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Quantitative Analysis of Geometric Structures and Experimental Evaluation of Rooster Beak

Xinping Li*, Kang Wu, Yidong Ma

College of Agricultural Engineering
Henan University of Science and Technology
Luoyang, Henan 471003, China
E-mails: aaalxp@126.com, hkdngwk@163.com, 1241793303@qq.com

**Corresponding author*

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Abstract: *Quantitative analysis of rooster beak maxillary bone is highly significant to reveal the mechanism of the easy discretization and low damage in kernel dispersal. A 3D scanner is used to collect point-cloud data of rooster beak as well as extract maxillary bone horizontal and longitudinal feature curves into Matlab for curve fitting and curvature analysis. Results show that curvature values of crosscutting curves increase from side to center. These values sharply increase when curves move from side close to the center. Curvature values of the longitudinal cutting feature curves of the rooster beak maxillary bone are evidently less than those of the crosscutting curves. Geometry characteristics of rooster beak facilitate the dispersal of corn ear. High-speed photography showed that, the beak can efficiently destroy the arrangement law between kernels, and the corn ear is dispersed. The discrete roller is based on the model of the rooster beak. The experiment of discrete roller showed that the discrete and damage rates of the dent corn are 77.34% and 0.19%, respectively. The discrete and damage rates of the flint corn are 31.19% and 0.29%, respectively, under discrete roller speed of 250 rev·min*$^{-1}$ *and moisture content of corn ear of 14.5%.*

Keywords: *Bionics, Corn, Discretization, Quantitative analysis, Rooster beak.*

Introduction

Corn is one of important food product in China. The level of corn harvest mechanization is low because of various factors, such as the machinery, equipment and cultivation technique of farmers [3]. Most areas are mainly dominated by manual harvesting. In this process, a thresher is required to finish the threshing work of corn. Corn threshing mainly involves impacting, kneading, brushing, rolling, and squeeze rubbing, among other processes [6, 11]. Impacting thresher is frequently used in China. This kind of thresher processes corn ear by using a high-speed threshing cylinder, but with high breakage rate of kernels. This limitation affects the production and storage of corn seed. Bionic studies show that creatures can adapt to their environment well after a long evolution. Bionic technology is currently widely applied in mechanics [2, 4, 7-9, 12-14].

Rooster belongs to vertebrate Aves. During the long evolution process, rooster beak has developed an excellent ability to insert space between corn kernels. Moreover, the beak can efficiently disperse kernels with low damage, and this principle provides the foundation for bionic threshing of corn seed. Thus, agricultural machinery experts introduce the threshing principle of pre-dispersion and post-threshing. The excellent ability of the beak is suitable for dispersing corn kernels, and basic studies on the new threshing principle are currently being conducted [5].

In this paper, a 3D scanner was employed to collect external contour data of a rooster beak. The characteristic curve of the maxillary bone was analyzed quantitatively [1, 10]. The mechanism of rooster beak characterized by easy dispersion and low damage was discussed. This paper could provide reference for developing threshing parts of a corn bionic thresher.

Materials and methods

Structural characteristic of a rooster beak

Rooster beak is equivalent to a mammalian lip, which includes maxilla and mandible. The beak consists of two parts, namely, the bone portion and skin-derived cuticle. The bone portion contains 38.7% protein and 20.7% fat. The cuticle, which is mainly composed of 93.32% protein, is the outer sheath that protects the beak. The cuticle enwraps the maxilla and mandible. The beak is pyramidal and hard.

The maxillary squeezes the kernels when the beak pecks a corn ear. The mandible shovels the kernels, which are then dispersed. The separation of kernels is mainly caused by the maxilla. Fig. 1 shows the structure of a rooster beak. This paper mainly analyzed the maxilla quantitatively.

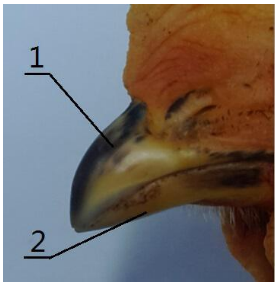


Fig. 1 Structure of rooster beak:
1. maxilla and 2. mandible.

