# EFFECTS OF DOUBLE V-SHAPED OPENERS WITH FURROW COMPACTION FUNCTION ON SEEDBED CHARACTERISTICS AND SOYBEAN EMERGENCE UNDER DOUBLE ROW RIDGE CULTIVATION TECHNIQUE
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# 垄上双行种植技术下具有种沟镇压功能的双 V 型筑沟器对种床特性和大豆出苗的影响

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## ABSTRACT
*Based on the technical characteristics of double-row ridge planting, a double V-shaped opener with the furrow compaction function was designed. This opener with the sliding knife and profiling mechanism was capable of furrow opening, compacting and profiling, and thereby created excellent seedbeds with tight bottom and soft soils. Through sunlight greenhouse tests, the effects of the double V-shaped opener on seedbed characteristics and soybean emergence were studied under the compaction forces of T1 (0 N), T2 (500 N), T3 (600 N) and T4 (700 N). The furrow compaction planting significantly affected the seedbed characteristics and soybean emergence and could preserve soil moisture in seedbeds. Under the semiarid condition, the average emergence time under T2 was 0.79 day earlier than under T1, and the emergence rates under T2, T3 and T4 were significantly raised. The seedling height uniformity under T2 was 5.34% higher than under T1. The average emergence time ranked from early to later as T3<T4<T2. The deep seeding uniformity, the emergence uniformity and the average seedling height were all improved as the furrow compaction force was enlarged within 500-700 N. Furrow compaction could preserve soil moisture in seedbeds, and the seedbed soil physical properties and soybean seedling emergence were optimized under the furrow compaction force of 600-700 N.*

## 摘要
*本文根据垄上双行的种植技术特点，设计了具有种沟镇压功能的双 V 型筑沟器，该筑沟器具有滑刀和仿形机构，可实现开沟、压沟和仿形功能，进而构建底部紧实，覆盖土壤松软的优良种床。*

*通过日光温室试验，研究分别在 T1（0N）、T2（500N）、T3（600N）、T4（700N）镇压力下，双 V 型筑沟器对种床特性和大豆出苗的影响。结果表明，种沟镇压播种对种床特性和大豆出苗的影响是显著的。在半干旱环境下，T2 的平均出苗时间比 T1 提前 0.79 天，T2、T3、T4 的出苗率显著提高，苗高一致性 T2 比 T1 提高了 5.34%，平均出苗时间由短到长依次为：T3<T4<T2。在 500-700N 镇压力范围内，随着种沟镇压力的增大，播深一致性越好，出苗一致性越好，平均苗高随镇压力的增大而增大。试验表明，种沟镇压对种床土壤具有保墒作用，种沟镇压力为 600-700N 时，种床土壤物理特性及大豆出苗情况最佳。*

## INTRODUCTION
Soybean is one of the three major crops in Northeast China *(Wei et al., 2015)*. The annual yield of soybean in the spring sowing areas of Northeast China accounts for 40% of total annual yield in China. The total soybean planting area in Northeast China is the largest and most productive in the country *(Xue, 2013)*. The double row ridge cultivation technique is one of the commonly-used planting techniques in the soybean planting areas of Northeast China *(Jia et al., 2016; Jia et al., 2017)*. The technique is defined as the way of planting two rows of soybeans in 60- to 65-cm-wide routine ridges at the between-row distance of 10 to-15 cm as well as the auxiliary advanced cultivation techniques. Compared with the single-row ridge planting at the same variety and density, the double row ridge cultivation raises the crop yield by 15%-20% and the water and fertilizer utilization rate by 10% *(Liu et al., 2010)*. This technique is illustrated in Fig. 1.

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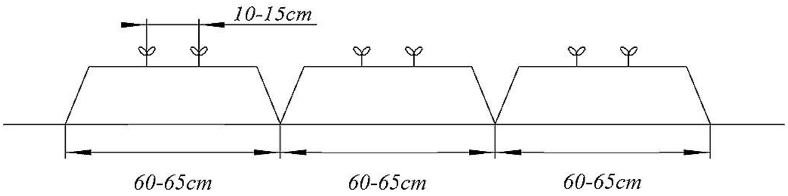



