Review of application of biomimetics for designing soil-engaging tillage implements in Northeast China

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Abstract: The reduction of water resources and soil fertility in Northeast China will have a requirement on higher working efficiency of agricultural soil-engaging components. The adhesion and resistance are main problems for soil-engaging tillage components. However, the soil-burrowing or soil-digging animals give inspirations to resolve those problems. Their fair, claw, toe, textured surface and scales have functions of anti-adhesion or resistance reduction. Those results provide a way to realize the sustainable development of modern agriculture by developing novel biomimetic agricultural machinery systems with independent intellectual property rights to meet conservation tillage requirements in the Northern China region. Biological structures of some soil-burrowing or soil-digging animals, such as beetle, mole cricket, earthworm, mole, vole, pangolin, and snake, as well as their mechanisms of anti-adhesion or reducing resistance were reviewed in this paper. Bioinspired applications in Northeast China were also presented in the paper, including moldboard, subsoiler components, furrow opener, roller, and biomimetic rototilling-stubble-breaking blade. In addition, the existed problems in agricultural engineering and the future development trends were discussed.

Keywords: review, agricultural engineering, biomimetics, soil-engaging tillage implements, conservation tillage
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1 Introduction

In China, cultivated land resources and agricultural water resources are becoming scarce, with cultivated land area decreasing at a mean annual rate of 0.3%. Moreover, soil fertility is also declining. The organic matter content in the black soil of Northeast China has decreased to about 2% from original 3.5%-5% before modern agriculture popularization, and the decreasing rate is continue to accelerate. This decline in soil fertility has become a bottleneck constraining the sustainable development of agriculture in China[1-4]. Many existing agricultural machines in Northeast China are single-task machines, with high-energy consumption and low efficiency that are not been adapted to the requirements of modern agriculture. Thus, there is a need to develop intelligent biomimetic systems with high efficiency, low energy consumption, good soil moisture storage and preservation capability, and good soil fertility improvement, and to popularize these new technologies through application demonstration. This has become an important topic for ensuring high and stable yields of grain and realizing the sustainable development of modern agriculture[5-8].

High-energy consumption, poor economic efficiency, serious soil moisture loss, and other negative equipment factors severely constrain the popularization of soil moisture storage and preservation tillage systems[9-11]. The results of field experiments in Northeast China showed that seedling emergence rate decreased by

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5%-12% due to soil adhesion and serious soil moisture loss during various operation processes such as furrowing, covering and rolling, which thus greatly reducing grain yield. Therefore, it is important to develop high-efficiency and energy-saving biomimetic tillage implements that meet the requirements of modern agriculture to reduce tillage resistance and soil adhesion. Soil adhesion causes working resistance increase during operation of soil-engaging components, which results in more energy consumption, poor operational quality, significant soil moisture loss, and even mechanical failure. For example, during the operation of a traditional agricultural tillage component such as a furrow opener and tillage blade, the energy consumption for overcoming the slide resistance between the soil and the tillage surface accounts for 30%-50% of total energy consumption due to soil adhesion and friction. It was pointed out that the crop yield per unit area has decreased by an average of 3% per year in Northeast China owing to poorly timed post-sowing rolling or poor rolling quality. In addition, there is a higher equipment cost associated with larger (and thus more effective) soil-engaging implements. A deep-loosening implement has the largest energy consumption per unit disking width among field tillage and seeding machines, which can only operate under being towed by a high-power tractor. The development of such implements is a significant factor in raising efficiency, reducing cost, raising natural water utilization rate, improving grain yield, increasing farmers' income, and overall realizing efficient agriculture[2]. It is therefore of necessity to assess the role-played by tillage tool design in controlling the energy consumption of soil engaging implements[12].

Nichols[13] presented a comprehensive discussion of soil-on-material sliding that included friction and adhesion. The concepts of adhesion were well-developed[14]. Different to cohesion, soil adhesion is the attraction of water molecules to solid surfaces[15]. Many researches focused on investigating the causes of soil adhesion, such as water film[16-18], soil type and soil condition[14], soil normal pressure[17], temperature[19], and interfacial friction[20]. Interfacial tension must also be considered as it leads to water films in interaction with solid walls, which is linked to surface properties and the topology of porosity in addition to capillary meniscus[21]. Therefore, various approaches have been developed to reduce soil adhesion[22], such as surface modified material[23-26], lubrication[27], electro-osmosis method[28,29], and vibration method[30]. While, those technologies are difficult to be applied in mechanical equipment due to poor abrasion resistance, high cost, complex operation, unstable technique or difficult for repair.

