Improvement and optimization of preparation process of seedling-growing bowl tray made of paddy straw

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Abstract: A new type of rice seedling carrier named seedling-growing bowl tray made of paddy straw (SGBTMPS) was developed in China. Traditional preparation process for SGBTMPS is complex and difficult to operate. Hence, a new SGBTMPS preparation method has been developed by using straw powder as the main raw material. In this method, modified starch-based adhesive was replaced by the binder of thermosetting adhesive, and preparation constraints such as forming pressure, forming temperature, and dwell time were decreased. The effects of factors such as glue (modified starch-based adhesive), forming pressure, forming temperature and dwell time on SGBTMPS preparation were evaluated by single factor experiment. Orthogonal experiment and comprehensive weight analyses were adopted to optimize the parameters for SGBTMPS preparation. The results showed that optimized parameters were 125% glue and 1.2 kg mixed materials with the forming pressure, temperature, and dwell time of 30 MPa, 140℃ and 330 seconds, respectively. Compared with traditional preparation process, the proportioning link, preparation link, and preparation time in the new preparation process were reduced by 66.7%, 33.3%, and 17%, respectively; the pot-hole percentage and the expansion ratio were increased by 0.09% and 0.05%, respectively. This study indicated that the new preparation process for SGBTMPS was simpler and easier to operate and would provide a useful reference for further research and industrialization on SGBTMPS.

Keywords: seedling-growing bowl tray, preparation process, paddy straw, rice production modified starch-based adhesive, straw powder

DOI: 10.3965/j.ijabe.20140704.002

Citation: Li L H, Wan C, Zhang X Y, Li G Y. Improvement and optimization of preparation process of seedling-growing bowl tray made of paddy straw. Int J Agric & Biol Eng, 2014; 7(4): 13－22.

1 Introduction

Heilongjiang Province is one of the most important grain production areas in China, with the total grain output of 111.41 thousand tons in 2012, accounting for 10% of the total grain in China. The total rice yield was 41.24 thousand tons, accounting for 37% of the total grain in China[1]. In the meantime, rice production in Heilongjiang Province plays a key role in grain production of China.

With the increasing grain demand and the limited rice planting area, it is increasingly important to increase rice production in Heilongjiang Province. It has been proved that rice seedling-growing-bowl technique is an effective way to increase rice yield in Heilongjiang Province [2].

Japan has the most advanced rice seedling-growing-bowl technique in the world[3]. In 1980s, Japanese seedling-growing-bowl technique was introduced in Heilongjiang Province and accepted by rice farmers because of its advantages, such as relatively independent seedling-growth space, good seedling quality, transplanting with soil, strong tillering ability of lower nodes and higher spike rate. Currently most of the

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Received date: 2013-12-16 **Accepted date:** 2014-08-10

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Japanese seedling-growing-bowl tray is made of polyethylene or polyvinyl chloride, with some made of high-cost resin. Its promotion and application are highly restricted due to high cost and the expensive ancillary equipment. It was reported that the market price for each unit was 17 Chinese Yuan (RMB) and 300 000-350 000 RMB for each set in China.

Last century in China, some research institutions carried on the study of seedling carrier and achieved a series of research results. For example, the research staff from China Agricultural University, Zhejiang University of Technology and other research institutions developed different specifications of seedling carrier made of different materials and achieved better high-yield results[4]. While the price has slightly decreased, its ancillary equipment still caused many problems such as expensive price, complicated operation and low reliability.

At the beginning of this century, Heilongjiang Bayi Agricultural University in China prepared the seedling carrier made of paddy straw (SGBTMPS)[5]. Its price greatly reduced, and its ancillary equipment was simply-operated and highly reliable.

But the traditional method of preparation of SGBTMPS had many problems such as complex process and difficult operation; therefore, we need to develop new methods.

So a new process for SGBTMPS preparation was developed, in which straw powder was used as the main raw material and modified starch was used for taking thermosetting adhesive. The objective of this study was to evaluate the performance of adhesive and factors in the preparation process (forming pressure, forming temperature and dwell time) for SGBTMPS.