**Fig. 1 - Schematic diagram of the double row ridge cultivation technique**

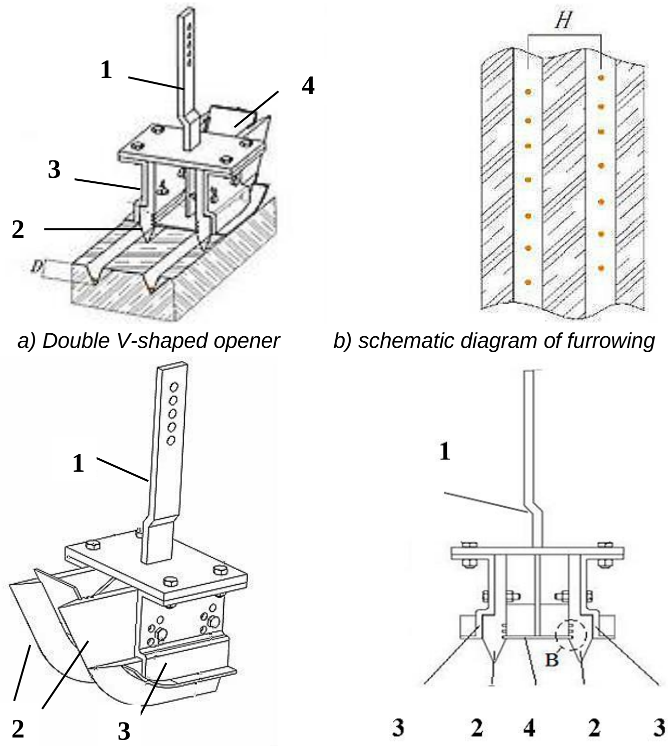
During furrow compaction, the soils of the planting layers are crushed and compacted prior to planting so as to eliminate gaps between soil clods. This procedure prevents moisture evaporation and loss (preservation of soil moisture) and is favourable for the elevation of soil moisture from deep layers through capillary pores, so that moisture can gather in the planting layers. This procedure promotes seed germination. Planting via agricultural mechanization depends on seed furrow compaction, which ensures seeding depth conformity and below-seed soil consolidation that are favourable for seedling emergence. Practice proves that loose seedbeds are favourable for soil moisture conservation, and compacted root beds contribute to raising humidity and to the root growth and development of crops *(Jia et al., 2015; Zhao et al., 2017; Li et al., 2019)*. As reported, too large or too low soil compactness is unfavourable for crop growth *(Nawaz et al., 2013)*. At the soil depth 0-200 mm, the threshold soil compactness for crop growth is 2-3 MPa, and soil compactness beyond this threshold will decelerate root growth *(Shah et al., 2017)*. The task of farmers is to create a "loose top and compact bottom" plowed soil layer for crops *(Pulkrabek et al., 2015)*, but this task cannot be accomplished only by the use of press wheels.

Furrow compaction can crush the large soil aggregates and makes the soil aggregates around the seedbeds uniform and tight *(Neto and Angelo, 2012; Song et al., 2009)*. Theoretically, furrow compaction can crush seedbed soil macroaggregates, makes the peripheral soils uniform and compact and significantly enhances crown dry weight, root length and seedling height, which are all favourable for raising soybean emergence rate and shortening the emergence time.

## MATERIALS AND METHODS

### Design of double V-shaped opener

The structure of the double V-shaped opener (*China Patent, CN 104584732 B*) is illustrated in Fig. 2.




*a) Double V-shaped opener* *b) schematic diagram of furrowing*

*c) axonometric view* *d) back view*

**Fig. 2 - Double V-shaped opener**

*1 - shovel-handle connection frame 2 - squeezing knife 3 - profiling pressing plate 4 - central plate*

*Note: D is furrowing depth, mm; H is space between two adjacent furrows, mm.*

According to the agronomic requirement of soybean ridge double-row precision planting, we designed a double V-shaped opener with furrow creating blades. It mainly consisted of a shovel-handle connection frame, two symmetrical profiling pressing plates, a central pressing plate, and two symmetrical V-shaped squeeze knives. This can opener creates two seed furrows with V-shaped sections. The seeds falling into the furrows will be retained at the bottom, which ensured the seeds will be linearly distributed. The furrow row space $H$ was 100-150 mm according to agronomic requirements, and the furrowing depth $D$ can be adjusted to 40, 50 or 60 mm. The seed furrows featured with smooth walls, compact soils, uniform shapes and consistent depth ensured the uniformity of planting depth, improved seeding quality, protected moisture and decreased water loss.

The profiling pressing plate, the central plate of the handle connection frame, and the lateral walls of the V-shaped squeeze knives functioned together, which imposed pressure on the side walls of the seed furrows, thereby tightening the furrow shape and creating smooth furrows. The large furrow compactness decreased moisture loss and wall coarseness, avoided wall soil glide, and reduced the probability of seeds being retained on walls or being brought out of furrows. The resulting furrows were smooth-surfaced and uniformly-shaped with consistent depth, which ensured the uniformity of planting depth (*Murray and Chen, 2019*).

**Experimental field**

Experiments were conducted in the sunlight greenhouse of College of Biological and Agricultural Engineering, Jilin University (N43.86°, E125.34°, 200 m altitude). This area was located in the cold temperate zone and enjoyed the continental monsoon climate in the north temperate zone, with frequent winds in spring and autumn. The average annual rainfall was 450-550 mm, sunshine duration was 2350-2450 h, and effective accumulated temperature was 2300-2700°C. The sunlight greenhouse was provided with the typical black soil in Northeast China and located in a flat terrain with fertile soils. In the past 30 years, the average summer temperature (June to August) was 20.9-22.8°C, and the precipitation in this period was 300-350 mm, accounting for about 60% of total annual precipitation. In dry and cold winters, the average precipitation was less than 30 mm, which accounted for only 5% of annual precipitation. The soil physical and chemical properties before the experiments are shown in Table 1.

**Table 1**

**Some physical and chemical properties of the soil from the experimental field at 0–100 mm depth range**

| Properties | Values |
|---|---|
| Cone index (MPa) | 0.920 |
| Bulk density (g/cm$^3$) | 1.233 |
| Water content (% d. b.) | 21.4 |
| Soil temperature (°C) | 14.3 |
| pH | 7.06 |
| Organic matter (%) | 2.56 |
| Total nitrogen (%) | 0.14 |
| Available Potassium ($K_2O$, mg/kg) | 172.2 |
| Available phosphorus ($P_2O_5$, mg/kg) | 16.5 |

**Experimental design and processing method**

During the experiments from August to September 2017, weeding and irrigation were conducted in the period 6-11 August. When the soil moisture content at 0-100 mm deep reached 10%-11%, soil preparation, ridging and suppression were started. Soybeans were sowed manually and equidistantly on August 11 and completed the same day. The experiments lasted 30 days and the tilling way was ridge tillage.