However, in nature the phenomena of soil adhesion almost are absent in soil-burrowing or soil-digging animals when they move through soil. With the continued development of biomimetic, researchers have noticed that soil-burrowing or soil-digging animals, such as dung beetle, ground beetle, mole cricket, house mouse, yellow mouse and pangolin have the functions of anti-adhesion or reducing resistance through long-term evolution (Figure 1), from macroscale to mesoscale or microscale[31-42]. Such excellent abilities of soil animals on anti-adhesion or reducing resistance are partly resulted from their non-smooth surface morphologies[43,44]. For example, dung beetles can break up dung pads and compact dung into balls and their cuticle surfaces do not stick dung or soil due to non-smooth or roughness in micro scales in the morphological body surface[34]. In terms of biomimetic non-smooth surface self-cleaning technologies[45], there have been more than 200 patents applied for or authorized all over the world between 1998, when the first patent obtained in Europe, 2004. Researchers have found that the convex-concave shape of of *Megaptera novaeangliae* (humpback whale)'s flippers have a resistance reduction function, the results of wind tunnel experiments show that a convex-concave shape flipper can increase the motive power by 8% and decrease the resistance by 40% compared with a smooth flipper of the same size[46]. Biological structures of some soil-burrowing or soil-digging animals, such as beetle, mole cricket, earthworm, mole, vole, pangolin, and snake were reviewed in this paper. In addition, their mechanisms of anti-adhesion or reducing resistance were present. Bioinspired applications which have been used in Northeast China were also presented in the following of the paper, including moldboard, subsoiler components, furrow opener, roller, and biomimetic rototilling-stubble-breaking blade. Finally, the existed problems in agricultural engineering and the future development trend were discussed.

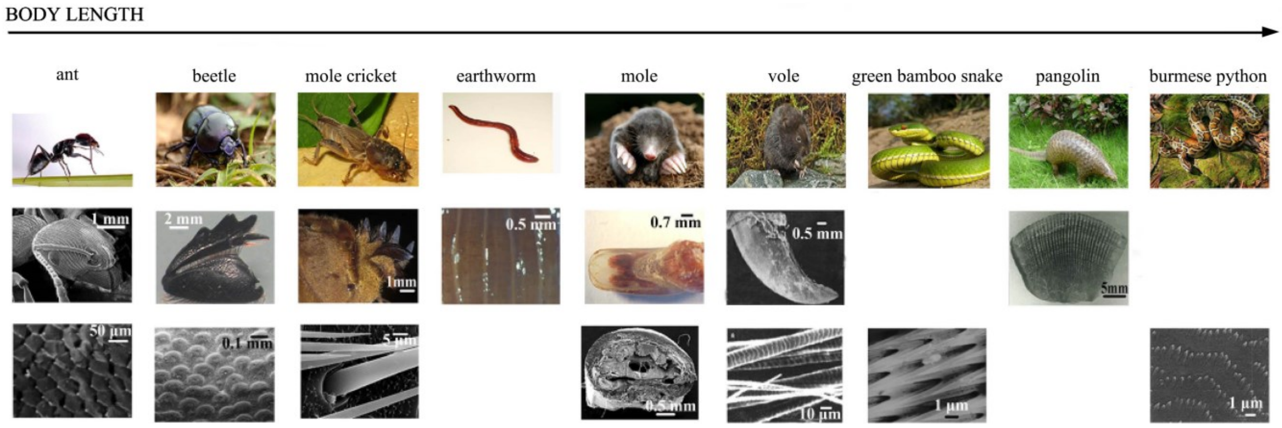


Figure 1 Some soil-burrowing or soil-digging animals that have functions of anti-adhesion or resistance reduction by different body length[31-42]

2 Biological structures of soil-burrowing or soil-digging animals and their mechanisms of anti-adhesion or reducing resistance

Biomimetic studies reveal that creatures achieve excellent functional capabilities by adapting to their living environment through long-term evolution[33,39]. Some animals continually living in a soil environment have evolved various activity modes to adapt to different soil environmental conditions. Meanwhile, these animals have gradually evolved appendages with optimized geometric structures and excellent mechanical properties to reduce cutting resistance during digging. These provide the basis for biomimetic studies on optimization of the geometric structure and mechanical properties of soil cutting tools[31,33,34,47]. In the following, the biological structures of soil-burrowing and soil-digging animals, which have functions of anti-adhesion or resistance reduction, including macro-scale to meso- or micro-scale structures, were described.

