Instability motion characteristics of overburden rock and the distribution pattern of fissures in shallow thick seam mining

Jianwei Li1, Changyou Liu2, Xinwei Guo1* & Xiangye Wu1

This paper analyzes the instability movement characteristics of overburden in shallow thick coal seam mining and its influence on the development and distribution of fault fractures. The similarity simulation experiment and theoretical analysis were combined based on the classification of the occurrence characteristics of the key bearing layer in the overburden rock of shallow thick seam mining. This study investigated the fracture characteristics and the instability motion mode of the key bearing layer in shallow thick seam mining and their effects on the distribution of fissures in the overburden rock. The results indicated that according to the horizon of the key bearing layer, the occurrence of overburden rock could be classified into 2 categories, i.e., the horizon of the key bearing layer within the caving zone and within the fissure zone. The horizon of the key bearing layer has a significant effect on the fracture characteristics and the instability motion mode of the key bearing layer. When the horizon of the key bearing layer is in the overburden caving zone, a "step rock beam" develops after fracture, and the instability motion mode is sliding instability. When the horizon of the key bearing layer is in the overburden fissure zone, a "masonry-like beam" develops after fracture, and the instability motion mode is rotary instability. The fracture instability of the key bearing layer could control the development and distribution of fissures in the overburden rock, and the whole favorable zone for the development of fissures extends along the advancing direction of the working face in a form of "diagonal stripes" with the instability motion of the key bearing layer.

As the focus of coal resource development in China shifts further to the west, especially due to the continuous escalation of the shallow coal seam mining scale represented by the Shendong Mining Area, the western region has become the principal source of coal in China1–3. Using Shendong Mining Area as an example, the mined seams are principally concentrated in the Yanan Formation of the Jurassic System. The buried depth of the coal seam is ≤ 150 m, which belongs to the shallow buried coal seam, and the overlying rock is relatively thin. The surfaces covered with loess or aeolian sand, and fragile ecological surface environments4–7. Shallow coal seams can cause serious surface damage, mining subsidence, and fissures during mining8,9. The surface collapses and fissures connected to the underground goaf area may frequently cause safety hazards, such as air leaks and water bursting-induced sand collapses on the working face, as well as the loss of groundwater resources and destruction of the surface ecology, which can affect safe and ecologically friendly mining in mines10–12. The typical mining strata pressure behaviors of shallow coal seams are as follows. The fracture and instability motion of the key bearing layer in the bedrock layer directly result in obviously higher resistance at stope supports, support damage, rib spalling, and sidestepped subsidence and may cause overall movement of the surface overburden, possibly causing mining fissures directly connected to the surface13–16. Therefore, the fracture instability of the key bearing layer has a controlling effect on the intensity of mine strata pressure behaviors on the working face and the development and distribution of fissures17,18.

Based on classification of the occurrence characteristics of the key bearing layer in the overburden rock of shallow thick seam mining, this paper combined similarity simulation experiment and theoretical analysis to...
study the fracture characteristics and instability motion mode of the key bearing layer for shallow thick seam mining and their effects on the distribution of fissures in overburden rock. The study findings are of certain guidance and reference significance to the surface subsidence of shallow thick seams, the coordinated control of the mine strata pressure on the working face, the water bursting-induced sand collapse in the goaf area, and the spontaneous combustion of leftover coal.

**Classification of the occurrence characteristics of the overburden rock of shallow thick seam mining**

According to previous research results\(^1\),\(^2\), there is a key bearing rock layer in the overlying rock layer of the coal seam. The periodic fracture of this rock stratum causes movement of its overlying strata and the loose layer and leads to ground ground surface fissures. This stratum is called key bearing layer. The key bearing layer is a hard and thick stratum, which supports the upper strata and the loose covering layer in some form of mechanical structure. Their periodic fracture directly influences roof pressure, strata movement, and mining subsidence. Therefore, studying the movements of the key bearing layer is of great significance for instability motion characteristics of the overburden rock and their effects on the development and distribution of fissures.