Four ridges were created in the experimental field. After the ridges were compacted, the height from the platform to the furrow was 180 mm-(with error of 20 mm), the ridge length was 10 m, and the upper surface of the platform was 200-300 mm wide. At both ends of each ridge, a 0.5-m-long adjusting zone was reserved. The 9-m-long central part was divided into three 3-m-long segments, which were the data acquisition areas under stable working. Two furrows were opened on each ridge, and the space between the furrows was 110 mm. The notations were T1 to T4: furrowing with total compaction force of 0, 500, 600 and 700 N respectively.

Subsidiary tests were conducted by using the parts that can create two V-shaped furrows on the seedbed and can compact furrows by increasing the counterweight (Fig. 3a). Bionic press wheels in diameter of 300 mm and width of 210 mm were used to compact the soils after covering (Fig. 3b).

*a) Parts of supplementary tests* *b) Bionic press roller*

**Fig. 3 - Test materials**

The variety of the tested soybean seeds was Hefeng50. The average soil temperature on the ridges during the test period was 19.1°C, which met the requirement for sowing. The seeding method is manual seeding at equal distance. The double V-shaped opener with furrow compaction ability was used to create two furrows on each ridge. On each ridge, 60 seeds were sowed, with 30 seeds in each furrow. The space between rows was 110 mm, the row distance was 110 mm, and the seeding depth was 50 mm. Theoretical research shows the crop yield is significantly related to the optical energy per unit area. The ideal planting way for higher soybean yield is the equal distance between rows. Under this planting mode, the between-plant competition is the smallest, and it creates the canopy that receives the largest irradiation energy *(Celik et al., 2007)* (Fig. 4a). Soil covering with shovels was conducted to avoid disturbance of soils. Profiling press rollers were used in soil compaction throughout (Fig. 4b).

*a) Manual sowing* *b) Design sketch after sowing*

**Fig. 4 - Furrowing, sowing and compaction in the sunlight greenhouse**

To simulate field mechanized sowing and avoid effects of fertilization on soybean seedling emergence, we did not apply watering or fertilization at the emergence stage.

**Soil physical properties**

From the start to the end of emergence, soil volumetric moisture contents were measured by a soil moisture analyzer (TDR300 Soil Moisture Meter, USA). Each ridge was divided equally into 3 segments. In each segment, measurement was conducted 10 times and the average was conducted. Before and after operations, soil compactness was measured using an SC900 soil compaction meter. Measurement was conducted every 50 mm at the depth of 0-100 mm by using a 3/4"-diameter cone head.

**Status of seedling emergence**

From the start to the end of seedling emergence, the seedlings in each segment were counted every two days. The emergence rate (PE) and mean emergence time (MET) were calculated. The average days when the PE and MET stabilized were computed as follows *(Jia et al., 2016)*:

$$PE = \frac{S_{te}}{m} \times 100\% \tag{1}$$

$$MET = \frac{N_1 T_1 + N_2 T_2 + \cdots + N_n T_n}{N_1 + N_2 + \cdots + N_n} \tag{2}$$

where $S_{te}$ is the total number of emerging seedlings per 5 m; $m$ is number of seeds sown per 5 m; $N_1, \ldots, {}_n$ is the number of emerging seedlings since the time of previous count;

$T_1, \ldots, {}_n$ is number of days after planting.

The conformity of seedling heights was measured since the 20th day after planting when all seedlings emerged. After that, the height of each seedling was recorded. Seedling height conformity is a key influence factor on crop yield. Seedling height conformity was computed as follows:

$$PC = \frac{\overline{X}}{\sqrt{\left[\sum X^2 - \frac{\left(\sum X\right)^2}{N}\right] \Big/ (N-1)}} \tag{3}$$

Where: $X$ is the seedling height, cm; $N$ is the number of seedlings.

On the 20th day after emergence, roots at the seedling stage were sampled. From each stable measurement zone in the four ridges, 5 plants that represented the local conditions were selected, or namely 15 plants were chosen from each ridge. The plants were stubbed out and immersed in water. After the earth pillars became loose, the roots were washed to leave the complete roots. Then the roots were spread onto glass plates and stretched out gently by using tweezers. When the roots were unoverlapped, the main root lengths, the lateral root length at the longest upper part, the lateral root length at the shortest upper part, the lateral root length at the longest lower part, and the lateral root length at the shortest lower part (the lateral roots growing at the hypocotyl were considered as the upper-part lateral roots, the lateral roots growing on the main root were regarded as the lower-part lateral roots) were measured using tapelines *(Zhu et al., 2018)*. The total length of lateral roots and total root length were calculated as follows:

$$L_C = 0.618 \times n \times \frac{(L_{\max} + L_{\min})}{2} \tag{4}$$

$$L = L_Z + L_C \tag{5}$$

where, $L_c$ is the total length of lateral roots, cm; $L_{max}$ is the longest lateral root length, cm; $L_{min}$ is the shortest lateral root length, cm; $L$ is the total root length, cm; $L_z$ is the main root length, cm; $n$ is the number of lateral roots.