The shape of the clypei of *Copris ochus* Motschulsky decreases resistance during earth cutting and burrowing (Tong and Wu, 2006)[48]. In addition, *Copris ochus* Motschulsky can automatically reduce resistance by adjusting the wedge angle through rotation of its head to execute efficiently different functions such as bulldozing and earth cutting. By applying a biomimetic curved surface as the stress-bearing surface, adjusting the angle of the components, and switching between various soil-engaging components based on slide cutting principles, the soil-engaging components can be functionally optimized and structurally innovated to minimize resistance[48].

The resistance reduction characteristics of the surface morphology and surface wettability of the earthworm were studied based on the biological coupling theory[49]. The lubrication mechanism of the earthworm surface was analyzed according to the parameters of surface dorsal pore and corrugation. The bionic coupling samples were prepared and obtained that the main factors affecting the soil sliding resistance were the positive pressure, the flow velocity and advancing velocity. The soil sliding resistance of the coupling and bionic sample with 5 holes distributing in the front part decreased by 20.1% compared to that of the sample with no pores or corrugation. The results showed that the lubrication could reduce the resistance between the sample and soil when the corrugation and the dorsal pores lay closely on the surface of the bionic coupling sample[49].

The forefeet of *Gryllotalpa* (mole cricket) have excavating feet with ultra-strong cave excavating capabilities. For example, the forefeet of *Gryllotalpa orientalis* Burmeister have a toothed structure, with toe tips bending towards the outside of body, so that the toes of the forefeet can exert force towards the outside of its body during soil excavation. This geometry is different from the excavating feet of most soil animals, which bend inwards and exert force towards the inside or underside of the body[50]. A comparison of the driving forces of the two geometries shows that the morphological structure and the force-exerting mode of the forefeet of *Gryllotalpa orientalis* Burmeister may require a larger driving force. However, the fact that the morphological structure of the forefeet of *Gryllotalpa orientalis* Burmeister has not significantly evolved for some time indicates that such a structure has a very high efficiency and is worth further study[51].

The mole is soil-burrowing animal that can excavate a 91 m underground passage in one night. The mole exhibits an extremely high earth-excavating efficiency, despite its' body length of only 100-180 mm. By analyzing the geometric structure of the soil-engaging surface of the toes of its forefeet, particularly the curvature and second derivative of the fitted contour curve of the toe surfaces, then a change law for the characteristic contour lines was developed. The first aspect of this model is that the minimal change in the longitudinal contour curvature of the toe means that the longitudinal surface of the toe will be smooth to ensure that the inner wall of the excavated passage is flat (Figure 2)[40]. Secondly, a structure with convex longitudinal and transverse contour curves, where the transverse contour line bends more at the middle and the end than the tip, makes the tip of the toe easier to enter the soil and allows the middle and end of the toe to enlarge the passage once dug in. The geometric structural features of the toe, and the characteristic contour curve changing law of the excavating organ of a mole, can provide a technical reference for the design of high-efficiency and energy-saving biomimetic soil cutting and excavating tools[52,53].

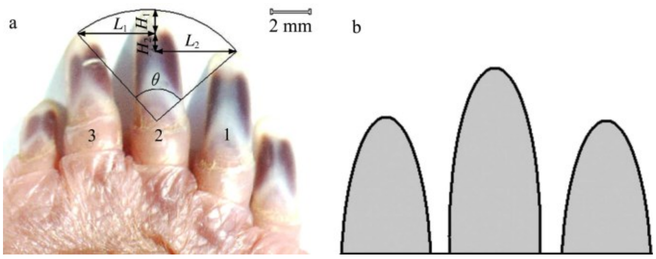
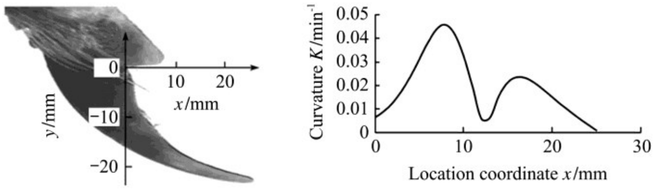


Figure 2 (a) Arrangement of middle three toes of the fore claw of mole rat (*Scaptochirus moschatus*); (b) Geometrical structures of biomimetic specimen[40]