Collection of beak countour data and point-cloud processing

Point-cloud data of a rooster beak (Fig. 2) were collected with a Handy SCAN3D-handheld scanner (Creaform). These extracted data were used for the quantitative analysis of the rooster beak maxilla (Fig. 3). Point-clouds of maxilla were severed from the transverse direction by five equal sections with 1.5 mm interval along the longitudinal direction of the maxilla. These sections intersected with the point-clouds of the maxilla and assigned as sl1-sl5 from the front of the maxilla to the end. The lines are shown in Fig. 4. The point-clouds of the maxilla were severed from the longitudinal direction by four equal sections with 1.0 mm interval along the transverse direction of the maxilla. These sections intersected with the point-clouds of the maxilla and assigned as sz1-sz4 from the left of the maxilla to the right. The lines are shown in Fig. 5.

Fig. 2 Point-cloud data of rooster break

Fig. 3 Point-cloud data of rooster maxilla

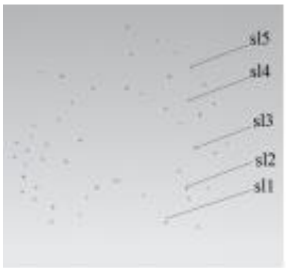


Fig. 4 Point-cloud data of transverse section curves of rooster maxilla

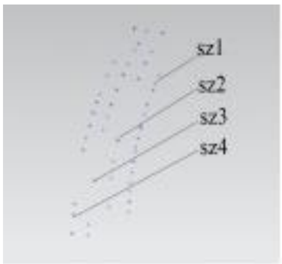


Fig. 5 Point-cloud data of longitudinal section curves of rooster maxilla

Characteristic curve fitting of maxilla

The lines were stored as coordinate data file. Data were then plotted and fitted using Matlab. The results of the transverse section fitting curves of the rooster maxilla are shown in Table 1. The results of the longitudinal section fitting curves are shown in Table 2. Fig. 6 presents the fitting graph of transverse section curves, with curvature chart shown in Fig. 7. Fig. 8 shows the fitting graph of longitudinal section curves, with curvature chart shown in Fig. 9.

Table 1. Results of transverse section fitting curves of rooster maxilla

Coefficient of equations	$f(x) = a_1 e^{-\left(\frac{x-b_1}{c_1}\right)^2} + a_2 e^{-\left(\frac{x-b_2}{c_2}\right)^2}$				
	sl1	**sl2**	**sl3**	**sl4**	**sl5**
a_1	14.38	17	8.21	3198	14.18
b_1	-58.86	-57.14	-55.11	-58.83	-58.1
c_1	5.181	4.733	2.438	3.625	6.602
a_2	0	0	13.56	-3184	0
b_2	-75.98	0	-59.25	-58.83	0
c_2	1.048	0	4.013	3.617	0
R^2	0.9778	0.9625	0.9923	0.9706	0.9354
SSE	0.06626	0.4401	0.2411	0.9348	1.978

Table 2. Results of longitudinal section fitting curves of rooster maxilla

Coefficient of equations	$f(x) = p_1 x^4 + p_2 x^3 + p_3 x^2 + p_4 x + p_5$			
	sz1	**sz2**	**sz3**	**sz4**
p_1	0.003129	0.002817	0.002758	0.002358
p_2	-3.938	-3.537	-3.459	-2.965
p_3	1858	1666	1627	1398
p_4	-3.898e+005	-3.487e+005	-3.401e+005	-2.928e+005
p_5	3.066e+007	2.737e+007	2.665e+007	2.301e+007
R^2	0.9994	0.9997	0.9996	0.9988
SSE	0.03984	0.03851	0.04071	0.4034