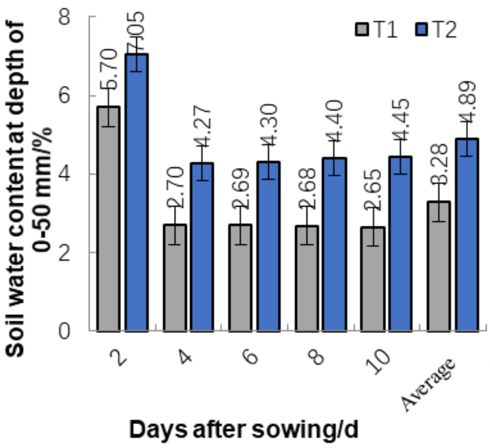
Crown dry weight: Each sample was oven-dried first at 105°C for 2 h and then at 75°C until reaching constant weight, which was the dry weight. The leaf area was measured using a Li-201 leaf area meter.

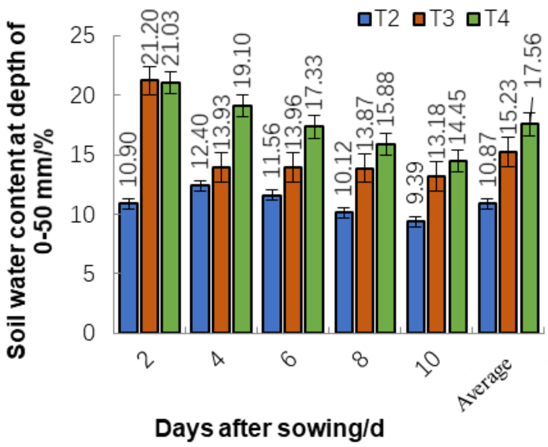
## RESULTS AND DISCUSSION

Through comparative tests with the compacted furrows, the water contents, soil compactness, average emergence time, emergence rate, total root length, dry root weight, and leaf area were measured. The measured data were qualitatively and quantitatively analyzed to clarify the effects of furrow compaction on the seedbed characteristics and soybean seedling emergence.

### Soil moisture content

Figures 5, 6, 7 shows the variation of water contents at the depth of 0-50 mm, >50-100 mm, and >100-150 mm from planting to emergence (11 to 20 August) on the furrows with or without compaction. The soil moisture contents under different treatments changed generally as follows: the water contents increased with the enlargement of soil depth within a certain range.



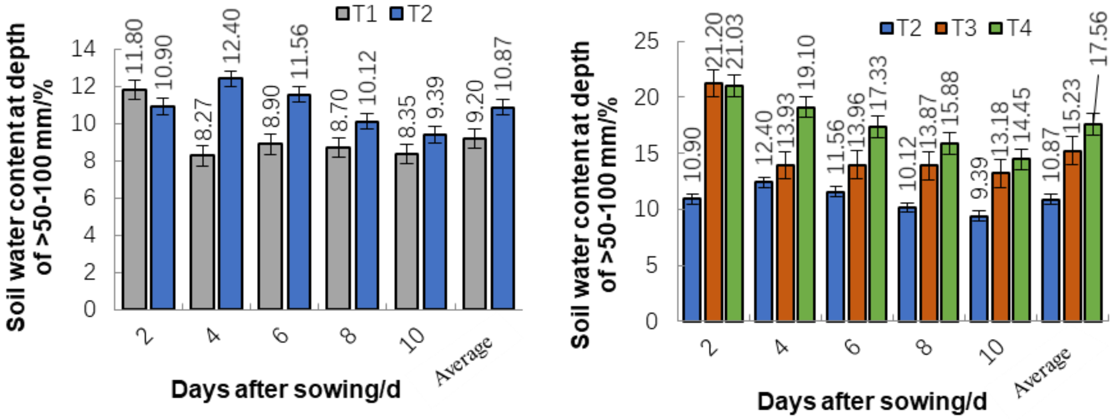

*a) Seed furrows without or with compaction* *b) Different compaction forces*

**Fig. 5 - Effects of different operating method on soil moisture content at the depth of 0-50 mm**

The operating methods significantly affected the soil moisture contents at the depth of 0-50 mm. Comparison between furrows without and with compaction showed the soil moisture contents were significantly affected by compaction and by the compaction forces.

At the soil depth of 0-50 mm, the average water content under T1 was significantly lower than that under T2, and the soil moisture contents under T1 and T2 both significantly declined since the 4$^{th}$ day, but stabilized within 4-10 days (Fig. 5a). The water content under T1 at the depth of 0-50 mm gradually declined with the increase of days, as it significantly dropped from the maximum of 5.7% to 2.7% on the 4$^{th}$ day and then slowly dropped to 2.65%. The water content under T2 significantly declined from the maximum of 7.05% to 4.27% on the 4$^{th}$ day, and rose within 4-10 days to 4.45%. The reason was that the soils around the seedbed under T2 were compacted and thereby the soil particle density and soil capillary porosity (equivalent pore size was 0.02-0.002 mm) rose. The evaporation rate was controlled by water conductivity when the water content was below the saturated level. With the decline of water content, the capillary water conductivity dropped; under the isothermal condition, the water vapors were affected by soil grain surface force and capillary force and slowly gathered at the soil compact surface, forming membranous water, namely aggregating around the compacted seeds. Thus, minor recovery of water content occurred in the seedbed under T2 at the depth of 0-50 mm. Though the humidity raising effect was not evident, it could preserve soil moisture at the depth of 0-50 mm to some extent.