2 Materials and methods

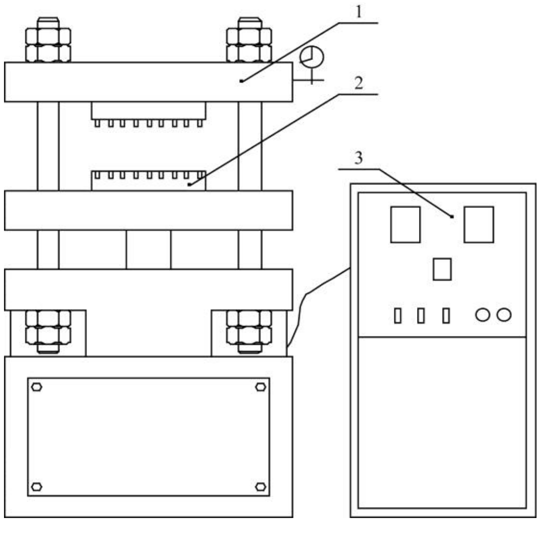
2.1 Adhesives and preparation of raw materials

Thermosetting adhesive was used as the binder for traditional preparation process for SGBTMP which increased the viscosity progressively over time. Operation of the thermosetting adhesive is difficult because the quality in actual application needs to be estimated again. However, the viscosity of modified starch-based adhesive does not change over time, which is suitable for the binder for new preparation process for SGBTMP.

The modified starch-based adhesive is made of dissolving polymer modified starch, additives and other materials in accordance with a certain percentage before stirring. The paddy straws in this experiment were all from rice fields in Daqing, Heilongjiang Province, China. They were firstly cut into 100-150 mm length with the chopper, and then crushed to powder with the grinder with mesh screen diameter of 10 mm. After 10 h of high-temperature (higher than 120℃) sterilizing and dewaxing on straw surface layer[6], the powder with moisture content of 16%-20% was stored in bags for use at any time.

2.2 Experimental equipment

The experimental equipment was forming machinery of the SGBTMPS (RY-1000 type). Its structure and structural parameters were shown in Figure 1 and Table 1 respectively. The forming mould was shown in Figure 2.

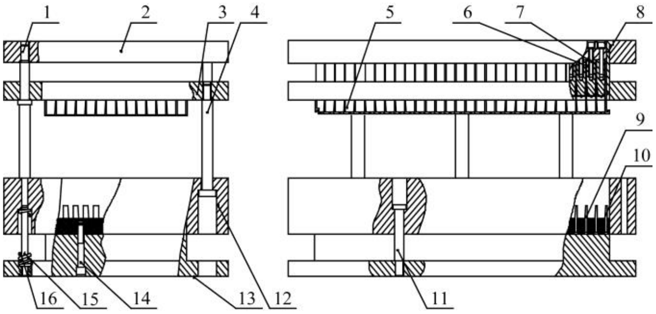


1. Pressure system 2. Forming mould 3. Control system

Figure 1 RY-1000 type forming machinery of SGBTMPS.

Table 1 Structure parameters of RY-1000 type forming machinery of SGBTMPS

Item	Value
Standard pressure/kN	1 000
Stroke/mm	300
Heating power/kW	≥5.6
Heating temperature of the upper and lower mold/℃	300
The slider return speed/m·min^{-1}	≥1.68
Mould dimensions (L × W × H) /mm^3	667×450×380
Efficiency/Number of SGBTMPS·h^{-1}	12



1. The upper limit lever 2. The upper mould 3. Return board 4. Return lever 5. SGBTMPS 6. Forming cylinder 7. Screws 8. Forming board 9. Forming pin 10. The bottom mould 11. The bottom limit lever 12. The mould container 13. Fixed board 14. Screws 15.Guide lever 16. Spring

Figure 2 Forming mould

2.3 Preparation process

Preparation process for SGBTMPS was shown in Figure 3. The adhesive, curing agent and intensifier were mixed with paddy straws in accordance with a certain percentage in the traditional preparation process with thermosetting adhesive[7]. However, in the preparation process with modified starch-based adhesive, only that the modified starch-based adhesive was mixed with paddy straws (name after mixed materials) was needed. The mixed materials were fed to the mould containers under the temperature and pressure. When dwell time reached, the system would open the mould by itself and SGBTMPS would be tied after cooling. In order to ensure the integrity of SGBTMPS in subsequent transport, protective measures were taken to four corners and the upper and lower edges of SGBTMPS when tying.