The distribution of the overlying strata in the shallow coal seam is shown in Fig. 1. The coal seam is covered with strata of 1 to \(m\) m. The upper layer is the loose covering layer which is composed of soil or weak rock\(^2\)–\(^4\). The thickness of each strata is set to be \(h_i\), bulk density is \(\gamma_i\) kN/m\(^3\), elastic modulus is \(E_i\) MPa, and \(i = 1, 2, 3, \ldots, m\). According to the theory of key strata, the loading key strata of overlying strata in shallow coal seam must meet the following three conditions\(^5\):

\[
\begin{align*}
q_n > q_{n-1} > \cdots > q_1 \\
q_n = (q_n)_{overburden}, \text{ and } (q_n)_{overburden} > (q_{n+1})_{overburden} > \cdots > (q_m)_{overburden} \\
L_n > L_{n+1} > \cdots > L_m.
\end{align*}
\]

(1)

Among them:

\[
\begin{align*}
(q_n)_{overburden} &= E_n h_n^3 \left( \sum_{i=n}^{m} \gamma_i h_i + \gamma_{overburden} h_{overburden} \right) / \sum_{i=n}^{m} E_i h_i^3 \\
(q_m)_{overburden} &= E_m h_m^3 \sum_{i=n}^{m} \gamma_i h_i / \sum_{i=n}^{m} E_i h_i^3.
\end{align*}
\]

In the formula:

- \((q_n)_{overburden}\)—the load of bedrock strata and covering layer upon strata \(n\), kN/m\(^2\);
- \((q_m)_{overburden}\)—the load of strata \(m\) upon strata \(n\), kN/m\(^2\);
- \(q_i\) (\(i = 1, 2, 3, \ldots, n\))—the load of the stratum \(i\), kN/m\(^2\);
- \(L_i\) (\(i = n, n+1, \ldots, m\))—the caving step of the stratum \(i\), m;
- \(\gamma_i, E_i, h_i\)—the average bulk density, elastic modulus and thickness of stratum \(i\), kN/m\(^3\), MPa, m;
- \(\gamma_{overburden}, h_{overburden}\)—the average bulk density and thickness of bedrocks and overburden, kN/m\(^3\), m.

The position and thickness of the key bearing layer in the overburden rock of a mining area not only affect the fragment dimensions and instability motion mode but also can significantly affect the instability motion and the distribution of mining-induced fissures in the overburden rock of shallow thick seam mining. Therefore,
the occurrence conditions of the key bearing layer in stope overburden rock were classified based on the typical occurrence conditions in overburden rock of shallow thick seam working faces in Western China, setting a foundation for further analysis of the fracture instability of overburden rock in shallow thick seam mining and the distribution patterns of fissures.

Table 1 shows the statistical analysis of the information about working face seam thickness and the horizon and thickness of the key bearing layer in shallow thick seam mining in Western China.

| Coal Mine          | Key bearing layer lithology | Seam thickness/m | Seam depth/m | Distance from coal seam/m | Thickness/m | Height/m | Position of key bearing layer |
|--------------------|----------------------------|------------------|--------------|--------------------------|-------------|---------|-------------------------------|
| Da Luta coal mine  | Fine sandstone             | 14.6             | 102.3        | 38.3                     | 10.3        | 58.2    | Caving zone                   |
| Bu Ertai coal mine | Sandy mudstone             | 17.7             | 145.8        | 75.1                     | 16.3        | 70.8    | Fissure zone                  |
| Chang Hangou coal mine | Medium sandstone         | 17.9             | 110.2        | 76.3                     | 32.2        | 71.6    | Fissure zone                  |
| Liu Ta coal mine   | Fine sandstone             | 9.2              | 90.9         | 30.5                     | 15.8        | 36.9    | Caving zone                   |
| Cun Caota coal mine| Sandy mudstone             | 7.8              | 146.2        | 45.1                     | 26.3        | 31.3    | Fissure zone                  |
| Shang Wan coal mine| Sandy mudstone             | 7.2              | 64.4         | 26.6                     | 14.4        | 28.9    | Caving zone                   |
| Ha Lagou coal mine | Fine sandstone             | 5.5              | 94.4         | 49.3                     | 18.5        | 22.0    | Fissure zone                  |
| Yu Jialiang coal mine | Fine sandstone           | 14.9             | 140.3        | 81.6                     | 31.9        | 59.5    | Fissure zone                  |
| Chuancao Gedan coal mine | Siltstone              | 12.8             | 116.6        | 63.4                     | 9.2         | 51.2    | Fissure zone                  |

Table 1. Statistics of the overburden rock occurrence characteristics of shallow thick seam mining in Western China (the rock hulking coefficient in the caving process is 1.25).