Spermophilus dauricus (a type of vole) exhibits real-time flexibility and adjustability of its toes and the structures that exist between its toes during digging. In other words, it has excellent biomechanical self-feedback capability, which is extremely favorable for anti-adhesion or reducing resistance during digging. For this kind of vole, the model describing the curvature trend line of the inside and outside contour lines of one of its toes can be roughly divided into three types (Figure 3)[54,55].



a. Photograph of the middle toe of vole's fore right claw (×10)

b. Curvature profile of the inside contour line of the same clawed toe

Figure 3 Clawed toe geometric features of a vole[54,55]

Pangolin scales are extremely resistant, which play an important protective role, and act as an effective digging tool as well. The surface of the pangolin's scale shows the non-equal-lattice geometric network morphology with the transverse grooves and longitudinal ridges crossed each other, and which is conducive to anti-adhesion[37]. Meanwhile, the corrugations on the pangolin scales can reduce wear under free abrasive wear conditions[56].

The ventral scale of *Trimeresurus stejnegeriis* was found that formed with a periodical arrangement of micro fibrils, micro pits and pits by atomic force microscopy (AFM)[41]. The micro fibrils are helpful to reduce the contact area, thus reducing the adhesion; the excreted and stored polar lipids by micro pits, and hydrophobicity of the ventral scales can reduce the adhesion of water. The similar microstructures were found in ventral scale surface of Burmese python, which has periodical arranged micro-convex, and plank structure[42]. The frictional force of the ventral scale surface mainly caused by intermolecular force, mechanical tooth function of micro-convex, and material's elastic hysteresis.

3 Biomimetic design of key tillage implements

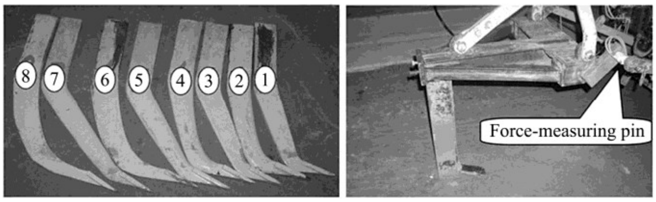
The black soil area of Northeast China is facing a series of serious problems, such as soil erosion and soil fertility degradation. Implementation of conservation tillage in the Northeast black soil area is necessary to the stable development of agriculture and to the long-term effective supply of agriculture products. The soil tillage has important implications for conservation tillage effects, such as the functions of anti-adhesion or reducing resistance. In the following, the biomimetic designing of components used in Northeast China were described, such as moldboard, subsoiler, roller, furrow opener, and the rototilling-stubble-breaking blade.

3.1 Biomimetic moldboard

A pimpled surface for the moldboard of plow, as first cast in Yangcheng, China in the 1960s, significantly reduced soil adhesion during animal power tillage. However, the design did not provide the same anti-adhesion qualities for a tractor-towed moldboard plowing at high working speeds and with significant impact force. In fact, many different moldboard designs have been studied, such as plastic covered moldboards, through-hole moldboards, grated moldboards, hydrophobic silicone oil treated moldboards, magnetic moldboards, and vibrating moldboards. However, none of those designs has moved beyond research in laboratory or limited trials. In the 1940s and 1950s, mole ploughs were developed abroad and used to excavate drainage ditches underground[57]. This kind of plough imitates underground caving of a mouse. Such a caving mode can reduce the resistance and earthwork quantity, compared to open ditch excavation. In the 1980s, a type of vibrating mole plough was studied in China to further reducing the resistance in drainage ditch excavations. Ren et al.[44] successfully developed a novel biomimetic non-smooth adhesion-reduction and resistance-reduction moldboard, which possessed a simple structure, abrasion resistance, corrosion resistance, low cost, low energy consumption, and high efficiency. The designed moldboard worked reliably with good soil turn up and significant soil removal. It reduced a tractor's tillage resistance by 8%-12%, thus cut down the tractor's fuel consumption by 5%-12% as compared with traditional smooth moldboards[58].

