Research on mechanics properties of crop stalks: A review

Du Dongdong, Wang Jun*

(*Institute of Intelligent Agricultural Equipment, College of Biosystems Engineering and Food Science, Zhejiang University, Hangzhou* 310058, *China*)

Abstract: As one of the foundational research areas in agricultural engineering, the study of agricultural materials includes an important branch: mechanics properties of crop stalks. This branch is now widely associated with design and improvement of agricultural equipment, breeding of new species, and development of reinforced composites. This article presents an overview of research on mechanics properties of crop stalks, including the mechanics measurement experiments, mechanics model and theory, microstructure and composition, and mechanics simulation experiments. The current research relies mainly on the mechanics theory of engineering material, neglects the fact that crop stalk is a biological material with complex structure, anisotropy, viscoelasticity and rheology. In addition, some simulation experiments are conducted in idealized conditions, beyond the application. Hence, the paper proposes to create new material models for crop stalks, conduct more practical and effective simulation experiments, and promote cooperation in interdisciplinary studies for the development of mechanics properties of crop stalks in the future research.

Keywords: crop stalk, mechanics property, measurement, model, theory, microstructure, composition, mechanics simulation

DOI: 10.3965/j.ijabe.20160906.1499

Citation: Du D D, Wang J. Research on mechanics properties of crop stalks: A review. Int J Agric & Biol Eng, 2016; 9(6): 10－19.

1 Introduction

The stalk is one of the most important parts of crop plants. As a biological material, it has complex structure, anisotropy, viscoelasticity and rheology, extremely different from engineering materials. In addition, various crop stalks differ from each other. Because of the biomass characteristics and massive throughput, the current research focuses on its possibility as an alternative to wood raw materials[1,2], and its potential for renewable resources, like biogas[3] and bio-ethanol fuel[4]. There is no doubt that it will play a crucial role in the sustainable development of energy. Moreover, the research regarding the crop stalk as working objective in agricultural machinery has the equal importance[5]. This research focuses on mechanics properties of crop stalks, including the physical size, tensile, compressive, shear, cutting properties and their relationship with external and internal factors. All of these are foundational and practical in the development of agricultural machinery.

The morphology of crop stalks is an important criteria for the design of machineries, especially for the determination of mechanical structure and key components. For instance, the investigation of physical size of cabbage plants was regarded as the primary task in the development of cabbage harvester[6,7]. The same principle is also applied in vegetable transplanter[8], carrot harvester[9], tomato harvester[10], etc. Moreover, the mechanics properties of crop stalks are also the vital referenced data to the hay baler or the like. Conducting the compression, blending and cutting tests are inevitable for the efficiency improvement of chopper and the baler[11]. Otherwise, some mechanics experiments can help optimize the machine construction and reduce

Received date: 2014-10-14 **Accepted date:** 2016-10-13

Biography: Du Dongdong, PhD Candidate, research interests: vegetable harvesting, Email: dudd@zju.edu.cn.

***Corresponding author: Wang Jun**, PhD, Professor, research interests: agricultural machinery and equipment. Mailing address: College of Biosystems Engineering and Food Science, Zhejiang University, Hangzhou 310058, China. Email: jwang@zju.edu.cn.

energy consumption. In terms of sugarcane harvesting, a comprehensive mechanics investigation of leaf sheath improved the machinery design for stripping leaves from the stalks[12]. And an optimized blade oblique angle to sugarcane reduced the cutting energy requirement[13]. As to explain the crop lodging phenomena, certain mechanics properties and chemical composition of the stalks could be used to reveal the theoretical analysis. Kashiwagi et al.[14] revealed that the lodging resistance is apparently associated with stem diameter and plant height. Actually, it is a capability related to Young's modulus which is a mechanics indicator of the rigidity of the stalks[15]. As for the chemical composition, lodging resistance is negatively related with total nonstructural carbohydrate, protein, and potassium in the stalks[16]. In the research of biomass, it is essential to determine the mechanics parameters for distinguishing a new synthesized biomass that may be made from crop stalks. Taking big bluestem[17], canola stalk[18], cotton stalk bast[19] and rice straw[20] as the reinforcing filler in different polymers, the mechanics testing results showed that the composites usually had improved flexural and tensile properties. Therefore, research on mechanics properties of crop stalks has been becoming an increasingly important discipline branch because of its multi-significance on the development of agricultural engineering.

In this overview, current studies on the mechanics properties of crop stalks, including mechanics measurement experiments, mechanics model and theory, microstructure and composition, and mechanics simulation experiments were reviewed, respectively. On these bases, it is suggested that creating new material models for crop stalks, conducting more practical and effective simulation experiments, and cooperating in interdisciplinary research are expected to promote the development of research on mechanics properties of crop stalks.

