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Review

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The physical cutting process of weeds

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Abstract

This article aims to further our understanding of the mechanics of physical weed control, specifically the mechanism of using a cutting blade to cut weeds. Research on weed stem cutting is sparse, so this paper draws on examples of plant stem cutting. It reviews the factors that affect the plant stem cutting process. Among the, Cutting speed, blade sharpness, and moisture content, factors that can easily be controlled, are discussed. The indicators for evaluating the cutting process and the methods for measuring the influencing factors are introduced as well. Finally, different blade designs, examples of the application of mechanisms that affect the cutting process of plant stems are provided. This review argues that, under conditions of high cutting speed, high blade sharpness, and high moisture content, plastic deformation would be reduced and the stems would exhibit brittle material characteristics. This would help to reduce the cutting force and energy, but excessive brittleness can cause stem fragmentation and degrade cutting quality. This paper also lists some possible future research directions. First, friction behavior during the cutting process of fresh plant stems. Another, cutting blade design based on the comprehensive application of cutting speed, blade wedge angle, and sliding cutting angle on the cutting process. At present, the mechanism of plant stem cutting process is still not clear. Further research is needed.

Introduction

The competition between weeds and crops has been present since the beginning of agriculture, and weeds continue to challenge crop production despite continuous management efforts (Hussain et al. 2018). Weeds can be considered as a type of serious pest of crop plants (Jabran and Chauhan 2018). Both weeds and crops require appropriate light, water, nutrients, and space for their growth and reproduction, which means they will inevitably compete with each other and cannot coexist stably with crops (Little et al. 2021; X Yang et al. 2021). Weeds also secrete substances that inhibit crop growth in order to compete for these resources. Weeds are also hosts for pathogens, which may lead to crop diseases (S Chen et al. 2024). The growth of weeds can be foreseen to have an impact on crop yield and even quality (Q Yang et al. 2021; Zhang et al. 2020). Weeds can cause a 23% to 64% loss in crop yields (Guo et al. 2020a; Larue et al. 2019). Due to the low biodiversity of farmland and the lack of complex food webs, stability and lower resistance to invasion, making it difficult to prevent the invasion of weeds (Adomako et al. 2019). Therefore, weed control is an indispensable element of agricultural production.

The commonly used weed control methods currently include chemical, mechanical, and biological weed control (Memon et al. 2025). Biological weed control is neither direct nor stable, and is used less frequently. Spraying herbicides is the most widely used method of weed control, but excessive use of herbicides has also led to a series of problems (A Wang et al. 2022). Herbicide spraying for weed control can pose health hazards to the workers. Excessive application can also lead to environmental and food residues, which in turn create environmental hazards and pose human health threats, including weed resistance, cancer, and endocrine disruption (Mei et al. 2016; A Wang et al. 2022; JW Zhou et al. 2018). Various methods have been proposed to reduce the harm caused by herbicides. Weed identification technology and variable-rate agrochemical spraying systems are incorporated into weed control machinery to reduce herbicide usage (Deng et al. 2025; Liu et al. 2021; Pei et al. 2022; Tao and Wei 2024; Y Wang et al. 2021); herbicide-resistant crops are bred and cultivated to reduce herbicide damage to crops (Guo et al. 2020a, 2022; F Wang et al. 2021); ultrasonic cleaning is used to remove herbicide residues from food (Alenyorege et al. 2018); and bacterial strains of rhizobia are used to degrade herbicide residues in soil (Chen et al. 2023). This significantly increases the overall cost of weeding and makes reducing herbicide harm more complex and difficult. Even so, there is no comprehensive system to address herbicide hazards. In summary, mechanical weed control is a sustainable and environmentally friendly weed management method (Zheng et al. 2025).

Mechanical weed control is an effective weed management method for row crops and organic agriculture (Hussain et al. 2018). However, the challenge faced by mechanical weeding is to improve the effectiveness of weeding without harming crops (Zheng et al. 2025). Mechanical weed control techniques include, interrow and intrarow weeding (Memon et al. 2025). In intrarow weeding, tools are repeatedly applied to the spaces between plants within a row, while avoiding collisions with crops. To reduce blind spots during weeding while avoiding collisions between weeding components and crops, different weeding methods have been integrated into weeding machinery. Some of them use movable touch rods, while others use laser radar to detect the position of crops for obstacle avoidance. However, there is no need to consider obstacle avoidance when interrow weeding.