3.2 Biomimetic subsoiler components

A way to reduce the working resistance of tillage components is to use a vibrating deep-loosening component. However, vibrating systems increase the complexity of the structure of the implement, which then increases manufacturing costs[30]. The handle of a traditional subsoiler implement generally has a transition section that uses a straight line, broken line, or arc shape to connect the tip of the subsoiler with the frame, so the soil tillage resistance of the implement remains high. Recently, this problem of large traction resistance during tillage by a subsoiler implement is primarily solved by using a high-powered tractor. As an alternative to this brute power approach, Tong et al.[54] and Guo et al.[55] designed a biomimetic bend-type subsoiler component based on analysis of the contour shape of the toes of a field mouse (Figure 4), and determined its tillage resistance through a large-scale indoor soil bin test. The experiment showed that the designed biomimetic deep-loosening component had an obvious resistance-reduction effect of 6%-10%.



a. Components 1-8 b. Force measurement device

Figure 4 Experimental cultivator parts[54,55]

3.3 Biomimetic flexible compression roller

The biomimetic flexible roller shown in Figure 5a was designed based on the study of the typical movements of soil animals including *Pheretima* and *Spirobolus bungii*[59]. The design of the modified roller exhibited a number of improved features over regular rollers: virtual elimination of soil adhesion, improvement of operational quality and efficiency, low energy consumption, clear and neat appearance and uniform compactness of the rolled soil (Figure 5b). In addition, it was beneficial in maintaining soil humidity and temperature and thus increasing the germination rate and seedling emergence rate after sowing. In the early stages of land reclamation in Northeast China in the 20th century, the soil was extremely adhesive when it was wet. In fact, people could only walk in the fields by wearing shoes lined with *Carex meyeriana*, from which the soil is easy to remove due to the deformation of *Carex meyeriana* during walking. This same concept inspired the design of the modified roller, where wrapping the roller with rubber generates a large deformation that improves soil removal.

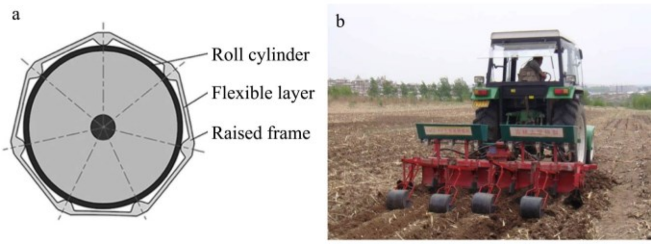


Figure 5 (a) Biomimetic flexible compression roller[59];
(b) The flexible compression roller have been using in the field

Based on that design, the elastic press wheel (Figure 6[60]) with the function of covering soil was made to improve the performance of seeding and pressing under conservation tillage. Based on groove type of furrow, the elastic press wheel model with a double-cavity structure was established. Owning special lateral edge, it can operate soil covering and soil compaction at the same time. The results of the field experiment showed that the seed depth was 3.4 cm, the coefficient of variation of the seed depth was 15.63%, the soil hardness was 0.325 kg/cm^2 (5 cm from ground surface), the coefficient of variation of the soil hardness was 19.62%, and all those indexes met the requirements of National standards. Through simulation and experimental analyses, an elastic press wheel that can attain good covering and compaction performance in sowing conditions have been designed.

Figure 6 Press wheel and sketch of the cavity's section[60]

Another improved profiling elastic press roller was designed (Figure 7)[61], which is suitable to the deep scarification combined land preparation machine under conservation tillage, based on the problem of insufficient pressure and uneven compactness in the process of work. The profiling elastic press roller adopts elastic spokes structure, elasticity is essentially a spring damper, which has the advantages of large enough pressure, even compactness and transverse profiling capability. Simulation of the roller' work process was done by the ADAMS software, which determined the influences of different stiffness coefficient and damping coefficient to the pressure, and the best stiffness coefficient and damping coefficient of the flexible spoke were obtained through theory calculation and simulation analysis[61]. Simulation results showed that under the premise of enough pressure and ensuring job stability, the optimum stiffness coefficient of flexible spokes was 5 N/mm, the soil compactness could reach 15 kPa. Meanwhile, it provides a reference for the calculation and design of spring dampers on press roller.