2 Mechanics measurement experiments

Measuring the mechanics parameters is a basic work for the research on mechanics properties of crop stalks, as well as of crop-reinforced composites[21]. As mentioned in mechanics guidelines, the tensile and compressive strength, Young's modulus, bending strength, and sheering strength are regarded as some of the most important mechanics parameters. Correspondingly, the measurement experiments include tensile and compression tests, bending tests, and sheering tests which require using universal testing machine (UTM), torsion testing machine, and self-designed apparatuses. Furthermore, the success of experiments usually depends on whether the researchers can design and choose the proper fixture. In other words, the crop stalks should be guaranteed that would not be dropped, slipped or broken in the experiment process.

2.1 Mechanics parameters measurement

The tensile tests reflect the mechanics characteristics when the material is stretched. The tensile strength, Young's modulus, elastic limit, etc. can be obtained in the tests. Xu et al.[22] measured the tensile strength of root, middle and head of fresh cucumber cane, and their Young's modulus in tensile tests. In order to prevent straw slipping from the clamp, they used a clamping head with rubber pad stuck to the surface, and clamped the two ends of the sample between the testing machine. We can see in some cases the commonly used fixture cannot be applied to stretch the stalk samples in tensile tests. Therefore, clamping methods should be designed by researchers themselves for specific application. For example, using special glue[23] and adding rigid materials[24] such as steels to fix and clamp the samples are the very common ways in biological material tests. On the other hand, almost all the crop stalks are anisotropic, which means the lateral mechanics parameters should also be taken into consideration. However, the small size of materials always creates difficulty in stretching samples in the lateral direction. By the gluing method in the lateral tensile tests, Liu et al.[25] proved that the tensile strength of sugarcane stalk in the axial direction is much bigger than in the lateral direction. So the mechanics properties in the lateral direction are usually ignored for simplification.

The compression tests can reveal the mechanics characteristics when the materials are compressed. Different from tensile tests, compression tests do not need the special fixture to fix the samples. But the samples must be processed to meet the standard. According to the axial and lateral compression tests, Khan et al.[26] determined the maximum compressive force and energy for two species of hemps (*Cannabis Sativa* L.) at different locations. The results demonstrated that the bigger maximum compressive force and energy are located at the lower compressive location in both axial and lateral compression. As mentioned above, different from the self-designed hydraulic clamp in tensile tests, compression tests usually took the compression rod as the standard component. Along with compressive properties, relaxation properties are usually observed to avoid the excessive expansion in volume and the decrease in density, especially for briquetting. Guo et al.[27] investigated the compressive and relaxation properties of selected biomass for briquetting, the relaxation tests showed that the higher applied stress resulted in a higher relaxation speed, and increasing moisture content reduced the relaxation speed. The similar results were also observed by Talebi et al.[28]

The shear tests demonstrate the mechanics characteristics of materials subjected to shear force. To measure the shear stress and shear energy, an effective fixture plays a key role in finishing the shear tests. Yu et al.[29] introduced a double-shear device as an attachment to the UTM for biomass shear tests. This device had inner (solid) and outer (hollow) elements with matching holes. The hole diameters were selected in such a way that a range of stem diameters could be accommodated. Then the prepared stems were inserted into the holes of the device corresponding to their diameters to finish the shear tests. The shear stress and specific shear energy can be calculated as:

$$\begin{cases} \tau = \dfrac{F_s}{2A_s} \times 10^{-6} \\ SE_s = \dfrac{SE}{2A_s} \end{cases} \tag{1}$$

where, τ is shear stress at failure, MPa; F_s is shear force at failure, N; A_s is single failure area of the sample at the notch, m^2; SE_s is specific shear energy, kN/m; SE is shear energy derived from the area under the respective force-displacement curve, kN·m.

From the current references, we summarized the mechanics parameters of some crop stalks, such as wheat[30,31], barley[30], safflower[32-34], reed[35], rape[36], *Miscanthus*[24], alfalfa[37,38], etc. As shown in Table 1, it is obvious that not all of the mechanics parameters were recorded, and it may depend on the detailed proposal in different research projects. We also found that the parameters for the same crop stalk may be different as a result of different testing conditions, varieties, and individual difference. In the future research, we think the metrical system based on the mechanics theory of engineering material cannot be appropriate for crop stalks because of their complex structure, anisotropy, viscoelasticity and rheology. We strongly encouraged the researchers to focus on creating new material theories for crop stalks.

Table 1 Mechanics parameters for some crop stalks

Crops	Tensile strength /MPa	Young's modulus /GPa	Compressive strength /MPa	Sheer strength /MPa	Bending strength /MPa
Wheat	30.4-52.6	1.14-2.05	-	6.81-7.12	13.70-19.31
Barley	-	-	-	3.90-4.49	8.14-8.55
Safflower	-	0.86-3.33	-	2.98-6.04	25.9-47.71
Reed	118	0.321	26	22	152
Rape	-	0.172	11.9	-	-
Miscanthus	288.1	4.6-11.3	-	65	-
Bluestem	25	-	-	7.33	-
Corn	69.30	-	-	8.53	-
Switchgrass	42	-	-	13.39	-
Alfalfa	16.8-36.0	0.544-1.979	-	9.27	-
Coronilla	11.7-18.8	0.371-0.789	-	17.33	-
Ice grass	50.6-74.8	3.519-4.462	-	50.32	-
Brome	57.4-105.7	1.441-3.041	-	35.69	-

2.2 Factors influencing mechanics properties

Because crop stalks have biological characteristics, their mechanics properties will not stay constant with the change of external and internal factors. The external factors mainly refer to the environmental impacts, like cultivation, storage condition, sample processing, etc. And the internal factors are the ones related to crop itself, like maturity stage, moisture content, individual difference, etc. These controllable and uncontrollable factors make us realize that the mechanics properties for the same crop stalk cannot be determined as accurately as engineering materials. Consequently, to control and optimize the influencing factors become an important issue in agricultural engineering.