Weeds differ in shape and size. This paper will use the experience of cutting plant stems as a reference for cutting weeds. The stems of most plant conform to the characteristics of composite materials, in contrast to metal materials, which has been extensively studied in cutting process (Du et al. 2020; Shen et al. 2015; Zhao et al. 2022; Zhou et al. 2016). Most plants have a fibrous structure, which means that they can bear large tensile stress along the direction of the fibers (Fortea-Verdejo et al. 2017). However, the binding force between the fibers of plants is very weak, so many plants are anisotropic materials, which are different from metal materials (Zhang et al. 2022). Therefore, even with the simplest blade, cutting is still an extremely complex process (Szymanek 2007).

W Wang et al. (2022a) make the point that the stress–strain process of cutting plant stems can be divided into three stages: elastic deformation, plastic deformation, and shear failure. First, the cutter squeezes the stem, causing it to sag and produce bending elastic deformation. Then, with continued compression, plastic deformation is produced and the fiber tensile stress keeps increasing, and the fibers near the blade break and fail. Finally, the whole fiber layer slips and fractures, resulting in the shear failure of the whole stem. Igathinathane et al. (2010) divided the force-displacement curve recorded during a stem-cutting test into five different regions that can be seen in Figure 1. In the first part, the blade edge compresses the stem and deforms it, accumulating strain energy in the stem. In the second part, the blade penetrates the compressed fibers of the outer skin and begins cutting. In the third part, the blade starts passing through the axis of the stem and cut pith fibers, which further reduces cutting resistance. In the fourth part, the cutting of the bottom stem and skin begins, as the stem and skin are harder than pith fibers, resulting in a second peak in the force-displacement curve. In the fifth part, only the residual resistance provided by clamping and friction remains.

Factors That Affect the Cutting Process

The factors that affect the cutting process can be divided into the characteristics of the stem of cutting object and those of the cutting tool. The stem characteristics include moisture content, Poisson's ratio, elastic modulus, degree of maturity, density, and diameter (Qian et al. 2024; Rabbani et al. 2015; Zhao et al. 2022). The cutting tool characteristics include cutting speed, sliding cutting angle, and wedge angle. In the cutting process, the mechanical properties of different kinds of stems vary. Even the same kind of stem has different mechanical properties due to factors such as crop maturity, moisture content, planting location, and so on (He et al. 2020). Therefore, some factors that are easy to control and have a significant impact are listed in the following sections.

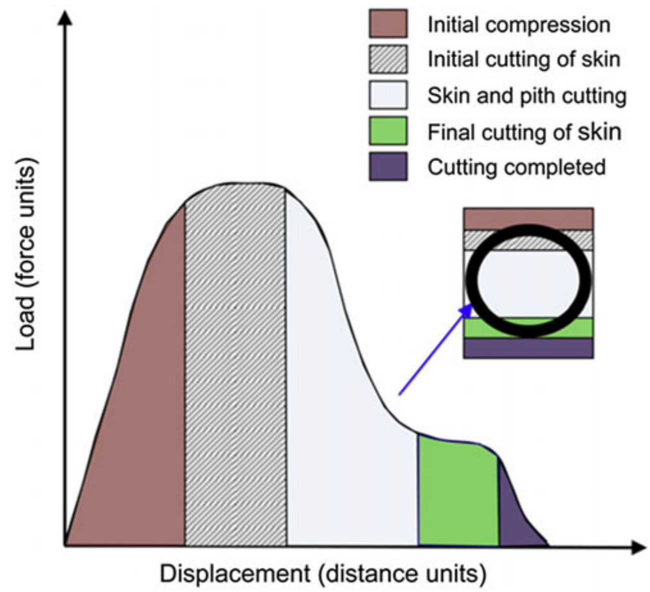

Figure 1. The force-displacement curve explaining the nature of cutting process (Igathinathane et al. 2010).

Cutting Speed

Cutting speed is the core factor that affects the cutting process and is the easiest to control in cutting operations. With the increase of strain rate from 10^{-8} s^{-1} to greater than 10^{7} s^{-1}, the material response can be divided into three sections: static response, quasi-static response, and dynamic response (B Wang et al. 2021). These responses of a material under different loading conditions represent different mechanical properties (Wang et al. 2015). Achieving a strictly static cutting response is generally impractical. Cutting at a speed to obtain a quasi-static response can be termed "quasi-static cutting" (Kamandar et al. 2018). With the speed to obtain dynamic response, the cutting experiment is used to measure the values and predict the deformation as well as failure process of materials during actual operation (Wang et al. 2015), which can be termed "impact cutting."