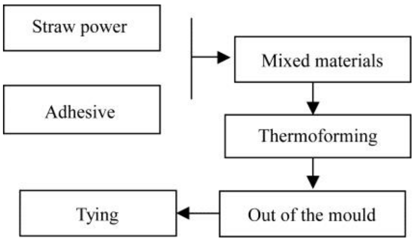


Figure 3 Preparation processes of SGBTMPS

2.4 Effect factors

A large number of experiments showed that the mixed materials (the total mass of straw powder and modified starch-based adhesive) of preparation for SGBTMPS based on modified starch-based adhesive should not be less than 1.2 kg to ensure completely forming. According to the experience, the glue rate (the percentage of modified starch-based adhesive and paddy straws power by mass, %) was one of the main performance effects in preparation for SGBTMPS. Main factors for performance of preparation process for SGBTMPS were the forming pressure (MPa), forming temperature (℃) and dwell time (s).

2.5 Assessment indicators

As the rice seedling carrier, SGBTMPS should meet the requirements of late seed and planting stage [8], whose assessment indicators were forming ability and water resistance, respectively. Forming ability is evaluated by the percentage of the pot-hole, and the higher the percentage of the pot-hole, the better the forming ability. Water resistance is evaluated by the expansion ratio, the lower, the better.

Qualified pot-hole is defined as that actual pot-hole depth is 1/2 of theoretical design pot-hole depth (17.8 mm) or more. The number of qualified pot-hole is used to calculate the percentage of the pot-hole, as shown in Equation (1):

$$K = \frac{K_1}{406} \times 100\% \tag{1}$$

where, K is the percentage of the pot-hole, %; K_1 is the number of qualified pot-hole (actual pot-hole depth is 1/2 theoretical design pot-hole depth (17.8 mm) or more).

The expansion ratio is defined as the percentage of SGBTMPS' width variation after immersion in water to original width. The original size of SGBTMPS is 565 mm × 272 mm × 25 mm with the width of 272 mm. The variation of expanded SGBTMPS's width was measure after it was immersed in water for 15 days. The expansion ratio was calculated with Equation (2):

$$P = \frac{P_1 - 272}{272} \times 100\% \tag{2}$$

where, P is the expansion ratio, %; P_1 is the completely expanded SGBTMPS's width, mm.

3 Results and discussion

3.1 Influence of glue on preparation performance for SGBTMPS

The initial preparation conditions were determined by pre-experiment with the forming pressure of 125 MPa, the forming temperature of 130℃ and dwell time of 330 s. The glue influence on the percentage of the pot-hole of SGBTMPS was analyzed, and the result was shown in Figure 4.

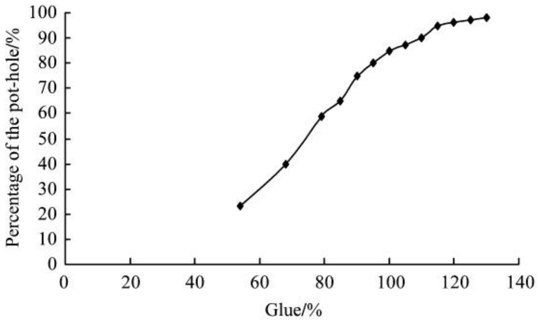


Figure 4 Influence of glue on the percentage of the pot-hole of the SGBTMPS

The percentage of the pot-hole increased with the increase in glue. When glue reached 105%, the percentage of the pot-hole was above 90%. This was mainly due to the fact that modified starch-based adhesive extracted from plants and the granular starch without adhesive can only produce adhesive force through chemical modification[9,10]. In order to guarantee a better porosity of the bowl [11,12], glue must be increased, so as the mass of mixed materials. However, the modified starch-based adhesive was aqueous adhesive, in which water accounted for a large proportion. It would turn into steam after forming mould being heated and discharge during exhaust process[13,14], so the mass of formed SGBTMPS varied little. When glue was over 120% the modified starch-based adhesive can wet straw powder and penetrate into the space after mixing and uniform bond, so the forming performance was good.