A few studies showed that crop stalks in different maturity stages have different tensile, compressive, shear and bending properties. Taking wheat straw as an example, O'Dogherty et al.[31] conducted a series of experiments to measure the physical properties, tensile and shear strength, and elastic modulus of wheat straw in four maturity stages. The results proved the hypothesis above that the plant maturity had some effect on shear strength and Young's modulus. It described that the shear strength was significantly larger for the first maturity stage than for the other three stages. Young's modulus significantly increased with increasing maturity up to the harvest time. With the above knowledge, we can try to explain the reasons why the plant seedlings are easier to suffer lodging influenced by heavy weather. We can also figure out the best time for machines to finish the harvesting works as well.

Sharma et al.[39] compared the tensile strength and shear strength of switchgrass before and after frost. The results showed that the mean tensile strength and shear strength before frost was significantly greater than those after frost. This phenomenon was attributed to the change of moisture content before and after frost. Indeed, the researchers found that the moisture content decreased rapidly after frost, but they did not analyze the relationship between mechanical properties and moisture content. Tavakoli et al.[40] detailed this relationship for wheat straw, and their experiments demonstrated that an increase in moisture content of straw led to decreases in bending strength and Young's modulus and increases in shear strength and specific shearing energy. This similar effect of moisture content was also reported by Esehaghbeybi et al.[41] Other studies also reported nitrogen fertilizer[41], stalk region[32], and target seeding rate[23] may influence the mechanics properties as well. All of these factors influencing the mechanics properties can be essentially attributed to the change in stalk structure and composition, which will be detailed in the following paragraphs.

3 Mechanics model and theory

Mechanics model and theory refer to the mechanical and mathematical model that was built in order to analyze the mechanics, kinematics, and dynamics of crop stalks in working conditions. Neglecting or simplifying the irrelevant factors and conditions, the research on this topic focuses on the main mechanics substance. It will make complicated issues become more simple and efficient, especially for some specific applications. Before the new model is applied, it is necessary to validate and verify the model according to small-scale tests. We realized that the relative research is rare, probably because of the difficulty in modeling. But we insist the research on mechanics model and theory is one of the most important topics in this area.

3.1 Material model and theory

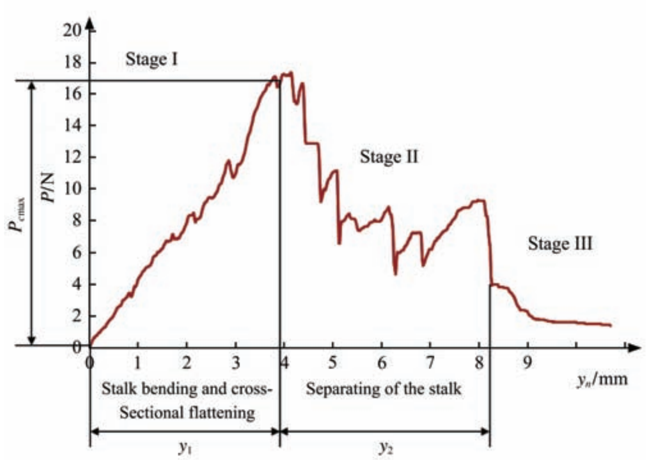
As a complicated biological material, crop stalk needs to be simplified on its material model. Like the research on soil dynamics, soil-structure model is a very useful element frequently used in numerical simulation application[42]. The developed material model can be added into finite element method (FEM) library for complicated system modeling and analysis[43].

Which factor should be simplified or retained actually depends on the accuracy and reliability of the required model. Hirai et al.[44] compared two crop models under the deflection force from reel operations. The first model had different flexural rigidities of each internode, and the second model added the effect of a crop ear to the first model. The authors found that the second model with a crop ear involved a certain amount of error due to the effect of initial posture and vertical force component, but coincided approximately with the experimental results. These two models had their own advantages, whether the crop ear should be added would be associated with the practical situations. In the application of a quasi-static bending model, Hirai et al.[45] measured and analyzed the reaction force of crop stalks under dynamic loading conditions according to experiments. When the simulated results by the bending model involved a large amount of error, they further took the accelerated motion into consideration. Then they identified that the inertial force in high loading speed was the main factor leading to the difference between experimental and simulated values. Unfortunately, they did not revise the previous bending model. These studies suggested that the modeling principles for crop materials should associate with the specific application, thereby avoiding the model distortion.

