analyzed using the Games–Howell test. No significant difference was observed in cracking time (P > 0.05). Different lowercase letters within the same column indicate significant differences among treatments (P < 0.05).*

Filler ratio had a pronounced effect on pellet quality and germination performance. As the proportion of diatomite and talcum powder changed, pellet uniformity, seed-bearing rate, and germination rate all showed clear variation. Among the tested treatments, the 7:3 ratio produced the highest pellet uniformity (90.54%), seed-bearing rate (94.42%), compressive strength (8.50 N), and germination rate (85.00%). Although cracking time did not differ significantly among filler ratios, the 7:3 treatment also showed a relatively low value, indicating satisfactory disintegration performance. When the talcum powder proportion was excessively high, both pellet quality and germination performance tended to decline. Therefore, the filler ratio of 7:3 was considered the most suitable level in the single-factor experiment.

Effect of seed-to-powder ratio on the pelleting performance of Leymus chinensis seeds

The pelleting-related indices obtained under different seed-to-powder ratios are presented in Table 5, and the corresponding variation trends are shown in Fig. 2(c).

Table 5

Effects of seed-to-powder ratio on pelleting-related indices of *L. chinensis* seeds

Seed-to-powder ratio	Pellet uniformity (%)	Seed-bearing rate (%)	Cracking time (s)	Compressive strength (N)	Germination rate (%)
1:3	68.54±2.94^{c}	77.18±1.82	82.23±10.52	7.40±0.03^{c}	73.33±2.89^{b}
1:4	83.93±4.50^{b}	86.30±0.61	85.54±10.67	6.74±0.19^{d}	80.00±5.00^{a}
1:5	91.81±1.29^{a}	92.94±4.26	67.59±15.02	8.40±0.18^{a}	83.33±2.89^{a}
1:6	83.14±3.19^{b}	90.12±5.64	82.46±15.21	7.95±0.10^{b}	81.67±2.89^{a}

***Note**: Data are presented as mean ± standard deviation. Pellet uniformity, compressive strength, and germination rate were compared using Duncan's multiple range test, whereas seed-bearing rate was analyzed using the Games–Howell test. No significant difference was observed in cracking time (P > 0.05). Different lowercase letters within the same column indicate significant differences among treatments (P < 0.05).*

As the amount of powder increased, most indices improved initially and then either stabilized or declined slightly. The seed-to-powder ratio of 1:5 gave the highest pellet uniformity (91.81%), seed-bearing rate (92.94%), and compressive strength (8.40 N), and also maintained a relatively high germination rate (83.33%). By comparison, insufficient powder addition resulted in poor pellet formation and lower overall performance, whereas further increasing the powder amount did not produce additional improvement. Cracking time was not significantly affected by seed-to-powder ratio. Taken together, these results indicate that a seed-to-powder ratio of 1:5 was the most suitable level in the single-factor experiment.

Comprehensive comparison of the single-factor experimental results

Overall, the single-factor experiments confirmed that CMC concentration, filler ratio, and seed-to-powder ratio all affected the pelleting performance of *L. chinensis* seeds. Among the evaluated indices, pellet uniformity, seed-bearing rate, and germination rate were the most responsive to changes in factor levels, whereas cracking time mainly reflected the disintegration characteristics of the pellets. Based on the overall results, the most suitable single-factor levels were 1.25% CMC, a filler ratio of 7:3, and a seed-to-powder ratio of 1:5, which were subsequently used to define the factor ranges for the orthogonal experiment. Representative pellet appearances under different coating conditions are shown in Fig. 3.

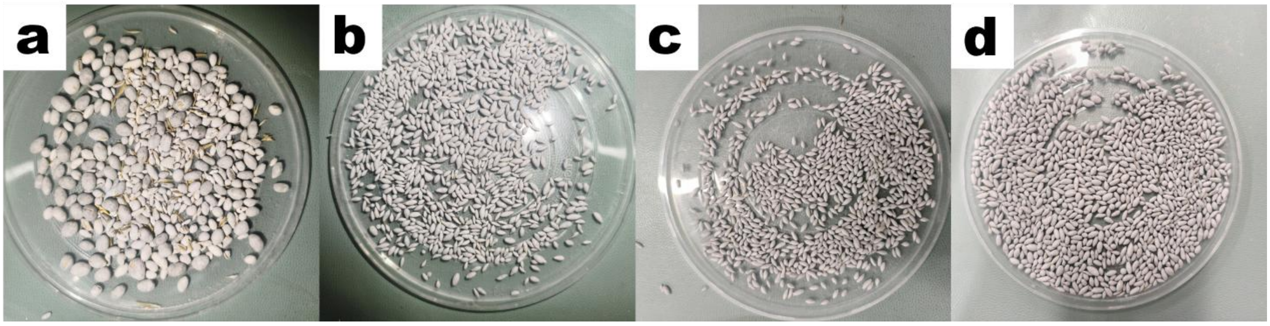


Fig. 3 - Appearance of pelleted *L. chinensis* seeds under different coating conditions