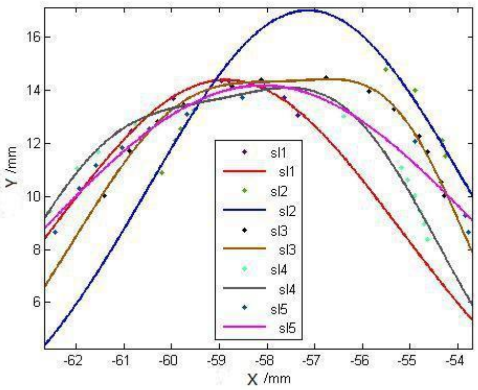


Fig. 6 Fitting curves of transverse section curves of rooster maxilla

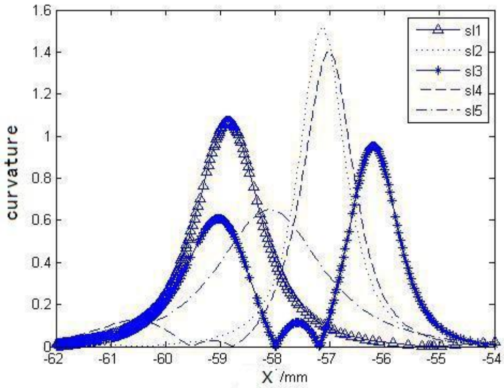


Fig. 7 Curvature chart of fitting curves of transverse section curves of rooster maxilla

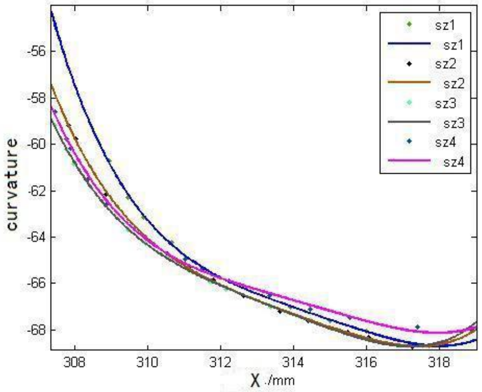


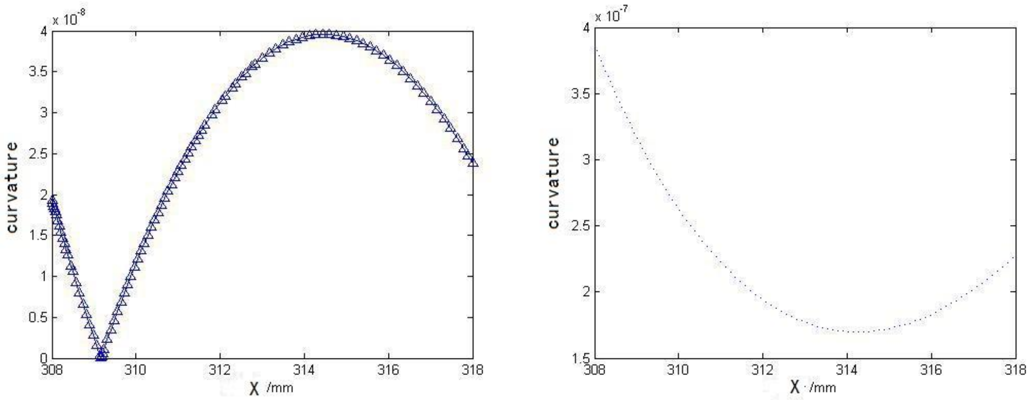
Fig. 8 Fitting curves of longitudinal section

Results and analysis

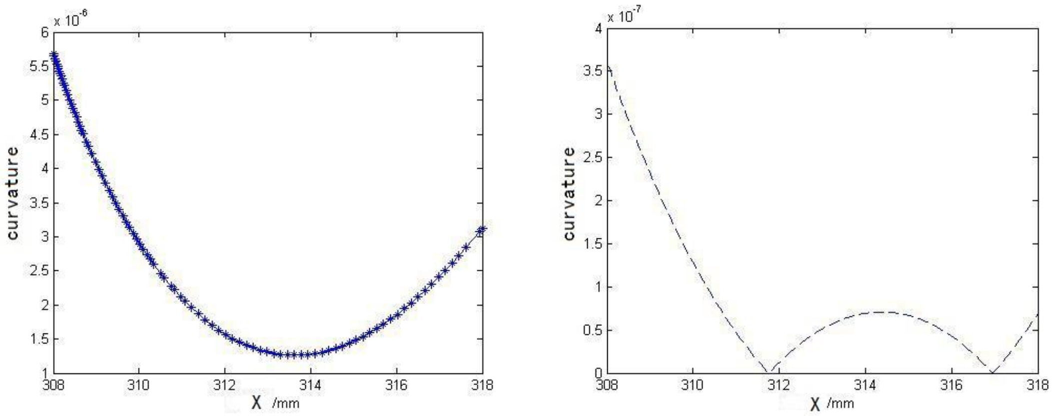
Curvature analysis of transverse section fitting curves of the rooster maxilla