3.2 Process model and theory

In practice, the crop stalk usually needs to interact with other objects, such as agricultural machinery, experimental apparatus, etc. Modeling the process of interaction will help us understand the mechanics, kinematics, and dynamics occurred during this period. It will further help to improve the process efficiency and save the energy consumption.

For harvesters, cutting process is regarded as the most energy-consuming working stage in the whole operation. Guarnieri et al.[46] developed a complete mathematical model for a single-blade cutter bar with a crank-conrod driven system. The analysis of the system behavior in pruning operations demonstrated that the model has succeeded in pointing out the system disequilibrium sources. In fact, it is a very common mechanical model for slider-crank mechanism. Zastempowski and Bochat[47] presented a meaningful mathematical model for the cutting process of plant material using a shear-finger cutting unit. The model divided the cutting process into three stages as shown in Figure 1. The mathematical model was verified to be adequate enough by the experimental results on a test stand.



Note: Stage I–the approach of the stalk to the counter-cutting edge; Stage II–the deformation of the stalk cross section; Stage III–the separation of the stalk.

Figure 1 Stages of the stalk cutting process

Although the references on mechanics model and theory are rare, we can conclude that the research on this issue still depend on the mechanics theory of engineering material. Thus most of the present studies built the material model of crop stalk based on the unidirectional model and analyzed the force-deformation relationship based on the elastic deformation theory. However, the crop stalk is a kind of viscoelastic material with rheological properties. Rodriguez et al.[48] used the Bowyer-Bader methodology to analyze the mechanical properties of fiber-reinforced polypropylene composites, which was a good attempt to solve the modeling problem. Otherwise, the research on process model and theory is rarely reported. We think the practical problems in agricultural machinery should be addressed urgently by the theoretical innovation, not by the means of empirical methods at present.

4 Microstructure and composition

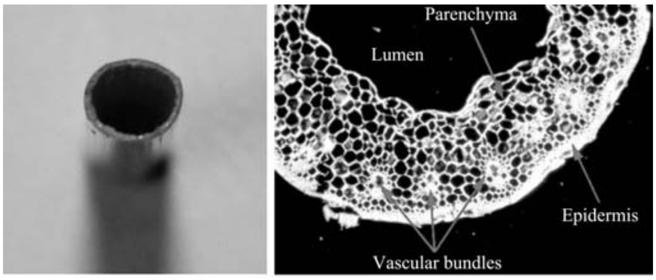
Essentially, the epigenetic characteristics of botany can be explained by its inner structure. So it is more persuasive to associate the mechanics properties of crop stalks with their microstructure and composition. Microstructure could be observed under the microscope, and the composition could be detected by chemical method. The research on this topic requires a multiple-discipline background for the qualification. More precisely, the researchers will focus on the mechanics properties of crop stalks as well as microscopic observation and chemical detection, and then conclude the meaningful results by statistics method. It is also an important content in the study of structural bionics and composite synthesis[49,50]. For instance, Hassan et al.[51] added carbonized waste maize stalk into the eco-composite as reinforcement, leading to the improvement of mechanics properties in microstructure.

4.1 Microstructure of crop stalks

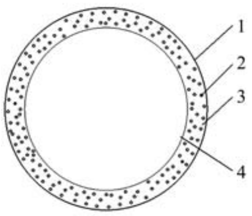
Taking wheat stalk as an example, the microstructure is mainly constituted of epidermis, vascular bundle, parenchyma, and lumen, as shown in Figure 2a. Its polarized optical microscopy (POM) photograph shown in Figure 2b displayed this structure very clearly[52]. If we would like to simplify the structure, the material model shown in Figure 2c will assist in the further application.

The microstructure also varied with the change of stalk location, age[53], and the experimental treatment.

Yu et al.[54] studied the structure change of surface area, morphology, crystallinity and pyrolysis characteristics of rice straw treated by hot acid solution. The BET, SEM, XRD and pyrolysis-GC-MS results showed that the morphology and structure on surface area and pore volume were enhanced, and crystallinity index of cellulose was increased but its crystalline was not changed. This research also explained the reasons leading to the changes, but we think its distinguished contribution was to provide a systematic method to analyze microscopic phenomenon of cellulosic structure. Li et al.[55] also introduced a new method, nano-indentation, to measure the physical and mechanical properties of hemp fiber cell wall. This is an emerging technology for studying objects at super-small scales and extremely thin surfaces. However, this research did not determine the mechanics properties of hemp stalk, lacking the comparison between microcosmical and macroscopical perspectives.



a. Physical image b. POM photograph



c. Simplified model

1. Epidermis 2. Vascular bundle 3. Parenchyma 4. Lumen

Figure 2 Microstructure of wheat stalk

4.2 Composition of crop stalks

Conventional analytical methods for the composition determination of crop stalks include chemical method and high performance liquid chromatograph (HPLC). Most composition can be determined based on the referred instructions by chemical instruments and HPLC. Billa et al.[56] measured and compared the content of cellulose, hemicelluloses, lignin, sucrose, glucose and ash in whole sweet sorghum, as well as in the stalk pith and bark. The results of composition distribution can help us understand the mechanics properties of crop stalks.

