

## **Research** Article

# Effects of High-Voltage Electric Field Process Parameters on the Water-Holding Capacity of Frozen Beef during Thawing Process

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Received 31 August 2019; Revised 6 December 2019; Accepted 10 December 2019; Published 28 December 2019

Academic Editor: Flora V. Romeo

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In order to investigate the thawing time and water-holding capacity under high-voltage electric field (HVEF), we studied the thawing experiments of frozen beef in a multiple needles-to-plate electrode system. The electric field, thawing characteristics, and quality parameters during the thawing process were measured. The results showed that compared with the control, the thawing time of beef under HVEF was significantly shortened, the thawing rate increased significantly, the drip loss decreased, and the centrifugal loss increased during the thawing process. By the response surface analysis and single-factor analysis of variance, the best thawing conditions for each thawing parameter were determined. It provides a theoretical basis and practical guidance for understanding the characteristic parameters of the high-voltage electric field thawing technology.

### 1. Introduction

In order to better maintain the original taste and nutrition of meat, freezing is the best and most important storage method at present [1-4]. Frozen meat is the most important raw material in the meat processing industry. Meat thawing is the final stage of refrigeration and storage and is one of the most critical steps. However, an improper thawing method used in the thawing process will affect the important food consumption indexes such as color, flavor, and texture of the meat products, and the drip loss and quality deterioration will be very serious, which will bring serious economic losses. The commonly used meat thawing methods are mainly water thawing, air thawing, vacuum thawing [5–8], refrigerator thawing [9–11], microwave thawing [3, 11–13], and so on. These thawing techniques have their own advantages, but there are also some disadvantages. Water thawing and air thawing are easy to operate, but they easily cause microbial contamination of the product and loss of soluble matter. Vacuum thawing products are of good quality, but thawing equipment is expensive. Refrigerator thawing can inhibit the growth of microorganisms, but the thawing time is long and the efficiency is low. Microwave thawing has a fast thawing rate, but it causes thermal damage and uneven thawing of products. Therefore, it is imperative to explore new thawing techniques.

High-voltage electric field (HVEF) thawing is a new nonthermal thawing technology, which has the advantages of high efficiency, low equipment cost, and simple operation, and is becoming a research hotspot [14-19]. He et al. found that during five days of post-thawing storage, the volatile basic nitrogen (VBN) levels increased from 10.64 to 16.38 mg/100 g at 10 kV applied voltage, while the VBNs of the control increased from 10.66 to 19.87 mg/100 g. This indicates that the high-voltage electric field thawing not only improves the thawing speed of pork, but also prolongs the shelf life of the product [15]. Wiktor et al. found that the thawing time of apples under HVEF was only 71.5% of the control group, and the mass loss was lower than that of the control group [16]. Mousakhani-Ganjeh et al. found that the thawing time of freezing fish under HVEF was 1.78 times lower than that of the control group, and the product quality was well maintained [17]. Rahbari et al. found that the thawing time of chicken under HVEF was 2.3 times lower than that of the control group [18]. Kantono et al. found that HVEF thawing can have beneficial effects on beef tenderness and the quality of its thawed products [19]. Although these studies have been very detailed on some issues, few studies

have systematically and comprehensively reported about the effects of high-voltage electric field process parameters on the water-holding capacity of frozen beef during the thawing process. These will directly affect the development of highvoltage electric field thawing technology and thawing equipment, thereby limiting the application of this technology, making it difficult to apply to large-scale meat industry production. Therefore, it is necessary to conduct indepth research through experiments.

In this paper, to further investigate the effect of process parameters and electrode configuration for optimizing and improving the thawing efficiency in high-voltage electric field system, we studied the thawing characteristic of frozen beef. To accomplish this, high-voltage electric field thawing characteristics and quality of frozen beef were studied, including the thawing time, thawing rate, drip loss, and waterholding capacity under different thawing conditions. It provides theoretical basis and reference for understanding the thawing characteristics and mechanism under highvoltage electric field.

#### 2. Materials and Methods

2.1. Materials. The beef used in the experiment was purchased in a supermarket (Beijing Hualian) near Inner Mongolia University of Technology, Hohhot, Inner Mongolia, China. The purchased beef was sliced into sheets about  $3.5 \text{ cm} \times 3.5 \text{ cm} \times 3.5 \text{ cm}$  using a knife and immediately placed in a refrigerator at  $-20^{\circ}$ C for 24 hours to prepare for the thawing experiment.