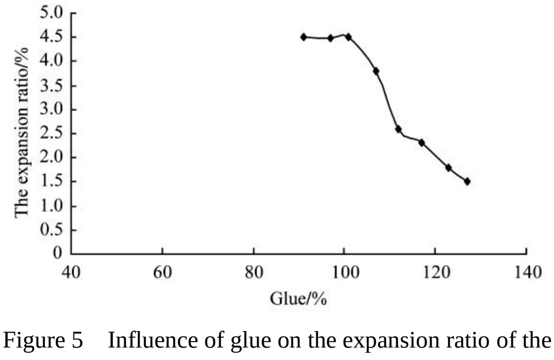


Figure 5 Influence of glue on the expansion ratio of the SGBTMPS

The influence of glue on the expansion ratio was shown in Figure 5. The expansion ratio reduced with the increase of glue, which showed that water resistance enhanced significantly with the increase of glue. When glue reached 95%-105%, the expansion ratio was unchanged, which was mainly due to straw powder still had certain absorbent capacity when the SGBTMPS formed incompletely. When glue reached 105%-130%, the modified starch-based adhesive distributed uniformly in the SGBTMPS and accounted for a larger proportion. The straw powder fully bonded[15], and the curing modified starch-based adhesive formed waterproof films on the surface of the SGBTMPS, which enhanced its water resistance. Therefore the expansion ratio showed a downward trend with the increase of glue.

3.2 Influence of forming press on preparation performance for the SGBTMPS

According to pre-experiment, glue 125% was selected to analyze the influence of forming press on performance of preparation to the SGBTMPS. The influence of forming pressure on the percentage of the pot-hole was shown in Figure 6. When the forming pressure was under 22.5 MPa, the pot-hole did not form because the forming pressure was insufficient to make the mixed material flow sufficiently.

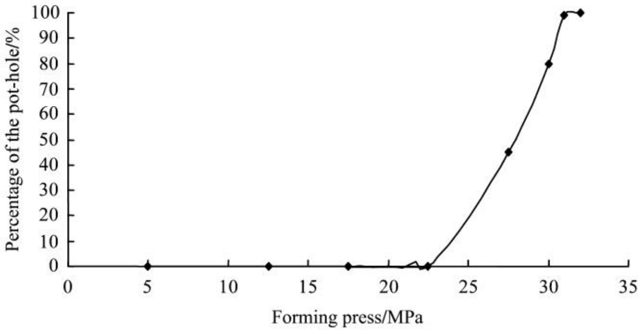


Figure 6 Influence of the forming press on the percentage of the pot-hole of the SGBTMPS

With the forming pressure increasing above 22.5 MPa, the percentage of the pot-hole of the SGBTMPS increased rapidly. It reached 100% when the forming pressure reached the limited value of 30 MPa. The curve diagram illustrated that huge forming pressure was needed for the preparation and form of the SGBTMPS based on modified starch-based adhesive. In order to ensure the completeness of the SGBTMPS, the forming pressure value should be set at 30 MPa.

The influence of forming pressure on the expansion ratio was shown in Figure 7. The expansion ratio reduced slightly with the increasing forming pressure. This was mainly because the low density of the SGBTMPS and the large space led to the strong capacity of water absorbing[16]. When forming pressure increased continuously, the mobility of the mixed material increased, the density of the SGBTMPS increased, the space reduced and overall water resistance enhanced. In a word, the forming pressure had slightly influence on the expansion ratio [17].

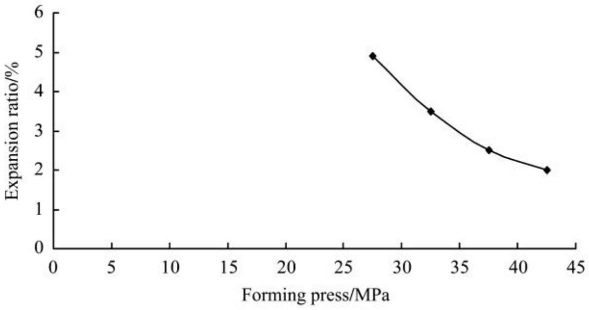


Figure 7 Influence of the forming press on the expansion ratio of the SGBTMPS

3.3 Influence of forming temperature on preparation performance for SGBTMPS

According to the pre-experiment, glue 125% was selected to analyze the influence of forming temperature on the performance of preparing the SGBTMPS. The influence of forming temperature on the percentage of the pot-hole was shown in Figure 8.