The cost, time, labor requirement, sample quantitative limitation, the potential for environmental pollution, and the requirement for sample pretreatment by conventional chemical method make it difficulty in analytical performance for current research. Compared with conventional chemical method, the new technology, near-infrared reflectance spectroscopy (NIRS) presented a series of advantages for the detection in protein, oil, moisture content, insoluble dietary fiber, etc. Jin and Chen[57] used NIRS for the determination of rice straw analytical parameters such as total ash, insoluble ash, moisture, cellulose, hemicellulose and Klason lignin. The results showed that the partial least-squares (PLS) regression calibration model was rapid and accurate, with R^2 values higher than 0.85. Although the NIRS calibration models were supposed to be used for prediction, the accuracy still cannot be compared to chemical method.

From the articles above, some of the research began to focus on the microstructure and composition of crop stalks. However, most of them were still confined to one single aspect[58], lacking the intensive research based on the combination of macroscopical mechanics properties, microstructure, and composition. These aspects below are deserved to promote: 1) Microstructural simulation of crop stalk may be applied in the bionics to synthesize advanced materials with high-performance. 2) The statistic technique could be used to reveal the specific contribution of each composition to mechanics properties.

5 Mechanics simulation experiments

Mechanics simulation experiments are defined as the tests which simulate the actual operating conditions, analyze the mechanics parameters and their effecting parameters, thereby obtaining the preferred working parameters. As a result, the research will achieve efficiency improvement and energy saving for agricultural machinery. To conduct the mechanics simulation experiments, the researchers could do the numerical calculation by computer simulation software, conduct the laboratory tests on UTM or experimental stand, and test in the field conditions with physical prototype. All of the experimental apparatuses and testing procedures are requested to closely simulate the actual operating conditions.

5.1 Computer simulation experiments

Computer simulation experiments have the advantages of high efficiency, low cost, and less disturbance. It is being increasingly applied in engineering science to solve the complicated problems. Li and Guo[59] simulated the mechanical responses to wind and rain loads for an individual and a group of wheat crop by using ANSYS, and draw the results which were similar to those of field experiments. The FEM model also calculated the critical loads under both rain load and wind load when instability and lodging occurred. The research presented the potential application of computer simulation experiments in agricultural engineering.

5.2 Laboratory simulation experiments

To improve the experimental reliability and reduce the test cost, laboratory simulation experiments would be a good choice. The tests could be conducted either on UTM or self-designed experimental stand. Taking cutting simulation experiments as an example, the effecting parameters usually include cutting force, cutting energy, cutting stress, and specific cutting energy. Optimizing cutting parameters would result in energy saving and efficiency improvement for cutting process. Igathinathane et al.[60] designed a modified Warner-Bratzler shear device attached to UTM in laboratory. The cutting experiment results revealed that the parallel orientation produced a significant reduction in cutting stress and specific energy on internodes and nodes compared to the perpendicular and inclined orientations. Because of the high accuracy of UTM, the graph results are more comprehensive in explaining the detailed changes of cutting curves.

However, the experiments on UTM cannot closely simulate the actual operating conditions, especially for the rotary cutting. So the researchers should design the experimental stand by themselves for specific purpose. Johnson et al.[61] developed an experimental setup consisted of an impact type cutting arm freely around a pivot for cutting bioenergy crops. The data acquisition and control system was realized by using LabVIEW. The experimental results demonstrated that the specific cutting energy was directly proportional to the cutting speed and the stem diameter, and increasing the oblique cutting angle would reduce the cutting energy. The test results on self-designed experimental stand in laboratory are much more reliable, and will play an important role in the improvement of agricultural machinery.

5.3 Field simulation experiments

Eventually, the agricultural machinery will work in the field conditions. Before its application, it is inevitable to do the field simulation experiments in the development. Based on the need-to-improve indexes, the researchers can focus on one of the mechanical parts, by simplifying the whole machinery. Maugham et al.[62] developed a single disk-cutter head platform to study the impact of blade oblique angle, cutting speed, and blade mounting on energy consumption. This platform was a simplified component, but was tested in the field conditions. The results suggested authors to set the oblique angle of 40° and operating at 31.5 m/s for the lowest energy consumption. So Maugham et al.[63] modified the existing mower-conditioner prototype based on these results. And the field verification experiments supported the original hypothesis, resulting in energy saving for harvesting *Miscanthus*. The results were also verified by Ghahraei et al.[64] in the cutting tests of kenaf stems.

In most agricultural situations, the mechanics relationship cannot be analyzed in theory. Conducting the mechanics simulation experiments becomes the only practical way to achieve detection, optimization and improvement of agricultural machinery. Except for cutting simulation experiments, we look forward to seeing various researches on other working process, like picking, gripping, bruising, etc. We also suggested the researchers should pay more attention to the environmental factors, time factors, and human factors, which may additionally influence the results of mechanics simulation experiments.