2.2. Experimental Facility. The HVEF thawing device is shown in Figure 1. It is mainly composed of a high-voltage power (YD(JZ)-1.5/50, made in Wuhan, China), a voltage regulator (KZX-1.5 KVA, made in Wuhan, China), and a multi-needle-to-plate electrode system. High-voltage power is connected to a controller, with an adjustable voltage ranging from 0 to 50 kV for alternating current (AC). The electrode system consists of a vertically mounted electrode with multiple sharp pointed needles projected onto a fixed horizontal grounded metallic plate on which the frozen beef samples to be thawed were placed. The adjustment range of the distance between two needle electrodes is from 4 cm to 12 cm. The adjustment range of the distance between the grounded electrode is from 8 cm to 12 cm.

2.3. Experimental Method. The mass of the frozen beef pieces was weighed by an electronic balance before thawing, and then the temperature sensor was inserted into the geometric center of the frozen beef. During the thawing process, the temperature was determined by a digital thermometer, and recorded every 5 minutes. Thawing continued until the temperature at the geometric center of the frozen beef sample reached 10°C. The time required to raise the temperature of the center of the frozen beef cube



FIGURE 1: Schematic diagram of high-voltage electric field thawing equipment. (1) Thermometer; (2) hygrometer; (3) frozen beef; (4) ground electrode; (5) temperature sensor; (6) needle electrode; (7) high-voltage power source; (8) voltage regulator.

from  $-10^{\circ}$ C to  $10^{\circ}$ C was determined as the thawing time. Thawing experiments were independently performed three times in this study and the average was taken.

The response surface methodology (RSM) was used to design the experimental scheme of high-voltage electric field thawing. The factor level table is shown in Table 1. There are three factors A, B, and C as the investigation factors, which are electrode distance (A), needle distance (B), and voltage (C). The three-factor test was designed according to the principle of the central composite design (CCD) test. The adjustment range of the needle distance is from 4 cm to 12 cm. The adjustment range of the electrode distance is from 8 cm to 12 cm. The adjustment range of the voltage is from 12 kV to 28 kV. The thawed temperature was  $20 \pm 2^{\circ}$ C and the humidity was  $35 \pm 3^{\circ}$ . Thawed experiments were independently performed three times in this study and the average was taken. The level table of orthogonal test factor for high-voltage electric field is shown in Table 1. The specific experiment design conditions using the response surface methodology are shown in Table 2.

In order to systematically and comprehensively study the effect of high-voltage electric field process parameters on thawing time, thawing rate, drip loss, and centrifugal loss of frozen beef, some groups of experiments were added in addition to the response surface design experimental scheme. Then, a systematic study of single electric parameter was investigated during the thawing process. The specific experiment design conditions are shown in Table 3.

#### 2.4. Measurement of Related Parameters

2.4.1. Drip Loss. Accurately weigh the mass of beef before and after thawing. The drip loss of material samples was calculated using the following equation:

$$\text{Drip loss} = \left(\frac{m_2 - m_3}{m_1}\right) \times 100\%,\tag{1}$$

where  $m_1$ ,  $m_2$ , and  $m_3$  are the weight of the frozen beef, the weight of the thawed beef before removing surface water, and the weight of the thawed beef after surface water removal, respectively.

T	Factor			
Level	(A) Electrode distance (cm)	(B) Needle distance (cm)	(C) Voltage (kV)	
-1.68179	8	4	12	
-1	8.8	5.6	15.2	
0	10	8	20	
1	11.2	10.4	24.8	
1.68179	12	12	28	

TABLE 1: Level table of orthogonal test factor for high-voltage electric field.

TABLE 2: The specific experiment design conditions using the response surface methodology.