The curvature of fitting curves indicates the bending degree of curves. Higher curvature values indicate sharper bending degree of fitting curves. Fig. 7 shows that the curvature values for the five fitting curves of transverse section curves of rooster maxilla are smaller on both sides but larger at the central area. The curvature rapidly increases on all sides of the maximum curvature of fitting curves. This general trend indicates that the cross-section of the maxillary beak shows that the bending degrees are small and substantially identical on both sides of the maxillary beak. The curves sharply bend to maximum value when they move closer to the middle from both sides. Curves sl1-sl5 are acquired by intercepting from the front of the maxillary beak along the longitudinal direction.

The maximum and average curvature values for these curves are as follows: sl1, 1.071 and 0.3136; sl2, 1.518 and 0.3498; sl3, 0.9542 and 0.2773; sl4, 1.403 and 0.2914; and sl5, 0.6507 and 0.2243. The average values of the five curves are basically similar, which indicate that the curves have similar bending degrees. Curvature variations of sl1, sl2, and sl5 are basically the same, that is, they exhibit only one peak. By contrast, curvature variations of sl3 and sl4 in the middle beak are slightly different from those of sl1, sl2, and sl5 at the front and rear parts of the beak. Curvatures sl3 and sl4 have three peaks at the middle of the curves, which suggest that the bending degree of upper curve changes repeatedly. The upper parts of sl3 and sl4 are smoother than those of sl1, sl2, and sl5.



(a) Curvature of sz1 (b) Curvature of sz2



(c) Curvature of sz3 (d) Curvature of sz4

Fig. 9 Curvature chart of fitting curves of longitudinal section curves of rooster maxilla

In summary, the bending degrees of the maxillary transverse section on both sides are small, whereas those at the middle maxillary transverse section are large. The upper part of rooster maxilla is curve and narrow, whereas the bottom part is flat and wide. The change in the rooster maxilla along the longitudinal direction is characterized by the rapid bending of the front and rear parts (sl1, sl2, and sl5) and relatively flat bending of the midsection of the rooster maxilla (sl3 and sl4).

Maxillary bone plays a major role during the beak dispersal of corn ear. The direction of the crack inserted by the maxillary bone between the kernels can be decomposed along the transverse and longitudinal directions of the beak. When the beak is inserted into the corn ear along the transverse direction, the upper part of maxillary bone initially contacts the crack. Given the aforementioned curvature values for the different sections, maximum curvature occurs on the upper part of beak transverse section. This structure aids the beak to insert crack between kernels. During beak insertion into the crack, the bottom part of rooster maxilla transverse section contacts the kernels gradually. The wide bottom part with small bending is beneficial for the beak to squeeze the peripheral kernels through the crack, which can loosen and disperse the kernels. When the beak is inserted into the corn ear along the longitudinal direction of beak, the upper part of the maxillary bone (sl1 and sl2) initially contacts the crack, which is characterized with remarkable bending. The middle part of the upper rooster maxilla transverse section (sl3 and sl4) has a small bend small and can broaden the crack. The back of the upper rooster maxilla transverse section (sl5) exhibits the smallest bend, which is favorable for the removal of the beak from the crack. The structure of rooster maxilla is beneficial for dispersing corn ear kernels.

Curvature analysis of longitudinal section fitting curves of the rooster maxilla

The maximum and average curvature values of sz1 are 3.59×10^{-8} and 2.267×10^{-8}, respectively, whereas those of sz2 are 3.877×10^{-7} and 2.551×10^{-7}, respectively. The corresponding values for sz3 are 5.683×10^{-6} and 3.042×10^{-6}, respectively, whereas those for sz4 are 3.625×10^{-7} and 1.281×10^{-7}, respectively. The curvature of the longitudinal section fitting curves of the rooster maxilla is evidently less than that of the transverse section fitting curves. This phenomenon indicates that the bending degree of longitudinal section fitting curves is less than that of the transverse section fitting curves. Therefore, the overall trend of the curvature of the longitudinal section fitting curves shows large front and rear parts but relatively smaller middle part. The front part, with larger curvature, is initially inserted into the crack when rooster maxilla is inserted into the kernels. Further insertion of the beak into the crack along the longitudinal direction results in smaller bending degree of rooster maxilla. The bending degree of rooster maxilla increases when the rooster maxilla is removed from the crack. These characteristics of the rooster maxilla longitudinal section are beneficial for dispersing corn ear kernels.