Note: *a, 2.00% CMC, filler ratio 8:2, and seed-to-powder ratio 1:5; b, 1.25% CMC, filler ratio 8:2, and seed-to-powder ratio 1:5; c, 1.25% CMC, filler ratio 8:2, and seed-to-powder ratio 1:4; d, 1.25% CMC, filler ratio 7:3, and seed-to-powder ratio 1:5.*

As shown in Fig. 3, obvious differences were observed in pellet sphericity, surface smoothness, and appearance uniformity under different formulations. Compared with the other treatments, pellets produced under the better-performing formulations were more regular in shape, denser on the surface, and more uniform in appearance. In contrast, excessive CMC concentration or insufficient powder addition led to poorer appearance consistency. These visual observations were consistent with the trends shown in Tables 3–5 and Fig. 2.

Results and analysis of the orthogonal experiment

Based on the single-factor experiments, CMC concentration, filler ratio, and seed-to-powder ratio were selected as the three factors for the orthogonal experiment, and an L9 (3^3) orthogonal design was adopted to further optimize the pelleting formulation for *L. chinensis* seeds (*Ma et al., 2023; Sun et al., 2025*). The mean values of the measured indices for each treatment are presented in Table 6.

Analysis of the results of each treatment in the orthogonal experiment

Table 6

Mean values of pelleting-related indices in the orthogonal experiment

Treatment No.	A CMC concentration (%)	B Filler ratio (diatomite:talcum powder)	C Seed-to-powder ratio	Pellet uniformity (%)	Seed-bearing rate (%)	Compressive strength (N)	Cracking time (s)	Emergence rate (%)
1	1.00	7:3	1:4	87.47	90.23	8.24	77.09	81.67
2	1.00	6:4	1:6	82.95	90.17	8.23	85.13	78.33
3	1.00	8:2	1:5	92.26	92.10	8.76	87.65	88.33
4	1.25	7:3	1:6	85.75	88.75	8.15	86.06	86.67
5	1.25	6:4	1:5	86.93	90.90	9.06	90.22	81.67
6	1.25	8:2	1:4	95.40	96.22	9.91	75.37	95.00

Treatment No.	A CMC concentration (%)	B Filler ratio (diatomite:talcum powder)	C Seed-to-powder ratio	Pellet uniformity (%)	Seed-bearing rate (%)	Compressive strength (N)	Cracking time (s)	Emergence rate (%)
7	1.50	7:3	1:5	93.26	94.29	8.78	87.12	90.00
8	1.50	6:4	1:4	83.69	88.29	8.06	107.19	80.00
9	1.50	8:2	1:6	86.07	88.43	8.60	96.11	81.67

As shown in Table 6, clear differences were observed among the nine treatment combinations. Treatment 6 exhibited the highest pellet uniformity (95.40%), seed-bearing rate (96.22%), compressive strength (9.91 N), and emergence rate (95.00%), while also maintaining the shortest cracking time (75.37 s) among the tested combinations. These results indicate that Treatment 6 had the most favorable overall performance among the orthogonal treatments. By contrast, some treatments showed acceptable performance for individual indices but lacked a balanced overall response. Therefore, direct comparison of the measured values already suggested that Treatment 6 had a clear comprehensive advantage.

Range analysis of the orthogonal experiment

Range analysis showed that, except for cracking time, the other four major indices consistently favored A2B3C3, corresponding to 1.25% CMC, a filler ratio of 8:2, and a seed-to-powder ratio of 1:5. As a reverse indicator, cracking time showed an optimal combination of A1B1C1. However, because cracking time carried a relatively low weight in the comprehensive evaluation, it was used mainly as a supplementary reference.