Building of a physical similarity simulation model and experimental schemes

Based on the occurrence conditions of coal and rock layers of shallow thick coal seam mining in a coal mine in western China, physical similarity simulation testing on the plane stress was performed to analyze the fracture instability characteristics of overburden rock with an advancing working face when the key bearing layer of shallow thick seam mining is in the overburden caving zone and fissure zone.

The size of the physical similarity simulation test stand was L × W × H = 2500 mm × 200 mm × 2000 mm. According to the theory of similarity, the geometric similarity ratio was 1:100, the bulk density similarity constant was 1.56, the stress similarity constant was 156 and the time similarity constant was 10^26. The similarity simulation models built for the key bearing layer located in the overburden caving zone and the fissure zone when the 4# seam was mined are shown in Fig. 3. According to scheme I in the figure, the key bearing layer of the overburden rock was 9.0 cm-thick medium-grained sandstone when the 4# seam was mined, and the height of the relax zone is 3.5 cm. According to scheme II, the key bearing layer was 9.0 cm-thick siltstone when the 4# seam was mined, and the height of the relax zone is 21.5 cm. In the similarity simulation test, the simulation materials for each rock formation were made from sand, calcium carbonate, lime, gypsum, and water mixed in certain proportions. The materials were horizontally arranged in layers, and the mica powder was spread between

Figure 2. Classification of the occurrence conditions in the overburden rock for shallow thick seam mining.
the layers to simulate the weak planes of the rock. For rock strata greater than 5.0 cm thick (except for the key bearing layer), a layered arrangement was performed according to the actual distribution of the weak planes. The compressive strength was taken as the principal similarity condition, and the similarity criteria were met during the modeling. The model does not require additional loads. Table 2 shows the physical and mechanical parameters of each layer.

After the model is made, parallel and vertical survey lines are arranged in the overall model, the spacing of survey lines is 10 cm, and survey points are arranged at the intersection of survey lines. During the simulation of excavation in the 4# coal seam, the mining height was 4.0 cm, the excavation step was 5.0 cm, and the length of the working face was 190 cm. For each excavation, the three-dimensional photogrammetry system is used to record the number of meters excavated in the working face and the data on the change in displacement of the overburden.

Fracture instability characteristics of overburden rock in shallow thick seam mining

Key bearing layer within the overburden caving zone. When the key bearing layer is within the overburden caving zone for 4# coal seam mining, the fracture instability characteristics of the overburden rock and the distribution characteristics of the fissures at different advancing distances are shown in Fig. 4.

As shown in Fig. 4, when the working face of the 4# coal seam advances approximately 75 m, the 9.0 m-thick medium-grained sandstone key bearing layer develops initial fracture weighting, and the length of fractured rock is 39 m. The fracture and instability motion of the key bearing layer cause the overburden rock to collapse and develop horizontal separation fissures. The vertical extent of the destruction zone is 25 m.
When the working face of the 4# coal seam advances approximately 95 m, the 9.0 m-thick medium-grained sandstone key bearing layer develops the first periodic fracture weighting, the fracture is located at the coal wall of the working face, and the length of the fractured rock is 24 m. The height of caving zone of the overburden rock increases, and the vertical extent of the destruction zone is 37 m. Longitudinal cracks appear on the ground surface.

When the working face of the 4# coal seam advances approximately 110 m, the vertical extent of the destruction zone is 40 m. The fracture depth from the ground surface downwards increases to approximately 17 m, but the ground surface fracture does not connect with the fissures in the overburden rock.

When the working face of the 4# coal seam advances approximately 130 m, the vertical extent of the destruction zone is 62.5 m. Multiple ground surface fractures and fissures in the overburden rock are connected. Significant subsidence on the ground.

Key bearing layer within the overburden fissure zone. The fracture instability characteristics of the overburden rock and distribution characteristics of the fissures at different advancing distances when the key bearing layer is within the overburden fissure zone for 4# coal seam mining are shown in Fig. 5.

As shown in Fig. 5, when the working face of the 4# coal seam advances approximately 115 m, the 9.0 m-thick siltstone key bearing layer develops initial fracture weighting, and the length of the fractured rock is 64 m. The fracture and instability motion of the key bearing layer cause the overburden rock to collapse and develop horizontal separation fissures and longitudinal fissures connected to the ground surface. The vertical extent of the destruction zone is 55 m.

When the working face of the 4# coal seam advances approximately 145 m, The vertical extent of the destruction zone is 62.5 m. Multiple ground surface fractures and fissures in the overburden rock are connected. Significant subsidence on the ground.