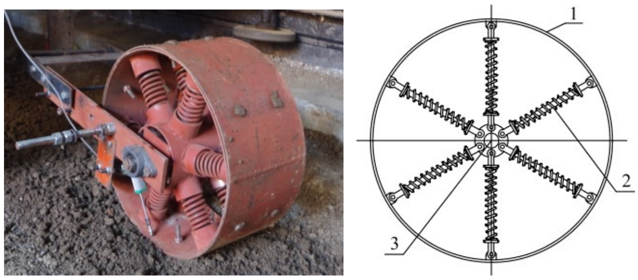


Figure 7 Profiling elastic press roller and its structural diagram[61]

3.4 Biomimetic furrow opener

The biomimetic furrow opener solves the problems that widely existed in furrowing components, such as soil adhesion, grass winding, and increased resistance. Geometrical structures (domes, cylindrical section ridges, and tubular section ridges) on the cuticle surface of the dung beetle *Copris ochus* Motschulsky, were imitated and applied to the furrow opener surface (Figure 8)[62]. A corrugated biomimetic structural morphology was formed using a series of ultrahigh molecular weight polyethylene (UHMWPE) structures attached to the surface of a general double share furrow opener. The goal of the altered geometric structure was to reduce soil adhesion and working resistance of the furrow blade.

Sometimes, furrow opener that cut the soil for fertilization and seeding can cause the blockage of the seeder and make it work abnormally. Therefore, the design of a fertilizer opener with good stubble cutting capacity is the focus of the development of no-tillage planter[63]. Learning from the toe curve of mole, the gear-tooth stubble cutting mechanism of no-tillage seeder was designed, as shown in Figure 9a. Figure 9b shows that the sliding-knife notched disc opener worked through the straw mulching area. Through the performance test of the improved no-till narrow-row planter, the pass rate of the seed spacing was 91% (≥75%), and the leak seeding rate was 1.79% (≤10%). The displacement instability coefficient and the inconsistency coefficient of each line was 11.9% and 0.82%, respectively.

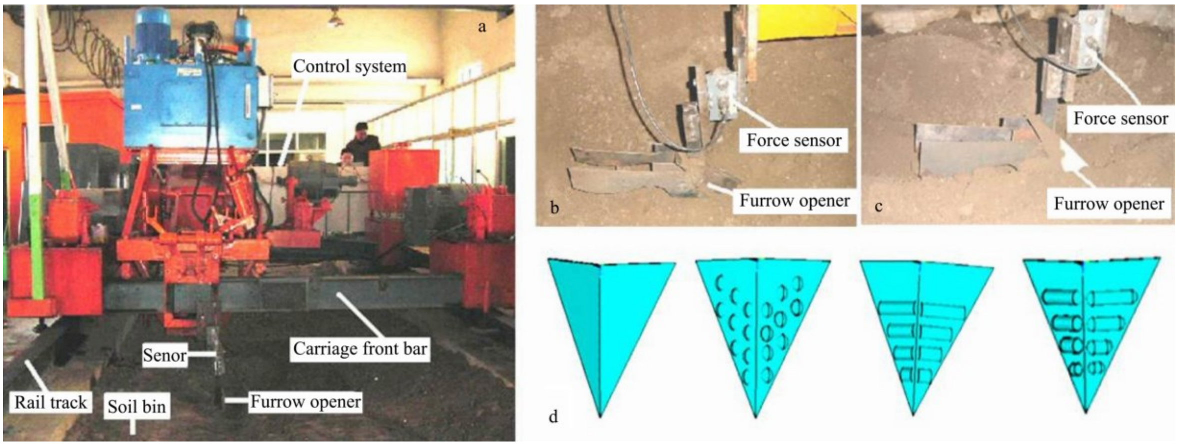
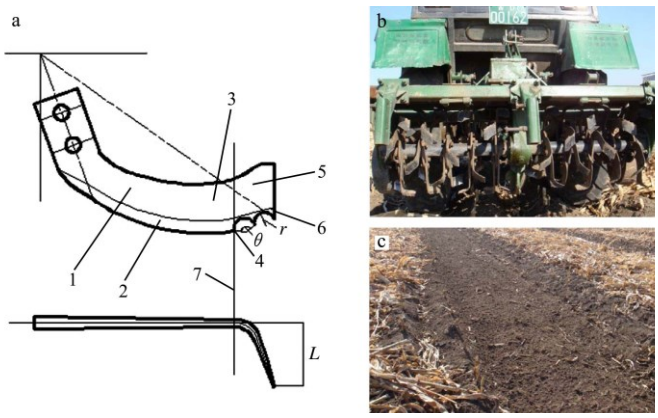


Figure 8 (a) Electric carriage used for soil resistance tests; (b) Conventional furrow opener and (c) Biomimetic furrow opener with force sensor; (d) Furrow opener surfaces, from left to right: conventional smooth, biomimetic convex domes, biomimetic cylindrical section ridges, and biomimetic surface structure with tubular section ridges[62]