Comprehensive scoring analysis

Considering the differences in the importance of the evaluated indices, the orthogonal experimental results were standardized and subjected to a weighted comprehensive scoring analysis (*Raja et al., 2025; Zhang et al., 2006*). The weights assigned to pellet uniformity, seed-bearing rate, and emergence rate were 0.25, 0.25, and 0.30, respectively, whereas compressive strength and cracking time were each assigned a weight of 0.10. The comprehensive scores for each treatment are presented in Table 7, and the range analysis of the comprehensive scores is shown in Table 8.

Table 7

Comprehensive scores of treatments in the orthogonal experiment

Treatment No.	A CMC concentration (%)	B Filler ratio	C Seed-to-powder ratio	Comprehensive score
1	1.00	7:3	1:4	0.3164
2	1.00	6:4	1:6	0.1378
3	1.00	8:2	1:5	0.5863
4	1.25	7:3	1:6	0.2921
5	1.25	6:4	1:5	0.3297
6	1.25	8:2	1:4	1.0000
7	1.50	7:3	1:5	0.7082
8	1.50	6:4	1:4	0.0449
9	1.50	8:2	1:6	0.1912

Table 8

Range analysis of comprehensive scores

Factor	K1	K2	K3	k1	k2	k3	R	Optimal level
A	1.0404	1.6218	0.9443	0.3468	0.5406	0.3148	0.2258	A2
B	1.3166	0.5124	1.7775	0.4389	0.1708	0.5925	0.4217	B3
C	1.3613	0.6211	1.6242	0.4538	0.2070	0.5414	0.3344	C3

***Note**: A, B, and C represent CMC concentration, filler ratio, and seed-to-powder ratio, respectively; 1, 2, and 3 represent Level 1, Level 2, and Level 3 of the corresponding factor, respectively.*

Treatment 6 achieved the highest comprehensive score and was therefore the best among the tested combinations. Range analysis further showed that the relative importance of the three factors was filler ratio > seed-to-powder ratio > CMC concentration. Although the theoretical optimal combination was A2B3C3 (1.25% CMC, 8:2, 1:5), this treatment was not included in the orthogonal array. Based on the measured results, Treatment 6 (1.25% CMC, 8:2, 1:4) was selected as the recommended formulation.

Comparison of seedling emergence performance among different treatments

Fig. 4 - Comparison of seedling emergence of *L. chinensis* seeds under different pelleting treatments in foam boxes

***Note**: a, unpelleted seeds; b, Treatment 6 (1.25% CMC, filler ratio 8:2, seed-to-powder ratio 1:4); c, theoretical optimal combination from range analysis (1.25% CMC, filler ratio 8:2, seed-to-powder ratio 1:5); d, Treatment 8 (1.50% CMC, filler ratio 6:4, seed-to-powder ratio 1:4).*

Clear differences in seedling number and spatial uniformity were observed among treatments. Unpelleted seeds and Treatment 8 showed poor emergence, with fewer and less uniformly distributed seedlings. In contrast, Treatment 6 and the theoretical optimal combination showed better emergence performance. Among them, Treatment 6 exhibited the best emergence uniformity, which was consistent with the comprehensive scoring results. These observations further support Treatment 6 (1.25% CMC, 8:2, 1:4) as the most suitable formulation among the tested combinations.

CONCLUSIONS

CMC concentration, filler ratio, and seed-to-powder ratio all affected the pelleting performance of *L. chinensis* seeds, indicating that formulation optimization depends on the coordinated regulation of binder properties, filler composition, and coating amount rather than on a single factor alone. The single-factor experiment identified 1.25% CMC, a filler ratio of 7:3, and a seed-to-powder ratio of 1:5 as suitable levels for subsequent optimization. Among the orthogonal treatments, Treatment 6 (1.25% CMC, 8:2, 1:4) showed the best overall performance and was selected as the recommended formulation. The results further indicate that pelleting formulation optimization for *L. chinensis* seeds is essentially a balancing process among pellet uniformity, seed-bearing rate, structural stability, cracking behavior, and seedling emergence. The recommended formulation provided a favorable compromise between coating compactness and post-sowing disintegration, which is important for maintaining both pellet quality during handling and biological performance after sowing. Therefore, this study provides not only a suitable pelleting formulation for *L. chinensis* seeds, but also a practical reference for seed processing, mechanized precision sowing, and grassland restoration. Future work should further evaluate field performance, storage stability, abrasion resistance, and cracking and emergence behavior under different soil moisture conditions.

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