Test number	Argument code (experiment design)			Experiment argument (experiment scheme)		
	Electrode distance (cm)	Needle distance (cm)	Voltage (kV)	Electrode distance (cm)	Needle distance (cm)	Voltage (kV)
Control				0	0	0
1	0	0	0	10	8	20
2	-1	-1	-1	8.8	5.6	15.2
3	-1	1	1	8.8	10.4	24.8
4	1	-1	-1	11.2	5.6	15.2
5	-1	-1	1	8.8	5.6	24.8
6	-1	1	-1	8.8	10.4	15.2
7	0	-1.68179	0	10	4	20
8	1	1	1	11.2	10.4	24.8
9	0	0	0	10	8	20
10	0	0	1.68179	10	8	28
11	0	1.68179	0	10	12	20
12	0	0	0	10	8	20
13	0	0	0	10	8	20
14	1	1	-1	11.2	10.4	15.2
15	0	0	0	10	8	20
16	1	-1	1	11.2	5.6	24.8
17	1.68179	0	0	12	8	20
18	0	0	-1.68179	10	8	12
19	0	0	0	10	8	20
20	-1.68179	0	0	8	8	20

TABLE 3: The experiment design conditions using single electric parameter analysis.

Experiment scheme	Voltage (kV)	Needle distance (cm)	Electrode distance (cm)
1	12	8	10
2	15.2	8	10
3	20	8	10
4	24.8	8	10
5	28	8	10
6	20	4	10
7	20	5.6	10
8	20	8	10
9	20	10.4	10
10	20	12	10
11	20	8	8
12	20	8	8.8
13	20	8	10
14	20	8	11.2
15	20	8	12

2.4.2. Centrifugation Loss. A portion of the meat sample that was thawed was placed in a centrifuge and centrifuged at 4000 r/min for 20 min. The centrifugation loss of material samples was calculated using the following equation:

Centrifugation loss = 
$$\frac{m_b - m_a}{m_b} \times 100\%$$
, (2)

where  $m_a$  and  $m_b$  are the weights of thawed beef before centrifugation and after centrifugation, respectively.

2.4.3. Thawing Time. Definition of thawing time: the time required for the beef cube center temperature to range from  $-10^{\circ}$ C to  $10^{\circ}$ C.

2.4.4. *Thawing Rate.* The thawing rate of material samples was calculated using the following equation:

Thawing Rate = 
$$\frac{m_1}{t}$$
, (3)

where  $m_1$  and t are the weight of the frozen beef and thawing time, respectively.

2.5. Statistical Analysis. In this paper, 20 sets of experimental schemes were simulated by central composite design (CCD). The thawing time and thawing rate between different electric field and the control were calculated using single-factor analysis of variance. The differences in thawing time and thawing rate are considered statistically significant when p < 0.05. Drip loss and water-holding capacity were analyzed using the response surface methodology and analysis of variance. The results of this study are expressed as mean ± standard deviation (SD).

#### 3. Results and Discussion

3.1. The Influence of HVEF on Thawing Time. Figure 2 shows the effect of different thawing conditions on the thawing time and thawing rate under HVEF. It was seen from Figure 2(a) that the thawing time ranged from 65 min to 101.7 min under high-voltage electric field. The thawing time under HVEF was faster than that of the control group (0 kV), which decreased 1.44 times to 2.26 times compared to that of the control group. Single analysis of variance showed that compared to control, the thawing time showed statistically significant difference (p < 0.05). Amiri et al. found that the thawing time of beef under a HVEF system would significantly shorten than that of the control [20], which was consistent with the results of this study. From Figure 2(b), we found that compared with the control group, when the needle distance is 8 cm and electrode distance is 10 cm, the thawing time was shortened by 1.44 times, 1.66 times, 1.83 times, 2.15 times, and 2.15 times, respectively, at 12 kV, 15.2 kV, 20 kV, 24.8 kV, and 28 kV voltages. These results agree with those studies that reported reduction in thawing time with increase of applied voltage [21]. Compared with the control group, the thawing time was shortened by 1.68 times, 1.76 times, 1.83 times, 1.91 times, and 1.83 times, respectively, at 4 cm, 5.6 cm, 8 cm, 10.4 cm, and 12 cm for needle distance when the voltage is 20 kV and electrode distance is 10 cm. So, the thawing time decreases first and then increases with the increase of needle distance. Compared with the control group, the thawing time was shortened by 1.91 times, 1.87 times, 1.83 times, 1.8 times, and 1.66 times, respectively, at 8 cm, 8.8 cm, 10 cm, 11.2 cm, and 12 cm for electrode distance when the voltage is 20 kV and needle distance is 8 cm. With the increase of electrode distance, the thawing time increased. According to the data analysis above, among the three parameters of voltage, electrode distance, and needle distance, the influence of

voltage on the thawing time is much larger than that of the electrode distance and the needle distance.