When the working face of the 4# coal seam advances approximately 165 m, the 9.0 m siltstone key bearing layer develops the second periodic fracture weighting, and the length of fractured rock is 39 m. The fracture movement causes longitudinal fissures directly connected to the ground surface to develop in the overburden rock and the cover layer, and the mean distance from other longitudinal fissures connected to the ground surface is approximately 30 m.

After, during the advancing process of the working face of the 4# coal seam, the number of ground surface fissures has increased. The ground surface subsides periodically.

Fracture instability motion mode of the overburden rock. According to the similarity simulation results, the instability motion modes of the key bearing layer with different horizons under periodic fracture and movement patterns of overburden rock are compared, as shown in Fig. 6. The results of the study (see Fig. 6) show that the fractured rock may turn into two structures, i.e., a "step rock beam" (Fig. 6a) and "masonry-like...
beam" (Fig. 6b), that is based on the geometrical characteristics and hinged structure of the rock. However, if the mined-out sections are not backfilled, the rock strata below the key bearing layer may collapse.

When the key bearing layer is located within the overburden caving zone. The vertical height range of the relaxation zone is small, and there are few collapsed rocks in the relaxation zone. The fallen rock cannot fill the destruction zone, there is a large free space in the destruction zone. In the broken key bearing layer, rock M and rock N form a "step rock beam" structure, rock N falls completely on the collapsed rocks, while rock M is unstable and moves with the advance of the working face.

When the key bearing layer is located within the overburden fissure zone. The vertical height range of the relaxation zone is big, and there are a large of collapsed rocks in the relaxation zone. Although the fallen rock cannot fill the destruction zone, there is less free space in the destruction zone. In the broken key bearing layer, rock M and rock N form a "step rock beam" structure. Rock N falls completely on the caved coal gangue, rock M rotates with the advance of the mining coal face, the movement form is manifested in downward sliding movement.

Figure 5. Overburden rock instability characteristics and fissures distribution characteristics of the key bearing layer located within the fissure zone.

Figure 6. Comparison of the periodic fracture instability motion modes of the key bearing layer and movement characteristics of overburden rock.
Effect of the instability motion of the key bearing layer on distribution of fissures in the overburden rock

The fissures in the overburden rock are caused by overburden movement exceeding the limit deformation during coal seam mining. During shallow coal seam mining, the rock strata movement causes vertical and horizontal displacements in the overburden rock, as shown in Fig. 7.

Points 4 and 5 in Fig. 7 are used as an example. The horizontal displacement difference $\Delta u = u_5 - u_4$ between two adjacent points in the overburden rock denotes the horizontal opening of a fissure between the two points. The vertical displacement difference $\Delta w = w_5 - w_4$ between the two points represents the vertical relative displacement of the fissure between the two points.

The coefficient of the displacement difference between two adjacent points is defined as $\gamma$, then $\gamma$ can be expressed as follows:

$$\gamma = \frac{\sqrt{(\Delta u)^2 + (\Delta w)^2}}{\Delta L},$$  \hspace{1cm} (2)

where $\Delta L$ stands for the distance between two adjacent points (m).

The value of $\gamma$ indicates the possibility of fracture between two points. The greater the $\gamma$ value is, the larger the displacement difference between the two points, and the greater the occurrence possibility of fracture.

According to the displacement change data of survey points, using “Surfer” drawing software, we plot the contour change cloud map of overburden rock displacement after the failure of the key bearing layer. As shown in Figs. 8 and 9.

Figures 8 and 9 show that as the coal seam is mined, the whole favorable zone for fissures development in the overburden rock extends along the advancing direction of working face in the form of "diagonal stripes". The position difference coefficient of overburden rock under the key bearing layer is large, which indicates that the fractured rocks within this range are often in an irregular or regular caving state, while the fissures in such rocks are disorderly and unsystematic.

The maximum value of the position difference coefficient of the overlying rock in the key bearing layer moves forward with the working face. The favorable zone for fissure development in the overburden rock above the key bearing layer extends with the instability motion of the key bearing layer.

Influenced by the caving angle of the rock strata, the horizon of the key bearing layer can significantly affect the extension range of the favorable zone for fracture fissure development in overburden rock; that is, when the key bearing layer is within the caving zone, the lag between the working face and favorable zone for fracture fissure development in the overburden rock is small, and when the key bearing layer is within the fissure zone, the lag is large.