6 Conclusions

Researches on mechanics properties of crop stalks in agricultural engineering have played an increasingly important role in breeding, composites synthesis, machinery design, analysis and improvement, etc. The current subjects mainly concentrated on the mechanics measurement experiments, mechanics model and theory, microstructure and composition, and mechanics simulation experiments. However, it is still a challenge to the researchers because of the fact that crop stalks have complex material characteristics and specific working circumstances. The breakthroughs may be made as we estimated:

1) The new material models of crop stalks were expected to develop, which can reflect the biological nature with complex structure, anisotropy, viscoelasticity and rheology. It is also useful to simplify the material models based on current research. At the same time, the main mechanics features for crop stalks should be retained.

2) The process of mechanics simulation experiments should be more practical and effective, relying more on computer simulation technique. On the other hand, various disturbance factors should not be neglected in the application of prototype optimization.

3) The agricultural engineers may conduct cooperative research with experts from agriculture science, environmental science, food science, etc. The interdisciplinary research will help us reveal more about the mechanics properties of crop stalks essentially from different aspects.

Acknowledgements

The authors acknowledge the financial support of the National High Technology Research and Development Program of China (2012AA10A504), Key R&D Project of China (2016YFD0701201). The authors would also like to acknowledge the assistance and advice from all the people who have contributed to this review.

[References]

[1] Oliveira L, Evtuguin D, Cordeiro N, Silvestre A J D. Structural characterization of stalk lignin from banana plant. Industrial Crops and Products, 2009; 29(1): 86–95.

[2] Ibrahim M, Daud W R W, Law K N. Comparative properties of soda pulps from stalk, bast and core of Malaysian grown kenaf. Bioresources, 2011; 6(4): 5074–5085.

[3] Cheng X Y, Zhong C. Effects of feed to inoculum ratio, co-digestion, and pretreatment on biogas production from anaerobic digestion of cotton stalk. Energy Fuels, 2014; 28(5): 3157–3166.

[4] Balat M, Balat H. Recent trends in global production and utilization of bio-ethanol fuel. Applied Energy, 2009; 86(11): 2273–2282.

[5] Liu Q T, Ou Y G, Qing S Y, Wang W Z. Study progress on mechanics properties of crop stalks. Transactions of the CSAM, 2007; 38(7): 172–176. (in Chinese with English abstract)

[6] Rehkugler G E, Shepardson E S, Pollock J G. Development of a cabbage harvester. Transactions of the ASAE, 1969; 12(2): 153–157.

[7] Kanamitsu M, Yamamoto K. Development of Chinese cabbage harvester. Japan Agricultural Research Quarterly, 1996; 30(1): 35–41.

[8] Kumar G V, Raheman H. Development of a walk-behind type hand tractor powered vegetable transplanter for paper pot seedlings. Biosystems Engineering, 2011; 110(2): 189–197.

[9] Horia M, El-Sahhar E A, Mostafa M M, Abd-Elhady F A. A developed machine to harvest carrot crop. Farm Machinery and Power, 2008; 25(4): 1163–1173.

[10] Li Z G, Lv K, Wang Y Q, Zhao B, Yang Z B. Multi-scale engineering properties of tomato fruits related to harvesting, simulation and textural evaluation. LWT-Food Science and Technology, 2015; 61(2): 444–451.

[11] Tumuluru J S, Tabil L G, Song Y, Iroba K L, Meda V. Grinding energy and physical properties of chopped and hammer-milled barley, wheat, oat, and canola straws. Biomass and Bioenergy, 2014; 60(350): 58–67.

[12] Mou X, Liu Q, Ou Y, Wang M, Song J. Mechanical properties of the leaf sheath of sugarcane. Transactions of the ASABE, 2013; 56(3): 801–812.

[13] Ma S, Karkee M, Scharf P A, Zhang Q. Sugarcane harvester technology: a critical overview. Applied Engineering in Agriculture, 2014; 30(5): 727–739.

[14] Kashiwagi T, Togawa E, Hirotsu N, Ishimaru K. Improvement of lodging resistance with QTLs for stem diameter in rice (*Oryza sativa L.*). Theoretical and Applied Genetics, 2008; 117(5): 749–757.

[15] Ishimaru K, Togawa E, Ookawa T, Kashiwagi T, Madoka Y, Hirotsu N. New target for rice lodging resistance and its

effect in a typhoon. Planta, 2008; 227(3): 601–609.

[16] Esechie H A. Relationship of stalk morphology and chemical composition to lodging resistance in maize (*Zea mays L.*) in a rainforest zone. The Journal of Agricultural Science, 1985; 104(2): 429–433.

[17] Theerarattananoon K, Xu F, Wilson J, Ballard R, Mckinney L, Staggenborg S, et al. Physical properties of pellets made from sorghum stalk, corn stover, wheat straw and big bluestem. Industrial Crops and Products, 2011; 33(2): 325–332.