Quasi-static Cutting

Increasing the strain rate can enhance the strength of a material (Melkote et al. 2017; Sirigiri et al. 2022). To reduce the influence of cutting speed on the physical properties and obtain the physical properties of the stem at static state, the quasi-static cutting should be selected. As shown in Figure 2, during quasi-static cutting, ultimate cutting stress and specific cutting energy decrease as the cutting speed increases (Rabbani et al. 2015; Song et al. 2022a; Y Wang et al. 2020; Wu et al. 2009). It is considered that with an increase in cutting speed, the compression process of the stem would be reduced, and the point where the stem would be compressed would gradually exhibit elastic or brittle behavior (Dowgiallo 2005; Song et al. 2022a). The reduction of the compression process and brittle behavior would contribute to reduced cutting resistance and energy consumption.

Impact Cutting

Brittleness is the property of a material breaking without plastic deformation when subjected to a force. The strength of materials increases with an increase of strain rate, including yield strength and ultimate tensile strength, while the toughness of a material

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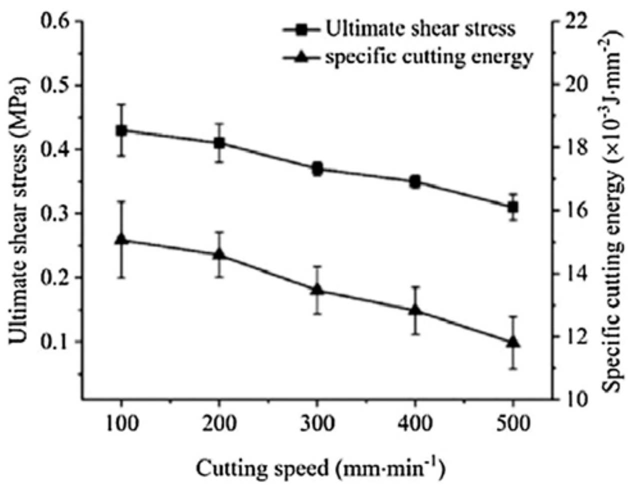

Figure 2. The effect of cutting speed on ultimate cutting stress and Specific cutting energy in a cutting test using sisal (*Agave sisalana* Perrine) leaves (Song et al. 2022a).

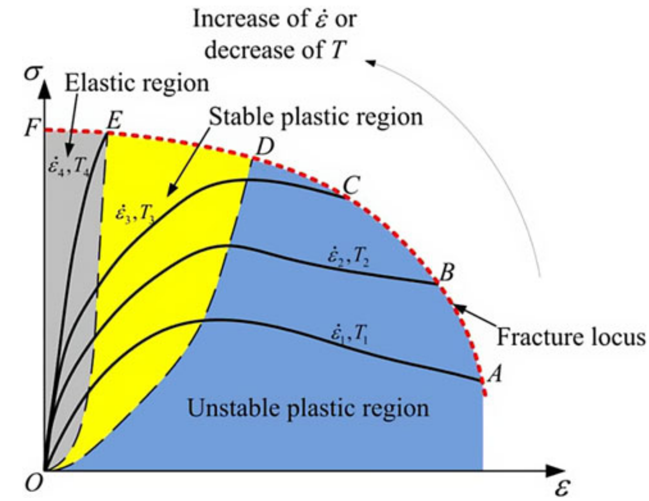

Figure 3. Mechanical response of materials under different loading conditions (Wang et al. 2015).

decreases as the strain rate increases (Yang and Zhang 2019). When yield strength is greater than ultimate tensile strength in the cutting process, brittle fracture instead of plastic deformation would occur, leading to material embrittlement (Zhou et al. 2003). Even if brittle materials have high material strength, they will absorb less energy during a brittle fracture compared to fracture without material embrittlement. Mechanical response of materials under different loading conditions is shown in Figure 3. Ignoring temperature parameters, the strain rate is ranked in descending order as $\dot{\varepsilon}_4$, $\dot{\varepsilon}_3$, $\dot{\varepsilon}_2$, $\dot{\varepsilon}_1$. The dashed EDCBA represents the critical condition for material failure, which can be referred to as the fracture trajectory. The solid lines OA, OB, OC, OE represent the stress–strain curves at different strain rates, and the material fractures at points A, B, C, and E. According to the different characteristics of the material, the entire region is divided into elastic zone, stable plastic zone, and unstable plastic zone. The dashed lines OE and OD represent the critical conditions for material transformation. When strain rate increases, the stress–strain curve would transition from OA to OE, which means that the cutting resistance and material deformation would decrease (Wang et al. 2015).