The effects of compaction force on the seedbed water content within the depth of 0-50 mm were illustrated in Fig. 5b. As the compaction force was enhanced, the water contents under T3 and T4 within the depth of 0-50 mm significantly surpassed those under T2, and the average water content under T4 was higher than that under T3, but not significantly. The changing trends of soil moisture content in Fig. 5b are similar to those in Fig. 5a, but significantly declined on the 4$^{th}$ day, and stabilized within 4-10 days.



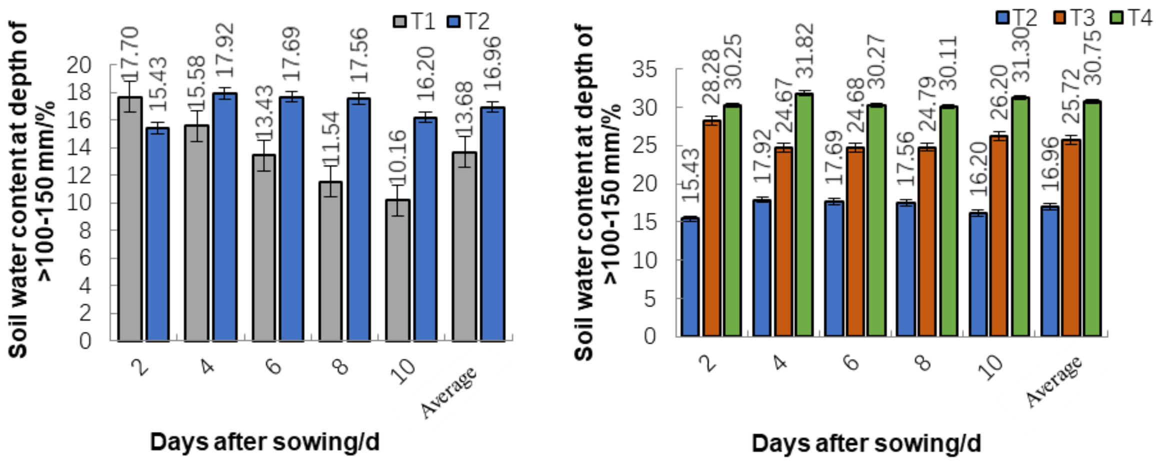

*a) Seed furrows without or with compaction* *b) Different compaction forces*

**Fig. 6 - Effects of different operating method on soil moisture content at the depth of >50-100 mm**

At the depth >50-100 mm, the average water content under T2 surpassed that under T1 (Fig. 6a). On the 2$^{nd}$ day, the water content under T1 was larger than that under T2. The water loss due to evaporation under T1 was more than that under T2. It was suggested that seed furrow compaction contributed to soil moisture preservation in the depth >50-100 mm to some extent. On the 4$^{th}$ day under T2, the soil water content did not significantly decline, but rose slightly. It was deduced that furrow compaction promoted water contents at the depth >50-100 mm to some extent.

The effects of furrow compaction force on the soil moisture content at the depth >50-100 mm were illustrated in Fig. 6b. The average soil water content was positively correlated with the compaction force, as the soil moisture preservation effect was improved at higher compaction force.

The soil moisture content at the depth >100-150 mm under T2 was higher than that under T1 (Fig. 7a). The soil moisture content under T1 gradually declined with the increase of days, and the seedbed soil moisture content under T2 did not drop significantly, indicating the seed furrow compaction could preserve soil moisture at the depth >100-150 mm.




a) Seed furrows without or with compaction b) Different compaction forces

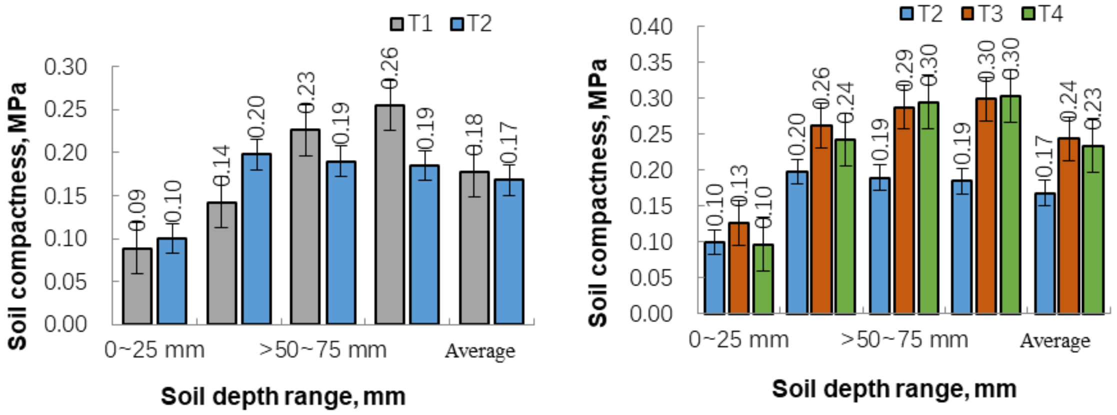
**Fig. 7 - Effects of different operating method on soil moisture content at the depth >100-150 mm**

The effects of furrow compaction forces on soil moisture contents at the depth >100-150 mm are illustrated in Fig. 7b. Clearly, the soil moisture content rose and the soil moisture preservation efficiency was higher at larger compaction force. Moreover, within the first 10 days of seedling emergence, the water content did not drop obviously, indicating that furrow compaction can well preserve soil moisture.