[18] Zahedi M, Tabarsa T, Ashori A, Madhoushi M, Shakeri A. A comparative study on some properties of wood plastic composites using canola stalk, paulownia, nanoclay. Journal of Applied Polymer Science, 2013; 129(3): 1491–1498.

[19] Qu J P, Tan B, Feng Y H, Hu S X. Mechanical properties of poly (butylene succinate) reinforced with continuously steam-exploded cotton stalk bast. Polymer-Plastics Technology and Engineering, 2011; 50(14): 1405–1411.

[20] Ismail M R, Yassen A, Afify M S. Mechanical properties of rice straw fiber-reinforced polymer composites. Fibers and Polymers, 2011; 12(5): 648–656.

[21] Khademieslam H, Khatibi R, Pour A F. Investigation on physical and mechanical properties of WPC from corn stalk (*Lignocellulosic Fiber*) and HDPE. Macromolecular Symposia, 2012; 320(1): 70–74.

[22] Xu Y F, Zhang X L, Sun X J, Wang J Z, Liu J Z, Li Z G, et al. Tensile mechanical properties of greenhouse cucumber cane. Int J Agric & Biol Eng, 2016; 9(5): 1–8.

[23] Khan M M R, Chen Y, Belsham T, Lague C, Landry H, Peng Q J, et al. Fineness and tensile properties of hemp (Cannabis sativa L.) fibre. Biosystems Engineering, 2011; 108(1): 9–17.

[24] Liu Q, Mathanker S K, Zhang Q, Hansen A C. Biomechanical properties of *Miscanthus* stems. Transactions of the ASABE, 2012; 55(4): 1125–1231.

[25] Liu Q T, Qu Y G, Qing S Y, Chen H B. Failure tests of sugarcane stalks under torsion, compression and tension load. Transaction of the CSAE, 2006; 22(6): 201–204. (in Chinese with English abstract)

[26] Khan M M R, Chen Y, Lague C, Landry H, Peng Q J, Zhong W. Compressive properties of hemp (*Cannabis sativa* L.) stalks. Biosystems Engineering, 2010; 106(3): 315–323.

[27] Guo L, Wang D C, Tabil L, Wang G H. Compression and relaxation properties of selected biomass for briquetting. Biosystems Engineering, 2016; 148: 101–110.

[28] Talebi S, Tabil L, Opoku A, Shaw M. Compression and relaxation properties of timothy hay. Int J Agric & Biol Eng, 2011; 4(3): 69–78.

[29] Yu M, Igathinathane C, Hendrickson J, Sanderson M, Liebig M. Mechanical shear and tensile properties of selected biomass stem. Transactions of the ASABE, 2014; 57(4): 1231–1242.

[30] Tavakoli H, Mohtasebi S S, Jafari A. Comparison of mechanical properties of wheat and barley straw. Agricultural Engineering International: the CIGR Ejournal, 2008; 10: 1–9.

[31] O'Dogherty M J, Huber J A, Dyson J, Marshall C J. A study of the physical and mechanical properties of wheat straw. Journal of Agricultural Engineering Research, 1995; 62(2): 133–142.

[32] Shahbazi F, Galedar M N, Taheri-Garavand A. Physical properties of safflower stalk. International Agrophysics, 2011; 25(1): 281–286.

[33] Shahbazi F, Galedar M N. Bending and sheering properties of safflower stalk. Journal of Agricultural Science and Technology, 2012; 14(4): 743–754.

[34] Ozbek O, Seflek A Y, Carman K. Some mechanical properties of safflower stalk. Applied Engineering in Agriculture, 2009; 25(4): 619–625.

[35] Cao Z, Jin X, Liao Q X. Experimental research on physical and mechanical parameters of matured bottom stalk of the reed for harvester design. Int J Agric & Biol Eng, 2011; 4(2): 1–7.

[36] Liao Q X, Liao Y T, Shu C X, Tian B P. Research on the physical mechanics properties of the rape stalk. 2007 ASABE Annual Meeting, 2007; No. 076136.

[37] Zhao C H, Zhang F W, Cao Z Z. Experiment on stalk mechanical properties on legume forage and grasses. Transaction of the CSAE, 2009; 25(9): 122–126. (in Chinese with English abstract)

[38] Galedar M N, Jafari A, Mohtasebi S S. Effects of moisture content and level in the crop on the engineering properties of alfalfa stems. Biosystems Engineering, 2008; 101(2): 199–208.

[39] Sharma B, Jones C L, Khanchi A. Tensile strength and shear strength of swithcgrass before and after frost. Biological Engineering Transactions, 2011; 4(1): 43–54.

[40] Tavakoli H, Mohtasebi S S, Jafari A. Physical and mechanical properties of wheat straw as influenced by moisture content. International Agrophysics, 2009; 23(2): 175–181.

[41] Esehaghbeygi A, Hoseinzadeh B, Masoumi A A. Effects of moisture content and urea fertilizer on bending and shearing properties of canola stem. Applied Engineering in Agriculture, 2009; 25(6): 947–951.