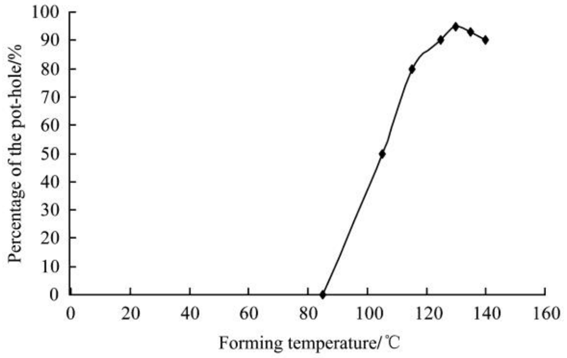


Figure 8 Influence of the forming temperature on the percentage of the pot-hole of the SGBTMPS

The curing process of modified starch-based adhesive needed to be completed under heating after chemically modified. The high forming temperature increased the adhesive force of the adhesive, the mixed material mobility and evaporated most of water in the modified starch-based adhesive. The percentage of the pot-hole increased with the increasing forming temperature. This was mainly because when the forming temperature was among 90-140℃, both the curing ability of modified starch-based adhesive and mobility of the mixed material increased with the rising forming temperature. However, when the forming temperature was low, the water in the modified starch-based adhesive was not easy to evaporate[18-20], reducing the percentage of the pot-hole. The released vapour accumulated in the mould may destroy the formed SGBTMPS. In order to avoid the damage, the vapour should be discharged many times according to actual circumstances, rather than one-time closure during the forming. It was proved that the yield of SGBTMPS could be improved by taking the exhaust method. When the forming temperature was over 150℃, the starch base was "gelatinized" and the straw powder was "charring" near the surface of the forming mould because of the high temperature, leading to reduction of the percentage of the pot-hole.

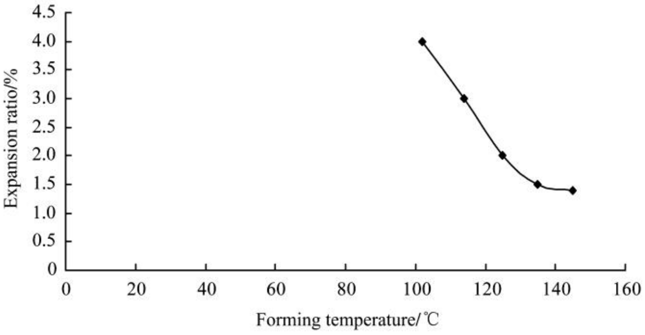


Figure 9 Influence of the forming temperature on the expansion ratio of the SGBTMPS

The influence of forming temperature on the expansion ratio was shown in Figure 9. When the forming temperature was low, the expansion ratio was high because of the incomplete solidified mixed material and low water resistance. The curing process of modified starch-based adhesive was accelerated, mobility of the mixed material was strengthened [21,22], the surface of the SGBTMPS was smooth and water resistance was enhanced with the rising forming temperature. When the forming temperature was over 140℃, the charring of SGBTMPS enhanced its water resistance and the expansion ratio of SGBTMPS, which remained unchanged.

3.4 Influence of dwell time on preparation performance of SGBTMPS

According to the pre-experiments, glue 125% was selected to analyze forming temperature influence on the percentage of the pot-hole was shown in Figure 10. The odour concentration and white smoke increased with the dwell time prolonged. When the dwell time was over 360 s, the SGBTMPS stuck to the bottom. When the dwell time reached 390 s, an extremely negative phenomenon came out that the texture of some places in the bottom of the SGBTMPS was of crisp sense[23-25]. Therefore, the dwell time should not be too long to increase the rate of imperfect SGBTMPS.