Discussion and limitations of results

Through the experimental study of mining shallow buried coal seam, we have concluded some conclusions. These conclusions may provide some ideas for the study of the development law of overburden fissures caused by coal seam mining, and can also provide some help or suggestions for ground surface damage and ground surface repair caused by coal seam mining.

When mining shallowly buried coal seams, the ground surface will be damaged regardless of whether the key bearing layer is in the caving zone. When the key bearing layer is in the caving zone, the damage to the ground surface is larger, and when the key bearing layer is in the fissure zone, the damage to the ground surface is smaller. This conclusion can be drawn from Fig. 10. This shows that the zone of the key bearing layer has an important influence on the land ground surface damage.

In the case of exploitation of deposits at shallow depths of about 100 m, it is very important to protect the ground surface. Compared with studying the breaking laws of rock formations during the mining of shallow coal seams, we should study more relevant methods for protecting the ground surface and repairing the ground surface environment. For example, the method of filling goafs is used to protect the ground surface, and the method of filling ground surface cracks is used to repair the ground surface.
Conclusion
This paper analyzes the instability movement characteristics of overburden in shallow thick coal seam mining and its influence on the development and distribution of fault fractures. The physical similarity simulation experiment is used to carry out the coal seam mining experiment on the key bearing layer model in different zones. According to the experimental results and the data analysis, the following conclusions can be drawn.
By the horizon of key bearing layer, the occurrence conditions of the key bearing layer in the overburden rock of shallow thick seam mining can be classified into two categories, i.e., the key bearing layer within the caving zone and within the fissure zone. After the fracture of the key bearing layer, the fractured rock may turn into two structures, i.e., a “step rock beam” and “masonry-like beam” according to the geometrical characteristics and hinged structure of the rock.

The instability motion mode of the key bearing layer within the caving zone is sliding instability. The instability motion mode of the key bearing layer in the fissure zone is rotary instability.

The whole favorable zone for fracture fissure development in the overburden rock extends along the advancing direction of the working face in the form of “diagonal stripes”, and the favorable zone for fissure development in the overburden rock of the key bearing rock extends with the instability motion of the key bearing layer, while the horizon of the key bearing layer can significantly affect the extension range of the favorable zone for fracture fissure development in overburden rock.

**Data availability**

All data used to support the findings of this study are available from the corresponding author upon request.

Received: 20 January 2022; Accepted: 28 March 2022
Published online: 13 April 2022