[42] Vasilev G, Parvanova S, Dineva P, Wuttke F. Soil-structure interaction using BEM-FEM coupling through ANSYS software package. Soil Dynamics and Earthquake Engineering, 2015; 70: 104–117.

[43] Kukielka L, Kulakowska A, Patyk R. Numerical modeling and simulation of the movable contact tool-workpiece and application in technological processes. Journal of Systemics, Cybernetics and Informatics, 2010; 8(3): 36–41.

[44] Hirai Y, Inoue E, Mori K, Hashiguchi K. Investigation of mechanical interaction between a combine harvester reel and crop stalks. Biosystems Engineering, 2002; 83(3): 307–317.

[45] Hirai Y, Inoue E, Mori K. Application of a Quasi-static stalk bending analysis to the dynamic response of rice and wheat stalks by a combine harvester reel. Biosystems Engineering, 2004; 88(3): 284–294.

[46] Guarnieri A, Maglioni C, Molari G. Dynamic analysis of reciprocating single-blade cuter bar. Transactions of the ASABE, 2007; 50(3): 755–764.

[47] Zastempowski M, Bochat A. Modeling of the cutting process by the shear-finger cutting block. Applied Engineering in Agriculture, 2014; 30(3): 347–353.

[48] Rodriguez M, Rodriguez A, Bayer J, Vilaseca F, Girones J, Mutje P. Determination of corn stalk fibers' strength through modeling of the mechanical properties of its composites. BioResources, 2010; 5(4): 2535–2546.

[49] Shanmugam D, Thiruchitrambalam M. Static and dynamic mechanical properties of alkali treated unidirectional continuous palmyra palm leaf stalk fiber/jute fiber reinforced hybrid polyester composites. Materials and Design, 2013; 50(24): 533–542.

[50] Oghenevweta J E, Aigobodian V S, Nyior G B, Asuke F. Mechanical properties and microstructural analysis of Al-Si-Mg/carbonized maize stalk particulate composites. Journal of King Saud University-Engineering Sciences, 2016; 447(2): 222–229.

[51] Hassan S B, Oghenevweta J E, Aigbodion V S. Morphological mechanical properties of carbonized waste maize stalk as reinforcement for eco-composites. Composites Part B: Engineering, 2012; 43(5): 2230–2236.

[52] Liu R G, Yu H, Huang Y. Structure and morphology of cellulose in wheat straw. Cellulose, 2005; 12(1): 25–34.

[53] Genet M, Stokes A, Salin F, Mickovski S B, Fourcaud T, Dumail J F, et al. The influence of cellulose content on tensile strength in tree roots. Plant and Soil, 2005; 278(1-2): 1–9.

[54] Yu C T, Chen W H, Men L C, Hwang W S. Microscopic structure features changes of rice straw treated by boiled acid solution. Industrial Crops and Products, 2009; 29(2-3): 308–315.

[55] Li X, Wang S, Du G, Wu Z K, Meng Y J. Variation in physical and mechanical properties of hemp stalk fibers along height of stem. Industrial Crops and Products, 2012; 42(1): 344–348.

[56] Billa E, Koullas D P, Monties B, Koukios E G. Structure and composition of sweet sorghum stalk components. Industrial Crops and Products, 1997; 6(3): 297–302.

[57] Jin S Y, Chen H Z. Near-infrared analysis of the chemical composition of rice straw. Industrial Crops and Product, 2007; 26(2): 207–201.

[58] Ashori A, Hamzeh Y, Amani F. Lemon balm (*Melissa officinalis*) stalk: chemical composition and fiber morphology. Journal of Polymers and the Environment, 2011; 19(1): 297–300.

[59] Li L, Guo Y. Analysis and Finite Element Simulation for mechanical response of wheat under wind and rain loads. Int J Agric & Biol Eng, 2008; 1(1): 82–88.

[60] Ingathinathane C, Womac A R, Sokhansanj S. Corn stalk orientation effect on mechanical cutting. Biosystems Engineering, 2010; 107(2): 97–106.

[61] Johnson P C, Clementson C L, Mathanker S K, Grift T E, Hanson A C. Cutting energy characteristics of *Miscanthus χ giganteus* stems with varying oblique angle and cutting speed. Biosystems Engineering, 2012; 112(1): 42–48.

[62] Maughan J D, Mathanker S K, Fehrenbacher B M, Hansen A C. Impact of cutting speed and blade configuration on energy requirement for *Miscanthus* harvesting. Applied Engineering in Agriculture, 2014; 30(2): 137–142.

[63] Maughan J D, Mathanker S K, Grift T E, Hansen A C, Ting K C. Impact of blade angle on *Miscanthus* harvesting energy requirement. Transactions of the ASABE, 2014; 57(4): 999–1006.

[64] Ghahraei O, Ahmad D, Khalina A, Suryanto H, Othman J. Cutting tests of kenaf stems. Transactions of the ASABE, 2011; 54(1): 51–56.