Figure 9 (a) Schematic diagram of sliding-knife notched disc opener[62] and (b) Passing through straw mulching area

3.5 Biomimetic rototilling-stubble- breaking blade

When a mole cuts and excavates soil, its front paws move in a rotating manner on the sides of its body, with the front ends of its excavating limbs moving elliptically[40]. The motion is similar to the rotating implements used in rotary tillage and stubble breaking operations. Ji et al.[40] designed the front cutting surface of a universal rotary tillage and stubble-breaking blade based on the geometric structure of the toes of mole. The redesign optimized the biomimetic structure of the blade by evenly distributing three inwards arcs with central angles of 60° along the front cutting surface to form a notch (Figure 10a). Figure 10b shows that the tillage machine was assembled with those biomimetic rototilling-stubble-breaking blade[64]. A comparison of power consumption results for a single blade of a universal rototilling-stubble-breaking blade versus a single blade of the biomimetic rototilling-stubble-breaking blade showed that the torque of the biomimetic blade was 3.91% lower than that of the universal blade in rotary tillage, and 1.62% lower than that of the universal blade in stubble-breaking. The results of field experiments indicated that the quality of both the rototilling-stubble-breaking operations with the biomimetic and the universal rototilling-stubble-breaking blade met the National Standards of China for rotary tillage blades (Figure 10c)[64]. Furthermore, the notch created by the biomimetic structure offers an average dimension loss less than that of the national standard specified for rotary tillage blades[52,53].



1. Side surface 2. Side-edge 3. Transition surface 4. Transition edge 5. Scoop surface 6. Sidelong edge 7. Meander-line

Note: L is the working width; θ is the sliding cutting angle; r is the sliding cutting radius.

Figure 10 (a) Diagram of biomimetic rotary stubble blade[53]; (b) Tillage machine was assembled with biomimetic rototilling-stubble-breaking blade; (c) Soil surface condition after the operation of stubble[64]

4 Conclusions and prospects

Biomimetic agricultural machinery can be directly used in production to generate economic and social benefits, help farmers, and advance agricultural modernization. Recent innovations in biomimetic implements show as following:

1) New biomimetic soil-engaging implements can reduce the amount of moved soil and disturbance to the soil, reduce tillage resistance, and offer good anti-adhesion capabilities to achieve higher efficiency, lower energy consumption, and better preserve soil moisture.

2) Biomimetic technology has been combined with information technology, intelligent control, engineering technology, and modern agriculture techniques of minimum- or non- tillage systems to form integrated technologies with high-efficiency mechanization in modern agriculture. These systems provide better soil moisture storage and preservation, and better soil fertilization, to improve production and yields. This higher efficiency means biomimetic implements have significant market potential.

3) These core capabilities of multi-functional biomimetic implements can help innovate existing agricultural equipment manufacturing and increase the comprehensive production capability of agriculture in Northeast China. These improvements will ensure efficient and environmentally friendly utilization of agricultural resources, promote agriculture restructuring, increase farmer income, and provide advanced equipment to support modern agriculture techniques.

Reducing the mass of agricultural equipment cannot only improve the performance of agricultural machinery, but also can reduce fuel consumption. The overall weight of agricultural equipment reduced by 10%, fuel efficiency can increase by 6%-8%, and per hundred kilometers fuel consumption can reduce from 0.3-0.6 L with reducing the equipment weight 100 kg. Along with a large number of applications of lightweight and high-strength materials, and combination of high-quality materials and optimized design will lighten the combine equipment by 30%-40% or even more.

Future research of lightweight design of agricultural engineering will focus on how to mix a diversification of manufacturing processes, how to configure the associated policy orientation, which would be the only way to ensure consistent between the high complexity product and its prototype design concepts. There are four main ways for agricultural equipment lightweight. First, develop new manufacturing process for agricultural engineering components, under the premise of retaining the main parameters of size specifications to enhance local reinforcement, and reduce the amount of materials. Second, use lightweight materials, such as plastic, Nano aluminum, magnesium, ceramic, glass fiber or carbon fiber composite materials. Third, use computer design, such as topology optimization method, to enhance the structural strength of the whole machine. The current main way is the use of lightweight materials, but which does still not fully achieve the purpose of saving materials. It will be more meaningful through structural optimization to guarantee the dynamic performance to achieve lightweight.

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