Experiment and discussion

High-speed photography

Zhengdan 958 corn, which was hand-picked and used in this study, has a moisture content of 11.8%.

As shown in Fig. 10, the chicken started to open its beak at 1.685 s, and then the beak was inserted into the gap between kernels at 1.693 s. The processing time for the kernels to fly out of the ear ranged from 1.701 s to 1.725 s. The images in Fig. 10 illustrates that the forepart of the upper beak produced extrusion pressure on the kernels, which moved forward because of forces and pushed other kernels. Kernels with thrust moved and pushed the front kernels. This process continued because of the constantly applied forces, until the corn ear was dispersed. At the discrete beginning of the corn ear, beak had buffer action to the corn kernels although rooster beak remarkably impacted the kernels because of the corneum surface of beak. Thus, the rooster beak did not damage corn kernels.

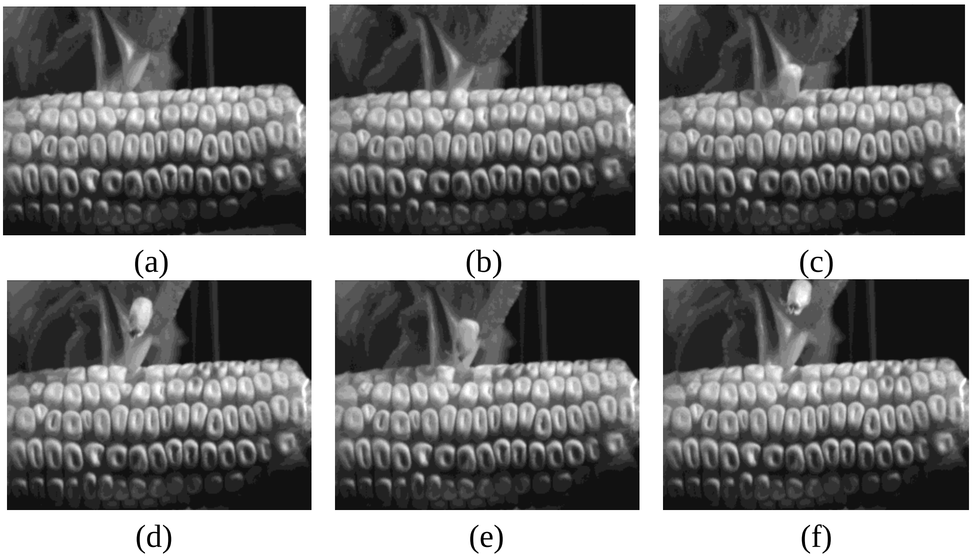

(a) (b) (c)
(d) (e) (f)

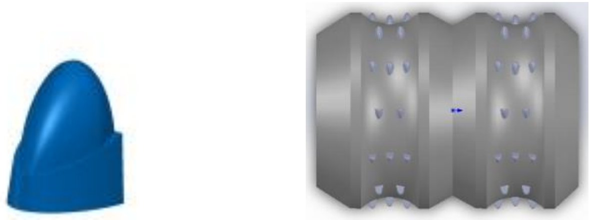
Fig. 10 The movement of kernels with high-speed photography

Design of discrete roller

A 3D model of the rooster beak was reversed based on the point-cloud data, which was planned to design a discrete unit. This paper reports on a 3D model of a discrete roller, as shown in Fig. 11, based on the discrete unit. A discrete roller is then designed. From Design Handbook of Agricultural Machinery, we conclude that the maximum diameter and length of the discrete roller is 180 and 242 mm, respectively. The widths of two concave surfaces used to decorate the discrete units are both 53 mm. By considering the factors of optimal discrete effect and processing, 12 rows of discrete units are arranged along the discrete roller circumference and intervals of 2 or 3 discrete units are arranged alternately in each row.