Embrittlement or brittle behavior not only occurs in metal; plants can also exhibit brittle-like behavior during cutting processes. Xu et al. (2016) found that the head and root of cucumber (*Cucumis sativus* L.) cane with high water content presents the characteristics of a brittle material, while the middle of cane with low water content presents the characteristics of plastic material. Song et al. (2022b) make the point that during the cutting process, with the increase of cutting speed, the deformation of a plant changes from plastic to brittle. This change would reduce the resistance of crop materials to the blade and the cutting energy consumption.

Stress and strain states propagate in the form of waves, which are stress waves. During the loading process, the propagation and reflection of stress waves can lead to material embrittlement (Yang and Zhang 2019). According to the propagation state of stress waves in materials, stress waves have different propagation modes, such as elastic waves, plastic waves, and viscoelastic waves. The propagation velocities of elastic waves and plastic waves are shown in Equations 1 and 2, respectively (Yang and Zhang 2019). Zhou et al. (2003) indicated that when the cutting speed is greater than the static plastic wave propagation speed v_p, the plastic flow of the material decreases, and the material would be embrittled.

$$v_e = \left(\frac{E}{\rho_0}\right)^{\frac{1}{2}} \quad [1]$$

$$v_p = \left(\frac{1}{\rho_0} \cdot \frac{d\sigma}{d\varepsilon}\right)^{\frac{1}{2}} \quad [2]$$

Here, v_e is the propagation speed of elastic wave (m s^{-1}), v_p is the propagation speed of static plastic wave (m s^{-1}), E is the Young's modulus of the material (Pa), $d\sigma/d\varepsilon$ is the slope of the tangent line corresponding to stress point σ_p on the stress–strain curve, and ρ_0 is the density of materials (kg m^{-3}).

The propagation and reflection process of the compressive wave with a wavelength λ is shown in Figure 4. In Figure 4A, the compressive wave approaches the free surface of the sample; in Figure 4B, the incident compressive wave and the reflected tensile wave from the surface overlap and form a composite wave, while tensile stress appears in the overlapping area (blue part); and in Figure 4C, the composite wave is tensile, representing the critical state. Before the critical state, the stress on the sample is partially compressive; and after the critical state, the stress on the sample is completely tensile. In Figure 4D, the overlapping area and tensile stress gradually decrease; in Figure 4E, the incident compression wave fades, and the reflection process of the stress wave ends (Wang 2011; Yang and Zhang 2019). The generation of composite waves contributes to embrittlement and fragmentation, so excessively high cutting speeds may reduce cutting quality (Wang et al. 2015).

Liu et al. (2015) conducted an impact tests on titanium alloy, which is ductile material. Figure 5 shows the section of the sample and the stress field during the impact process. No plastic deformation was found in regions 1 and 3 of the section, indicating that the ductile material underwent embrittlement during the impact process. Simulation shows that there are significant tensile stresses in regions 1 and 3, indicating that material embrittlement is closely related to stress waves.

Constitutive Models

A constitutive model is a mathematical model that reflects the macroscopic physical properties. It describes the interrelationships between specific continuous medium kinematic quantities,

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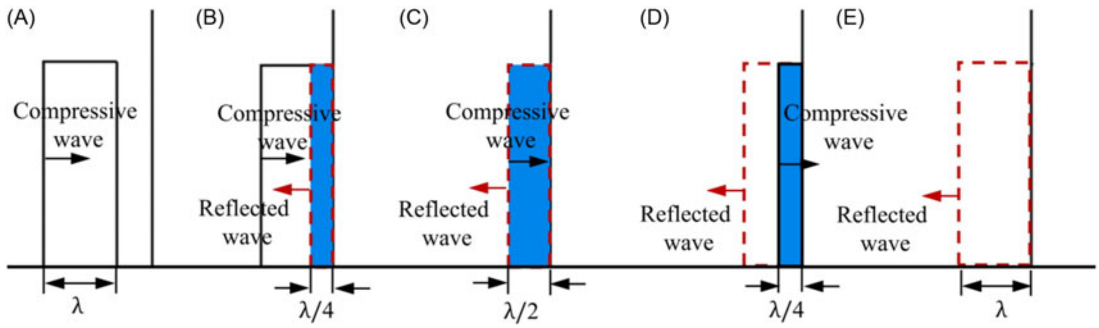

Figure 4. Mechanical response of materials under different loading conditions (Yang and Zhang 2019).