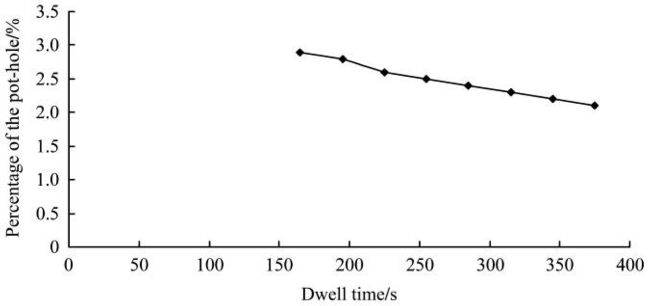


Figure 10 Influence of dwell time on the percentage of the pot-hole of the SGBTMPS

Figure 11 showed that the dwell time had slightly influence on the expansion ratio. The shorter the dwell time was, the higher the expansion ratio. This was mainly because the modified starch-based adhesive was incompletely solidified so that water resistance was low. When the dwell time prolonged, the modified starch-based adhesive was completely solidified and the expansion ratio decreased because of the increasing water resistance. However, "Charring" phenomenon occurred due to the long dwell time leading to a lot of smoke when opened [26, 27].

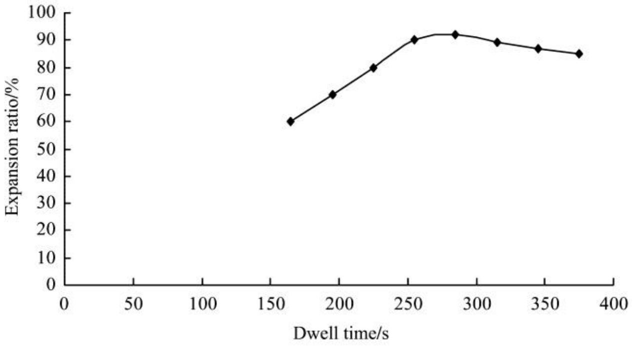


Figure 11 Influence of dwell time on the expansion ratio of the SGBTMPS

4 Optimization of preparation parameters

According to the above research, the forming pressure 30 MPa was set to improve the percentage of the pot-hole, to decrease the expansion ratio as much as possible and to ensure the normal conduct of the experiment. It was not the influencing factor in the follow experiments.

The percentage of the pot-hole and the expansion ratio were taken into consideration to optimize the preparation parameters (quantity of glue, forming temperature and dwell time). Orthogonal experiment ($L_9(3^4)$ orthogonal table)[28-30] was carried with three replications. The factors and levels were shown in Table 2.

Table 2 Factors and levels of the orthogonal experiments

Level	A Quantity of glue/%	B The forming temperature/℃	C The dwell time/s
1	105	120	360
2	125	130	330
3	115	140	300

ANOVA analysis and range analysis were applied to analyze the factors' significance[31] and influence on the percentage of the pot-hole and the expansion ratio. The results of ANOVA analysis and range analysis for the percentage of the pot-hole were showed in Tables 3 and 4, which showed that glue had an extremely significant influence on the percentage of the pot-hole, the forming temperature had significant performance influence of forming, and the dwell time's influence was weakest among these three factors.

Table 3 ANOVA analysis for the percentage of the pot-hole

		A	B	Blank columns	C
Sum	K1	578.1100	674.9700	738.0300	772.6100
	K2	863.0100	747.1000	750.5700	716.9500
	K3	792.0200	811.0700	744.5400	743.5800
Average	K1	64.2344	74.9967	82.0033	85.8456
	K2	95.8900	83.0111	83.3967	79.6611
	K3	88.0022	90.1189	82.7267	82.6200
Maximum value		95.8900	90.1189	83.3967	85.8456
Minimum value		64.2344	74.9967	82.0033	79.6611
Range R		31.6556	15.1222	1.3933	6.1844
Adjustment R		28.5111	13.6201	1.2549	5.5701

Table 4 ANOVA analysis for the percentage of the pot-hole

Variation source	Sum of squared deviations (SS)	Degree of freedom (df)	Mean square (MS)	Mean square ratio (F)	Significance
A	4887.5955	2	2443.7977	215.4541	**
B	1030.3003	2	515.1501	45.4175	**
Blank	8.7405	2	4.3702		
C	172.2198	2	86.1099	7.5918	*
Deviation	218.1105	2	12.1172		
Sum	6316.9666	10			

The results of ANOVA analysis and range analysis for the expansion ratio were showed in Tables 5 and 6, which showed glue had an extremely significant influence on the expansion ratio, the forming temperature and the dwell time had slightly significant influence on the expansion ratio.