3.2. The Influence of HVEF on Thawing Rate. It was also seen from Figure 2(a) that the thawing rate ranged from 0.3796 g/ min to 0.6576 g/min under high-voltage electric field. The thawing rate under HVEF was faster than that of the control group (0 kV), which increased 1.3 times to 2.25 times compared to that of the control group. Single analysis of variance showed that compared to control, the thawing rate showed statistically significant difference (p < 0.05). From Figure 2(b), we found that compared with the control group, when the needle distance is 8 cm and electrode distance is 10 cm, the thawing rate was quickened by 1.3 times, 1.55 times, 1.82 times, 2.09 times, and 2.25 times, respectively, at 12 kV, 15.2 kV, 20 kV, 24.8 kV, and 28 kV voltages. With the increase of voltage, the thawing rate accelerated. Ding et al. found that the high-voltage electric field can significantly accelerate the thawing rate of tofu samples compared with the control, and increasing the voltage has an important effect on increasing the thawing rate [22], which was consistent with the results of this study. Compared with the control group, the thawing rate was quickened by 1.64 times, 1.71 times, 1.82 times, 2.41 times, and 1.84 times, respectively, at 4 cm, 5.6 cm, 8 cm, 10.4 cm, and 12 cm for needle distance when the voltage is 20 kV and electrode distance is 10 cm. The thawing rate accelerated first and then reduced with the increase of needle distance. Compared with the control group, the thawing time was quickened by 1.88 times, 1.85 times, 1.82 times, 1.8 times, and 1.77 times, respectively, at 8 cm, 8.8 cm, 10 cm, 11.2 cm, and 12 cm for electrode distance when the voltage is 20 kV and needle distance is 8 cm. With the increase of electrode distance, the thawing rate reduced. According to the data analysis, among the three parameters of voltage, electrode distance, and needle distance, the influence of voltage on the thawing rate is much larger than that of the electrode distance and the needle distance.

The HVEF process is based on the production of an electric wind of air ionized in a needle plate electrode system by a corona discharge [22]. At present, it is generally believed that the main reason of thawing rate accelerating and thawing time decreasing is the generation of corona wind which was produced by the high-voltage electric field [22, 23]. In fact, the secondary motions in the electrohydrodynamic (EHD) flow process induce an electric instability in the thermal boundary layer adjacent to the heat transfer surface to give rise to enhanced bulk and turbulent convective heat transfer coefficients and heat transfer rates. Lai et al. found that the water evaporation rate is shown to depend on the strength of the electric field and the velocity of the air flow [23-27]. The results show that the thawing time and thawing rate are shown to depend on the strength of the electric field and the velocity of the air flow. The voltage can change the electric field strength. Electrode distance and needle distance can change air flow. Increased electric field strength and increased air flow can accelerate thawing.



FIGURE 2: Effect of different treatments on thawing time and thawing rate. (a) The response surface methodology; (b) the single electric parameter analysis. Data are shown as the mean  $\pm$  SD for each response. For each response, means with different lowercase letters are significantly different (p < 0.05). The order of the parameters is voltage, needle distance, and electrode distance.



FIGURE 3: Effect of different treatments on drip loss. (a) The response surface methodology; (b) the single electric parameter analysis. Data are shown as the mean  $\pm$  SD for each response. For each response, means with different lowercase letters are significantly different (p < 0.05). The order of the parameters is electrode distance, voltage, and needle distance.

3.3. *The Influence of HVEF on Drip Loss.* Drip loss is part of the total thawing loss, and drip loss has an important effect on the taste of beef. The drip loss of beef under high-voltage

electric field is shown in Figure 3. As shown in Figure 3(a), the drip loss under high-voltage electric field ranges from 0.13% to 2.30%. The drip loss of beef under high-voltage

Evelve		Responses	
r-value	Drip loss	Centrifugation loss	
A-electrode distance	12.09**	0.016 <sup>n.s</sup>	
B-needle distance	0.17 <sup>n.s</sup>	0.8 <sup>n.s</sup>	
C-voltage	0.066 <sup>n.s</sup>	0.0025 <sup>n.s</sup>	
AB	5.65*	2.94 <sup>n.s</sup>	
AC	2.52 <sup>n.s</sup>	$4.04^{n.s}$	
BC	1.31 <sup>n.s</sup>	$1.32^{n.s}$	
$A^2$	7.75*	$4.2^{n.s}$	
B <sup>2</sup>	3.98 <sup>n.s</sup>	7.2*	
$C^2$	6.61*	5.86*	

TABLE 4: Effect of different treatments on drip loss and centrifugation loss.