Experiment of discrete roller

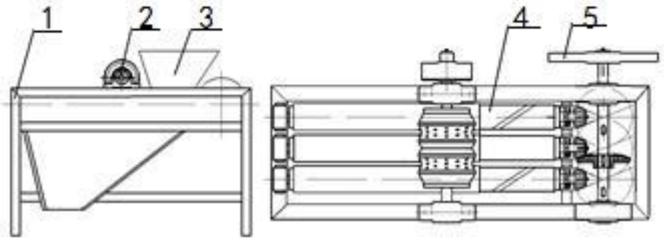
At the beginning of the test, corn ear entered the discrete space formed by the discrete and differential rollers. This part of the differential roller was bare, which mainly had supported and pushed the corn ear. The discrete roller then destroyed the arrangement rule between kernels of the entire corn ear, thereby dispersing corn kernels.



(a) discrete unit (b) discrete roller

Fig. 11 3D model of discrete roller

An experiment was conducted on the discrete test-bed to verify the effect of bionic discrete roller. The discrete test-bed consisted of a discrete roller, differential rollers, feeding inlet and frame, among others, as shown in Fig. 12.



(a) main view (b) top view

Fig. 12 Discrete test-bed of corn ear: 1. frame; 2. discrete roller;
3. feeding inlet; 4. differential roller; 5. belt pulley.

Corn varieties dent Zhengdan 958 (dent corn) and flint 335, which are widely grown in Henan Province and northeastern China, respectively, were the varieties used. Corn moisture, which was the water level in the actual threshing production, was 14.4-14.5%. Speed of the discrete roller was within the range of 150-350 rev·min^{-1}, whereas that of the differential roller was 50-250 rev·min^{-1}. Optimal parameters were determined as discrete roller speed of 250 rev·min^{1}, and differential roller speed of 100 rev·min^{1}. Experiment with optimum parameters was conducted. The discrete rate and damage rate were calculated with Eqs. (1) and (2):

$$R_1 = \frac{N_1}{N}, \tag{1}$$

$$R_2 = \frac{N_2}{N}, \tag{2}$$

where R_1 means the discrete rate, R_2 – the damage rate, N_1 – discrete kernels, N_2 – damage kernels, N – total kernels.

The test results are shown in Table 3.

Table 3. Experimental data of discrete roller

Variety	Kernels moisture	Damage rate	Discrete rate
Zhengdan 958	14.5%	0.19%	77.34%
335	14.4%	0.29%	31.19%

Table 3 shows that the discrete and damage rates of the dent corn ear were 77.34% and 0.19%, respectively, whereas those of flint corn ear were 31.19% and 0.29%, respectively. Thus, the discrete effect is better with low damage rate, and corn kernels were loosened after dispersion, which provided the basis for further full threshing. Meanwhile, the results indicated that the geometrical characteristics of beak are suitable for dispersing corn ear.

Conclusions

The main conclusions could be summarized as:

1. The transverse section curves of the rooster maxilla are fitted by Gauss equation. The bending degrees of both sides of the maxilla are small, contrary to the large bending degree of the middle part. The upper side is narrow and bends sharply, contrary to the wide and flat bottom part. These characteristics are beneficial for dispersing and loosening corn ear kernels.
2. The bending degree of longitudinal section fitting curves shows an overall trend of sharp bending for the front and rear parts, contrary to the relatively flat middle portion. These characteristics reduce the damage during beak dispersal of kernels.
3. The bending degrees of longitudinal section fitting curves are less than those of the transverse section fitting curves.
4. Experimental results show that bionic discrete roller has better discrete effect on corn ear as shown by the resulting low damage, and the geometric structure of rooster beak is suitable for dispersing corn kernels from cobs.

Acknowledgements

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Assoc. Prof. Xinping Li, Ph.D.
E-mail: aaalxp@126.com

Xinping Li is an Associate Professor of Henan University of Science and Technology, China. He also holds a Ph.D. in Engineering. Assoc. Prof. Li has published many articles and patents in mechanics and bionics. His research interests are in agricultural harvesting and processing machinery.

Kang Wu, M.Sc. Student
E-mail: hkdngwk@163.com

Kang Wu is studying for a M.Sc. degree in Henan University of Science and Technology, China. His major is design and manufacturing of agricultural machinery.

Yidong Ma, M.Sc. Student
E-mail: 1241793303@qq.com

Yidong Ma is studying for a M.Sc. degree in Henan University of Science and Technology. His major is engineering of agricultural mechanization.