Table 5 Range analysis for the expansion ratio

		A	B	Blank columns	C
Sum	K1	18.8000	15.6100	14.5400	15.3900
	K2	11.8700	14.9600	14.9300	14.6900
	K3	13.8100	13.9100	15.0100	14.4000
Average	K1	2.0889	1.7344	1.6156	1.7100
	K2	1.3189	1.6622	1.6589	1.6322
	K3	1.5344	1.5456	1.6678	1.6000
Maximum value			1.7344	1.6678	1.7100
Minimum value			1.5456	1.6156	1.6000
Range R			0.1889	0.0522	0.1100
Adjustment R			0.1701	0.0470	0.0991

Table 6 ANOVA analysis for the expansion ratio

Variation source	Sum of squared deviations (SS)	Degree of freedom (df)	Mean square (MS)	Mean square ratio (F)	Significance
A	2.8403	2	1.4202	297.9818	**
B	0.1635	2	0.818	17.1550	**
Blank	0.0141	2	0.0070		
C	0.0576	2	0.0288	6.0390	
Deviation	0.0813	2	0.0045		
Sum	3.1568	10			

The optimal combined program was determined by comprehensive weight analysis [32-34]. The weight of the percentage of the pot-hole and expansion ratio was determined through expert judgement (Table 7).

Table 7 Results of weight of index on experts' judgment

Index	Expert A evaluation	Expert B evaluation	Expert C evaluation	Average
Percent of the pot-hole/%	71	69	70	70
Expansion ratio/%	29	31	30	30

The higher the percentage of the pot-hole, the better the performance, but the expansion ratio was the opposite. The reciprocal of the expansion ratio was taken to facilitate the post-optimization analysis. In this way, the higher the percentage of the pot-hole and the reciprocal of the expansion ratio (the lower the expansion ratio) were, the better the performance was. Therefore, the comprehensive value = (the percentage of the pot-hole/ maximum in the percentage of the pot-hole group) × 70% + (the reciprocal of the expansion ratio/maximum in the reciprocal of the expansion ratio group) × 30%. The comprehensive value was used to determine the optimal factor combination. The results were shown in Table 8.

Table 8 Results of the orthogonal experiment

Number	A	B	C	Percent of the pot-hole/%	Expansion ratio/%	Comprehensive value
1	105	120	360	58.95	2.17	0.58
2	105	130	330	62.18	2.1	0.6
3	105	140	300	71.57	1.96	0.68
4	125	120	300	88.78	1.37	0.88
5	125	130	360	99.35	1.42	0.95
6	125	140	330	99.55	1.17	0.99
7	115	120	330	77.26	1.63	0.76
8	115	130	300	87.51	1.47	0.85
9	115	140	360	99.24	1.51	0.93

The comprehensive weight analysis showed that the combined programs of preparation process A3B3C2 had the maximum comprehensive value of 0.99 (Table 8). In order to verify the correctness of selected optimal combined programs, experiments were conducted according to the optimal combined programs. The result of performance indicators were: the percentage of the pot-hole of 99.95%, and the expansion ratio of 1.17%. The performance indicators could fully meet the actual demands that SGBTMPS formed completely with smooth look and water resistance meet planting requirements. The final product and seedling effect were shown in Figures 12 and 13, respectively.