\* p < 0.05, significant correlation; \*\* p < 0.01, very significant correlation; \*\*\* p < 0.001, extremely significant correlation; n.s, not significant.



(c)

FIGURE 4: Response surface analysis of electrode distance and needle distance at 15.2 kV, 20 kV, and 24.8 kV for drip loss of beef. (a) 15.2 kV; (b) 20 kV; (c) 24.8 kV.

electric field is lower than that of the control group. Single analysis of variance showed that compared to control, the drip loss showed statistically significant difference (p < 0.05).

From Figure 3(b), we found that compared with the control group, when the needle distance is 8 cm and voltage is 20 kV, the drip loss was decreased by 1.48%, 2.04%, 1.60%, 0.70%,



FIGURE 5: Effect of different treatments on centrifugation loss. (a) The response surface methodology; (b) the single electric parameter analysis. Data are shown as the mean  $\pm$  SD for each response. For each response, means with different lowercase letters are significantly different (p < 0.05). The order of the parameters is needle distance, electrode, and voltage.



FIGURE 6: Response surface analysis of centrifugal loss. (a) Electrode distance and voltage; (b) Needle distance and voltage.

and 0.40%, respectively, at 8 cm, 8.8 cm, 10 cm, 11.2 cm, and 12 cm at electrode distance. The drip loss decreased first and then increased with the increase of electrode distance. Compared with the control group, the drip loss was decreased by 2.10%, 1.87%, 1.60%, 2.39%, and 2.53%, respectively, at 12 kV, 15.2 kV, 20 kV, 24.8 kV, and 28 kV for

voltages when the needle distance is 8 cm and electrode distance is 10 cm. With the increase of voltage, the drip loss increased first and then decreased. Compared with the control group, the drip loss was decreased by 1.97%, 2.00%, 1.60%, 0.93%, and 2.36%, respectively, at 4 cm, 5.6 cm, 8 cm, 10.4 cm, and 12 cm for needle distance when the voltage is



FIGURE 7: Response surface model diagnostic analysis of drip loss. (a) Internally studentized residuals of the predicted value; (b) Internally studentized residuals of the normal ploy; (c) Perturbation curve. Actual factors: (A) electrode distance = 10 cm, (B) needle distance = 8 cm, and (C) voltage = 20 kV.

20 kV and electrode distance is 10 cm. With the increase of needle distance, the drip loss increased first and then decreased.

It was seen from Table 4 that the influence of needle distance and voltage single factor on drip loss is small. The interaction between electrode distance and needle distance is significant. From Figure 4, it can be seen that the increase of the electrode distance under the conditions of voltages of 15.2 kV, 20 kV, and 24.8 kV, the drip loss firstly decreases and then rises. The response surface analysis is consistent with the results of single-factor experiment.

The response surface equation between the establishment of drip loss and the influencing factors is as follows:

$$DL = 6.75701 - 3.21163A + 1.82464B + 0.16654C$$
  
- 0.10386AB + 0.034692AC - 0.012485BC  
+ 0.18127A<sup>2</sup> - 0.032496B<sup>2</sup> - 0.010468C<sup>2</sup>(R<sup>2</sup> = 0.8072),  
(4)

where A is the electrode distance, B is the needle distance, and C is the voltage. Using this equation, the drip loss at any electrode distance, needle distance, and voltage within the study range can be calculated. The results showed that the drip loss of beef was the least when the electrode distance was 10 cm, the needle distance was 8 cm, and the voltage was 28 kV.



FIGURE 8: Response surface model diagnostic analysis of centrifugal loss. (a) Internally studentized residuals of the predicted value; (b) Internally studentized residuals of the normal ploy; (c) Perturbation curve. Actual factors: (A) electrode distance = 10 cm, (B) needle distance = 8 cm, and (C) voltage = 20 kV.