The above experimental results imply that furrow compaction can preserve soil moisture, which is consistent with the existing studies *(Pulkrabek et al., 2015)*. Our results also suggest soil moisture and volume weight both affect the water use efficiency of plants and interact, but the effect of soil moisture is more significant. Moreover, the spatial variation of soil bulk density is favourable for enhancing water use efficiency *(Li et al., 2019).*

**Soil compactness**

The furrow compaction compared with no compaction significantly affected the soil compactness at different layers (P<0.05), and the soil compactness at different layers changed to different extents along with the enhancement of compaction force. The furrow compaction experiments were conducted from 11 to 20 August, 2017. The soil compactness at a specific depth was measured every 2 days (Fig. 8). The soil compactness significantly varied with the furrow compaction compared with T1. The soil compactness under T1 was enlarged with the increase of soil depth. The soil compactness under T2 maximized at the depth >25-50 mm, and declined slowly with the increment of soil depth, forming a false or true interphase soil layer environment (Fig. 8a). In conclusion, the soil compactness increased abruptly at a certain depth and was higher than that at upper or lower layers, so that the water content at this depth range increased.




a) Seed furrows without or with compaction b) Different compaction forces

**Fig. 8 - Effects of different treatments on soil compaction**

The effects of compaction forces on the soil compactness at different layers are shown in Fig. 8b. As the furrow compaction force was enlarged, the soil compactness under T3 or T4 was strengthened with the increase of soil depth, and such changes were more evident than under T2. The soil compactness degrees were not significantly different between T3 and T4. In our experiments, the soil compactness at any soil depth was below 2-3 MPa, so the soil compactness after any treatment obeyed agronomic requirement.

**Mean emergence time**

Table 2 lists the daily seedling numbers within the first 15 days of seedling emergence under T1, T2, T3, and T4. Seedling emerged the earliest under T3 and the latest under T1. The seed furrow compaction significantly affected the emergence time ($P<0.05$) (Fig. 9). The average emergence time under T2 was 0.79 day earlier compared with T1.

The average emergence time under different furrow compaction forces ranked as T3<T4<T2. On the 2nd day of planting, the water contents at the depth of 0-50 mm and 50-100 mm both maximized under T3 and ranked as T3>T4>T2. The compaction under T2, T3 or T4 compared with T1 relatively well reserved water contents, and the water content was inversely proportional to the seedling emergence time.

**Table 2**

**The seedling numbers under different treatments within the first 15 days of planting**

| Date | Days of planting | Total number of seedlings | | | |
|---|---|---|---|---|---|
| | | T1 | T2 | T3 | T4 |
| 14 Aug. | 4 | 0 | 0 | 3 | 0 |
| 15Aug. | 5 | 0 | 4 | 21 | 9 |
| 16 Aug. | 6 | 4 | 10 | 27 | 18 |
| 17 Aug. | 7 | 6 | 17 | 29 | 29 |
| 18 Aug. | 8 | 7 | 24 | 30 | 32 |
| 19 Aug. | 9 | 10 | 25 | 36 | 42 |
| 20 Aug. | 10 | 13 | 26 | 39 | 43 |
| 21 Aug. | 11 | 14 | 27 | 40 | 43 |
| 22 Aug. | 12 | 14 | 29 | 41 | 45 |
| 23 Aug. | 13 | 14 | 30 | 42 | 46 |
| 24 Aug. | 14 | 14 | 31 | 42 | 46 |
| 25 Aug. | 15 | 15 | 31 | 43 | 46 |

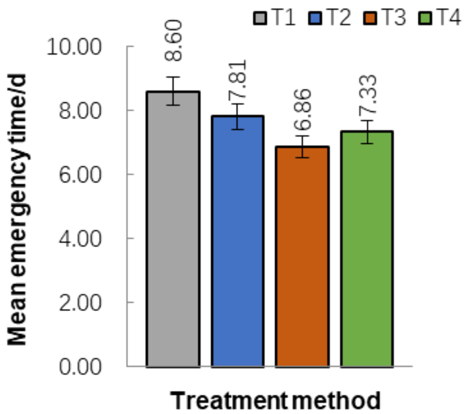
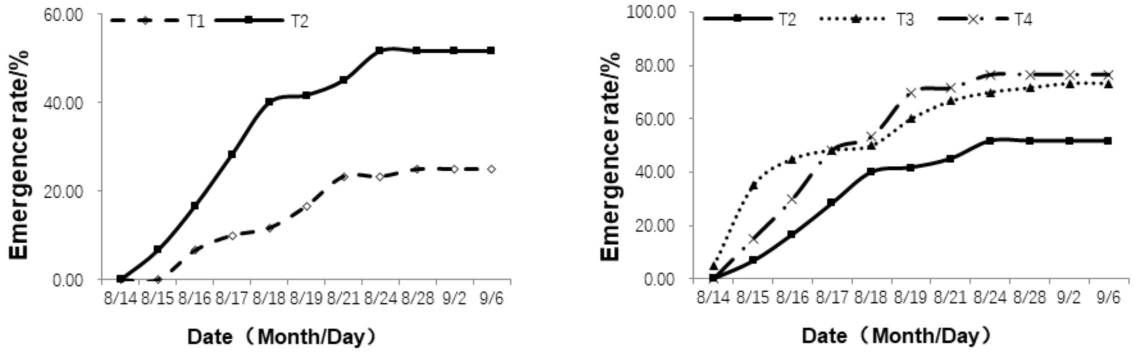