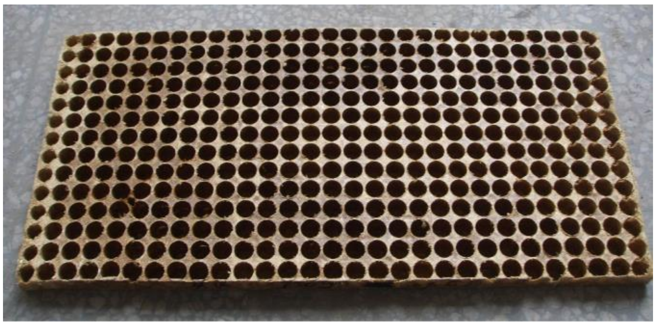


Figure 12 Final product


Figure 13 Seedling effect

5 Analysis of application prospects and comprehensive comparison

5.1 Analysis of industrialization

Based on the results of the above research, the project team carried out full demonstration and practice of industrialization of the SGBTMPS based on modified starch-based adhesive, including setting up two industrial production bases in Mudanjiang Branch of China Heilongjiang Land Reclamation Bureau and Yanshou County. Practice proved that the optimal combined programs meet industrial production requirements.

5.2 Cost analysis

1) Cost of raw materials: 97.5 RMB/t, according to 2012 market price.

2) Cost of production: set 8 workers of single shift of production running, the staff salaries was 80 RMB per person per day, electricity price was 0.60 RMB/(kW ·h), water price was 1 RMB/t, thus the production cost was 654.9 RMB per ten thousands ton.

3) Depreciation and other: calculated the plant in accordance with the 30-year depreciation, and the equipment in accordance with the 15-year depreciation, the depreciation costs 63.2 RMB per ten thousands ton. Workshop transportation costs 34.7 RMB per ten thousands ton.

4) Total cost: From the above calculation, total cost of the final production was 878.9 RMB per ten thousands ton.

5.3 Application prospects

The SGBTMPS has been demonstrated and applied in Heilongjiang reclamation area in 2006-2012. Practice has proved that, compared to conventional seedling carrier, the rice yield was increased by 13% to 20%, the net income was increased 3 780 RMB/hm^2, and the rice quality was improved significantly by using SGBTMPS as the rice seedling carrier. The above analysis showed that SGBTMPS has a broad application prospects with the increasing consumption level and the results also showed the need to upgrade the rice quality.

5.4 Comprehensive comparison

Contrast in technology, ratio reduced from 3 (ratio of straw and glue, curing agent and intensifier) to 1 (straw and glue ration); constraint conditions of preparation process reduced from 3 (the forming pressure, the forming temperature, the dwell time) to 2 (the forming temperature, the dwell time); average time of preparation process reduced from 570 s per one to 480 s per one. The reduction of link of preparation process was mainly determined by the feature of modified starch-based adhesive.

Contrast in effect, the cost of production reduced from 1 121.4 RMB per ten thousands ton to 878.9 RMB per ten thousands ton, which saved 19.9%; the percent of the pot-hole resulted of the optimal combined programs increased by 0.09% from 99.46% to 99.55%, the expansion ratio increased by 0.05% from 1.12% to 1.17%. The expansion rate has increased within reasonable limits (0.25%) and cost of production reduced reduction benefits of links of preparation process.

6 Conclusions

1) Analysis showed that the performance influence factors of the SGBTMPS determined the influence factor ranges. Optimum process parameters obtained by optimizing the analysis were: 125% glue, 1.2 kg mixed materials, 30 MPa forming pressure, 140℃ forming temperature, and 330 s dwell time.

2) Verification experiment of prepared SGBTMPS showed that the percent of the pot-hole was 99.95%, and the expansion ratio was 1.17%, which fully meet the actual needs of post-seedling and planting.

3) Comprehensive comparison with preparation process of the SGBTMPS based on thermosetting adhesive showed that the ratio link reduced 66.7%, preparation link reduced 33.3%, and preparation time saved 17%; the percent of the pot-hole increased by 0.09%, the expansion ratio increased by 0.05%, and the cost of production saved 19.9%. The expansion rate increased within reasonable limits, meeting the needs of planting.

Acknowledgements

The authors appreciate the projects financially supported by National Agricultural Science and Technology Achievement Transformation Project (No.

2009GB2B200101), 2011 Specialized Research Fund for the Doctoral Program of Higher Education (No. 20112305120003), 2009 Specialized Research Fund for the Doctoral Program of Higher Education (No. 20092305110002), and Start-up Capital of Doctoral Research of Heilongjiang Bayi Agricultural University (No. 2011YB-08).

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