3.4. The Influence of HVEF on Centrifugation Loss. Water-holding capacity (WHC) capability is one of the important quality attributes of meat products [28]. Centrifugal loss can directly reflect water-holding capacity. The centrifugal loss of beef under HVEF is shown in Figure 5. It was seen from Figure 5(a) that the centrifugal loss under the HVEF is 1.49% to 4.83%, and the majority is higher than that of the control group. Rahbari et al. found that the waterholding capacity of chicken breast under HVEF was higher than that of the control group [18], which is consistent with the results of this study. After single analysis of variance, it was shown that there was a significant effect of HVEF treatment on centrifugal loss compared to the control group (p < 0.05). From Figure 5(b), we found that compared with

the control group, when the needle distance is 8 cm and voltage is 20 kV, the drip loss was increased by 0.54%, 1.08%, 1.52%, 1.65%, and -0.05%, respectively, at 8 cm, 8.8 cm, 10 cm, 11.2 cm, and 12 cm at electrode distance. The centrifugal loss increased first and then decreased with the increase of electrode distance. Compared with the control group, the centrifugal loss was increased by 2.22%, 1.23%, 1.52%, 2.61%, and 2.96%, respectively, at 4 cm, 5.6 cm, 8 cm, 10.4 cm, and 12 cm for needle distance when the voltage is 20 kV and electrode distance is 10 cm. With the increase of needle distance, the centrifugal loss decreased first and then increased. Compared with the control group, the centrifugal loss was increased by 0.08%, 0.62%, 1.52%, 0.83%, and 0.67%, respectively, at 12 kV, 15.2 kV, 20 kV, 24.8 kV, and

28 kV for voltages when the needle distance is 8 cm and electrode distance is 10 cm. With the increase of voltage, the centrifugal loss increased first and then decreased.

It was seen from Table 4 that the influence of the electrode distance, the needle distance, and the voltage on the centrifugal loss of the beef is not significant. It was seen from Figures 6(a) and 6(b) that simultaneously increasing the voltage and the electrode distance, and decreasing the needle distance can increase the centrifugal loss of the beef.

The response surface equation between the establishment of centrifugal loss and the influencing factors is as follows:

$$SR = 18.01293 - 5.63929A + 3.17172B + 0.10779C - 0.14275AB + 0.083748AC - 0.023975BC + 0.25437 - 0.083284B^{2} - 0.018790C^{2}(R^{2} = 0.7328),$$
(5)

where A is the electrode distance, B is the needle distance, and C is the voltage. Using this equation, the centrifugal loss at any electrode distance, needle distance, and voltage within the study range can be calculated. The results showed that the centrifugal loss of beef was the largest when the electrode distance was 12 cm, the needle distance was 8 cm, and the voltage was 20 kV.

3.5. Response Surface Model Diagnosis. The residual can measure the accuracy of the prediction. And the internally studentized residuals of the predicted value are randomly scattered, indicating that the homogeneity of the residual variance meets the requirements. The residuals are normally distributed, indicating that the model is highly accurate. The perturbation curve compares the response values of the respective variables in a specific area of the response optimization surface, and the curve steeply indicates the degree of influence of the response value on the factors. The steep curve has a large influence. On the contrary, the smooth effect of the curve is small. The growth and decline of the line indicate the positive and negative effects of the factors, respectively. It was seen from Figure 7 that the importance of drip loss is A > C > B. It was seen from Figure 8 that the importance of water-holding capacity is B > A > C, where A is the electrode distance, B is the needle distance, C is the voltage.

#### 4. Conclusion

The HVEF technique may reduce the thawing time and enhance the thawing rate of frozen beef. Compared with the control group, the average drip loss of beef under HVEF was reduced by 1.75%. The average centrifugal loss of beef under HVEF increased by 0.9%.

This provides a theoretical basis for the development of a relatively complete high-voltage electric field beef thawing technology.

### **Data Availability**

The data used to support the findings of this study are included within the article.

#### **Conflicts of Interest**

All authors declare that they have no conflicts of interest regarding the publication of this paper.

#### Acknowledgments

This research was funded by National Natural Science Foundations of China (nos. 51467015 and 51767020), Natural Science Foundations of Inner Mongolia Autonomous Region of China (no. 2017MS(LH)0507), and College Students' Innovative and Entrepreneurial Training Program of Inner Mongolia University of Technology (No. 2018137).

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