**Fig. 9 - Average emergence time under different treatments**

**Soybean emergence rate**



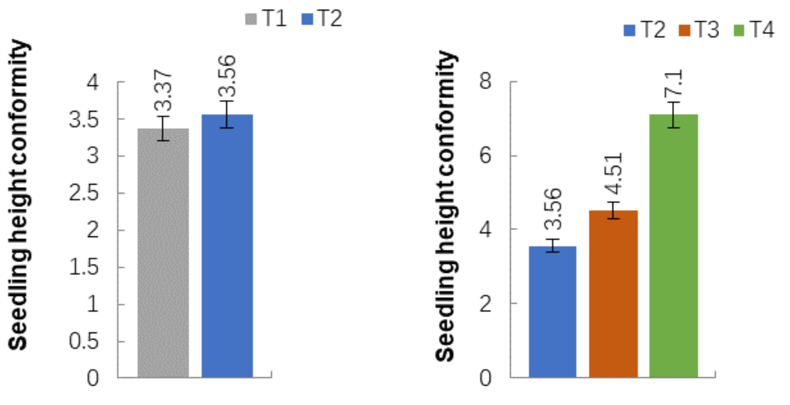

*a) Seed furrows without or with compaction* *b) Different compaction forces*

**Fig. 10 - Effects of furrow compaction on soybean emergence rate**

Results showed under the same conditions, the furrow compaction affected soil moisture content, as the soybean seed emergence rate rose at higher soil moisture content, and the emergence rates after furrow compaction were higher than that without compaction. The emergence rates ranked as T4 > T3 > T2. The furrow compaction and the compacting forces both significantly affected the emergence rates (Fig. 10). The emergence rate under T2 was significantly higher than that under T1 ($P< 0.05$) (Fig. 10a). The emergence rates under T3 and T4 were both higher than that under T2 (Fig. 10b). The emergence rate under T3 from planting to the 4$^{th}$ day of emergence was higher than that under T4, and the emergence rate beyond the 4$^{th}$ day was higher under T4 than under T3. According to the variation of water content at different depths, the water content on the 2$^{nd}$ day at the depth of 0-100 mm was higher than T3 than under T4. Beyond the 4$^{th}$ day after planting, the seedling emergence rates and soil moisture contents both declined abruptly. At this moment, the water content under T4 decreased at lower rate than under T3. The water content beyond the 4th day was higher than under T3, indicating the seed emergence rate was positively correlated with the soil moisture content. The furrow compaction significantly affected water contents and directly impacted the seed emergence rate. Under the same conditions, the emergence rate under larger soil moisture content was higher. The seedling numbers ranked as T4>T3>T2. The seed furrow compaction by the opener crushed the soils around the seedbed and made the seeds and seedbed soils fully contact, which increased the seed emergence rates.

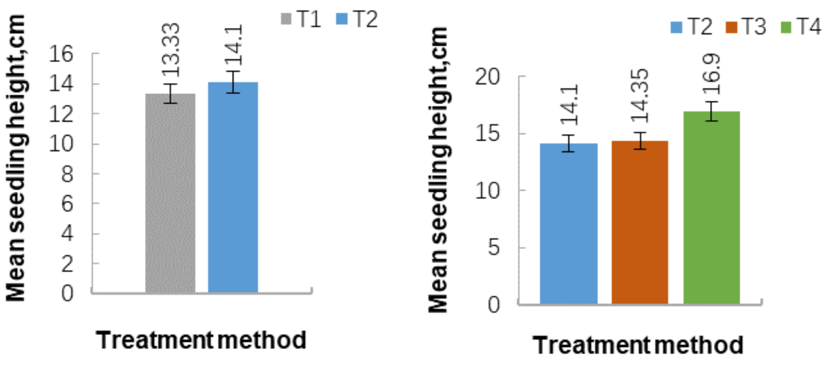
**Conformity of seedling height**

The seedling height conformity is a key influence factor on crop yield. The seedling height conformity was significantly affected by furrow compaction ($P<0.05$) and by the compaction force. The seedling height conformity under furrow compaction compared with no compaction was 3.56, with an increase of 5.34%. The seedling height conformity was the highest under the largest compaction force of T4, and ranked as T4>T3>T2>T1. The reason was that during furrow compaction by using the opener, the compaction efficiency was higher under a larger compaction force, so the variation coefficient of seed deep seeding minimized and the compaction force during the compaction was uniform, leading to the conformity of emergence time *(Jia et al., 2015; Zhao et al., 2017)*. The seeds with high consistency of deep seeding can absorb moisture and nutrient consistently, which increased the seedling emergence conformity and the regularity of crop growth. Thus, the seedling emergence conformity was higher under the treatment of T4.