**References**

1. Qian, M. G. On sustainable coal mining in China. *J. China Coal Soc.* 35(4), 529–534 (2010).
2. Li, J. W. & Liu, C. Y. Spatial-temporal distribution and gas conductivity of overburden fissures in the mining of shallow thick coal seams. *Eur. J. Environ. Civ. Eng.* 23(8), 1019–1033 (2019).
3. Zhang, D. S. et al. Development on basic theory of water protection during coal mining in northwest of China. *J. China Coal Soc.* 42(1), 36–43 (2017).
4. Li, J. W., Liu, C. Y. & Zhao, T. Effects of gully terrain on stress field distribution and ground pressure behavior in shallow seam mining. *Int. J. Min. Sci. Technol.* 26(2), 255–260 (2016).
5. Zhu, W. B. Study on the instability mechanism of key strata structure in repeating mining of shallow close distance seams. *J. China Coal Soc.* 36(6), 1065–1066 (2011).
6. Cui, X. M., Gao, Y. G. & Yuan, D. B. Sudden ground surface collapse disasters caused by shallow partial mining in Datong coalfield, China. *Nat. Hazards* 74(2), 911–929 (2014).
7. Tang, Z. S., An, H. & Shangguan, Z. P. The impact of desertification on carbon and nitrogen storage in the desert steppe ecosystem. *Ecol. Eng.* 84, 92–99 (2015).
8. Li, J. W., Liu, C. Y. & Bu, Q. W. Spatio-temporal evolution of overburden fissures in shallow thick coal seam mining. *J. Min. Saf. Eng.* 37(2), 238–246 (2020).
9. Hu, Z. Q., Fu, Y. H., Xiao, W., Zhao, Y. L. & Wei, T. T. Ecological restoration plan for abandoned underground coal mine site in Eastern China. *Int. J. Min Reclam. Environ.* 29(4), 316–330 (2015).
10. Chen, C. & Hu, Z. Q. Research advances in formation mechanism of ground crack due to coal mining subsidence in China. *J. China Coal Soc.* 43(3), 810–823 (2018).
11. Zhang, D. S., Fan, G. W. & Wang, X. F. Characteristics and stability of slope movement response to underground mining of shallow coal seams away from gullies. Int. J. Min. Sci. Technol. 22(1), 47–50 (2012).
12. Yu, X. Y., Guo, W. B., Zhao, B. C. & Wang, F. L. Study on mining subsidence law of coal seam with thick overlying loess stratum. Coal Sci. Technol. 43(7), 6–10 (2015).
13. Altun, A. O., Yilmaz, I. & Yildirim, M. A short review on the surficial impacts of underground mining. Sci. Res. Essay 21(5), 3206–3212 (2010).
14. Colesanti, C. et al. Detection of mining related ground instabilities using the permanent scatterers technique—A case study in the east of France. Int. J. Remote Sens. 26(1), 201–207 (2005).
15. Ma, L. Q., Zhang, D. S., Li, X., Fan, G. W. & Zhao, Y. F. Technology of groundwater reservoir construction in goafs of shallow coalfields. Int. J. Min. Sci. Technol. 19(6), 730–735 (2009).
16. Ma, L. Q., Cao, X. Q., Liu, Q. & Zhou, T. Simulation study on water-preserved mining in multi-excavation disturbed zone in close-distance seams. Environ. Eng. Manag. J. 12(9), 1849–1853 (2013).
17. Ju, J. F. & Xu, J. L. Ground surface stepped subsidence related to top-coal caving longwall mining of extremely thick coal seam under shallow cover. Int. J. Rock Mech. Min. Sci. 78(1), 27–35 (2015).
18. Li, J. W. & Liu, C. Y. Linkage-induced mechanism and control technology of pressure bump and ground surface geological damage in shallow coal seam mining of gully area. Arab. J. Geosci. 12(11), 349 (2019).
19. Qian, M. G. & Shi, P. W. Coal Mine Ground Pressure and Control (China University of Mining and Technology Press, 2003).
20. Huang, Q. X. Experimental research of overburden movement and subground surface water seeping in shallow seam mining. J. Univ. Sci. Technol. Beijing 14(6), 483–489 (2007).
21. Xu, J. L., Zhu, W. B. & Wang, X. Z. Classification of key strata structure of overlying strata in shallow coal seam. J. China Coal Soc. 34(7), 865–870 (2009).
22. Xu, J. L., Zhu, W. B. & Xu, J. F. Supports crushing types in the longwall mining of shallow seams. J. China Coal Soc. 39(8), 1625–1635 (2014).
23. Wang, X. F., Zhang, D. S., Sun, C. D. & Wang, Y. Ground surface subsidence control during bag filling mining of super high-water content material in the Handan mining area. Int. J. Oil Gas Coal Technol. 13(1), 87–102 (2016).
24. Li, J. W. & Liu, C. Y. Formation mechanism and reduction technology of mining-induced fissures in shallow thick coal seam mining. Shock. Vib. 2017, 1–14 (2017).
25. Skrzypkowski, K., Korzeniowski, W., & Nguyen Duc, T. Choice of powered roof support FAZOS-15/31–POz for Vang Danh hard coal mine. Inżynieria Mineralna. 21, 175–182 (2019).
26. Fan, G. W., Zhang, D. S. & Ma, L. Q. Overburden movement and fracture distribution induced by longwall mining of the shallow coal seam in the Shendong coal field. J. China Univ. Min. Technol. 40(2), 196–201 (2011).
27. Skrzypkowski, K. Determination of the backfilling time for the zinc and lead ore deposits with application of the BackfilCAD model. Energies 14, 3186 (2021).

Acknowledgements

The National Natural Science Foundation of China (51864036), the Program for Young Talents of Science and Technology in Universities of Inner Mongolia Autonomous Region (NJYT-19-B33), the Inner Mongolia Autonomous Region "Grassland Talents" Project Youth Innovation and Entrepreneurship Talent Training Program, and Support the Reform and Development of Higher Education-Postgraduate Education (0404062107) supported this work.

Author contributions

Conceptualization, J.L. and C.L.; methodology, J.L., C.L. and X.W.; experiment, J.L., X.G., X.W.; and supervision, X.G. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to X.G.

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2022