*a. Seed furrows without or with compaction* *b. Different compaction forces*

**Fig. 11 - Effects of treatments on seedling height conformity**



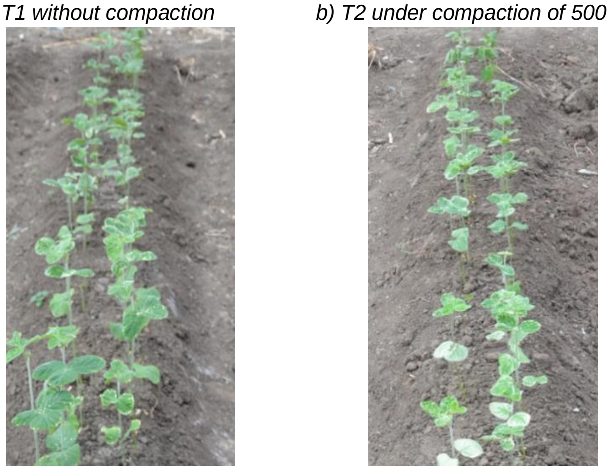

*a. Seed furrows without or with compaction* *b. Different compaction forces*

**Fig. 12 - Effects of treatments on mean seedling height**

Figure 12 shows the average height of soybean seedlings on the 20$^{th}$ day after different treatments. Clearly, the seedlings under T2 were higher than those under T1. The average seedling height under T4 was significantly larger than that under T2 and T3. This was because seed furrow compaction ensured the relatively high water content around seeds, so that the seeds can germinate quickly. As the compaction force was enhanced, the field moisture capacity also increased and at late stage of seedling emergence, continually supported seed growth. Furthermore, as the compaction force was strengthened, the deep seeding consistency and the seedling emergence conformity both increased. As for T1, however, the seedling emergence conformity was low, and the soil moisture loss was accelerated, so the seedlings became irregular. Thus, the average seedling height maximized under T4 and minimized under T1.

The seedling height conformity under T4 was higher than under T3 and T2 (Fig. 13). Missing seedling or seedling height unevenness occurred in the plots treated by T1. The seedling heights under T2 were irregular; the seedling heights under T3 were non-uniform. However, the emergence rate under T2 was high, and the seedling heights under T4 were relatively uniform.

*a) T1 without compaction* *b) T2 under compaction of 500 N*



*c) T3 under compaction of 600 N* *d) T4 under compaction of 700 N*

**Fig. 13 - Seedling heights on the 20th day after different treatments**

## Roots and crown

The compaction force larger than 600 N can significantly increase the crown dry weight, seedling height, leaf areas, main root length and total root length.

**Table 3**

**Effects of pre-planting compaction on soybean roots**

| Processing method | Root number | Main root length cm | Root length cm |
|---|---|---|---|
| T1 (no compaction) | 9.9±0.9 a | 16.8±1.6 a | 50.5±3.1 a |
| T2 (500N compaction) | 11.1±1.1 a | 16.6±1.5 a | 57.5±4.6 a |
| T3 (600 N compaction) | 12.6±1.2 a | 19.5±2.1 b | 66.2±4.8 b |
| T4 (700 N compaction) | 12.9±1.3 a | 21.2±2.7 c | 75.4±5.1 c |

*Note: letters denote significant differences (P<0.05); the same below.*

Table 4

**Effects of furrow compaction on soybean crown**

| Processing method | Crown dry weight g/pot | Seedling height cm | Leaf area $cm^2$/pot |
|---|---|---|---|
| T1 (no compaction) | 0.48±0.12 a | 13.33±2.3 a | 162±15 a |
| T2 (500N compaction) | 0.53±0.10 a | 14.10±2.2 a | 165±15 a |
| T3 (600N compaction) | 0.62±0.11 b | 14.35±2.8 b | 175±18 b |
| T4 (700N compaction) | 0.58±0.12 b | 16.90±1.2 b | 172±16 b |

Compared with T1, the average root number after treatment by T2 increased by 1.2, with an amplitude of 12.12% (Table 3). The average root length rose by 7 cm, with an amplitude of 13.9%. The soybean root length maximized after treatment of T4, with an amplitude of 31.10% from the treatment of T2. The soybean root length was enlarged with the rise of compaction force within 500-700 N. The compaction force larger than 600 N can significantly increase the crown dry weight, seedling height and leaf area compared with T1 (Table 4).

Furrow compaction can refine and tighten furrow soils and decrease the aggregate size. When the compaction force surpassed 600 N, the total root length was the largest and significantly larger than that under T1 ($P<0.05$). As reported, total root length and root surface area both significantly increased with the decrease of aggregate size, and under low soil moisture content *(Song et al., 2009)*. The small-size aggregates (especially the size of 1-2 mm) compared with large-size aggregates and the unscreened soils can largely shorten the emergence time, and significantly increase, soybean emergence rate crown dry weight, seedling height, leaf area, total root length and root surface area. These findings are consistent with our results.

## CONCLUSIONS

Through sunlight greenhouse tests, the effects of the double V-shaped opener on seedbed characteristics and soybean emergence were studied under the compaction forces of T1 (0 N), T2 (500 N), T3 (600 N) and T4 (700 N). The furrow compaction planting significantly affected the seedbed characteristics and soybean emergence and could preserve soil moisture in seedbeds. The furrow compaction significantly affected soil moisture content at different soil depths. Thus, furrow compaction could preserve soil moisture at shallow soil layers. Under the semiarid condition, the average emergence time under T2 was 0.79 day earlier than under T1, and the emergence rates under T2, T3 and T4 were significantly raised. The seedling height uniformity under T2 was 5.34% higher than under T1. The average emergence time ranked from early to later as T3<T4<T2. The deep seeding uniformity, the emergence uniformity, and the average seedling height were all improved as the furrow compaction force was enlarged within 500-700 N. The compaction force larger than 600 N can significantly increase the crown dry weight, seedling height, leaf areas, main root length, and total root length. Furrow compaction can preserve soil moisture in seedbeds, and the seedbed soil physical properties and soybean seedling emergence were optimized under the furrow compaction force of 600-700 N.

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