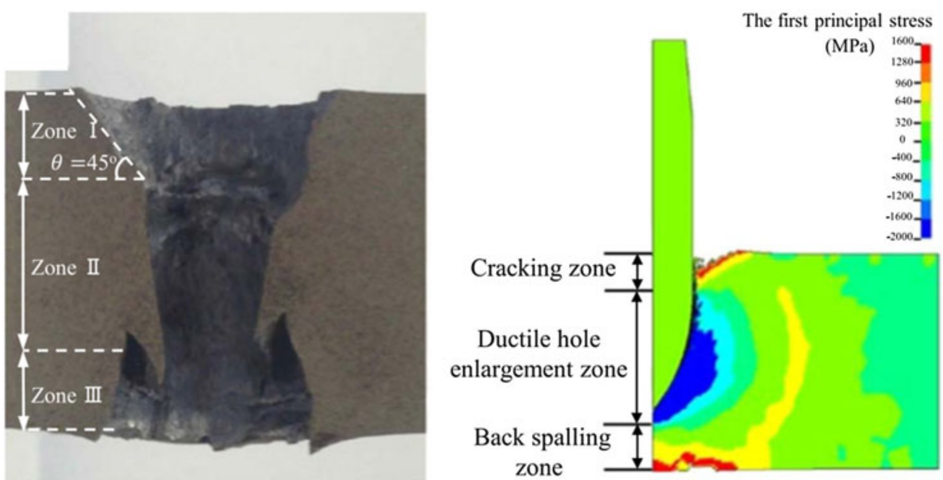

Figure 5. The section of the sample and the stress field during the impact process (Liu et al. 2015).

dynamic quantities, and thermodynamic states. The constitutive model reflects the inherent properties of a research object, which would vary with the specific object and motion conditions being studied.

The Johnson Cook model, or J-C model, is applied to forecast the behavior and failure of materials. The J-C model can reflect the interaction between material stress and strain under conditions of large deformation and high strain rate. Due to its simple form and less input in predicting material constants, the J-C model is widely used to predict the flow behavior of materials (Sirigiri et al. 2022). It can be applied also to predict the behavior of plant stems. On one hand, plant stems would also undergo plastic deformation until material failure and fracture during cutting and destruction, which is similar to the behavior of metals. On the other hand, plant stems also exhibit significant strain hardening effect and strain rate strengthening effect in the destruction process, consistent with the main factors affecting flow stress in the J-C model. Therefore, the J-C model can be used as a constitutive model for plant stem cutting (J Liu et al. 2020). The flow stress equation is shown in Equation 3.

$$\sigma = (A + B\varepsilon^N)(1 + C\ln\dot{\varepsilon}^*)(1 - T^{*M}) \quad [3]$$

Here, σ is equivalent stress (Pa); ε is equivalent plastic strain; $\dot{\varepsilon}^*$ is the dimensionless strain rate; T^* is the dimensionless temperature; A is the yield strength of sample with the influence of strain rate and temperature; B is strain hardening coefficient; C is strain rate hardening coefficient; N is strain hardening exponent; and M is the thermal softening coefficient. There are three parenthetical expressions on the right side of the flow stress equation. From left to right, they represent strain hardening effect, strain rate strengthening effect, and temperature effect, which can influence flow stress.

The dimensionless strain rate $\dot{\varepsilon}^*$ and the dimensionless temperature T^* can be calculated based on Equations 4 and 5.

$$\dot{\varepsilon}^* = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \quad [4]$$

$$T^* = \frac{T - T_r}{T_m - T_r} \quad [5]$$

Here, $\dot{\varepsilon}$ is strain rate; $\dot{\varepsilon}_0$ is reference strain rate; T is the temperature at deformation (C); T_r is the reference temperature at deformation (C); and T_m is the material melting temperature (C).

When cut, plant stems would not heat up significantly, and the stem temperature would be approximately equal to room temperature, that is, $T = T_r$. When predicting the cutting process of plant stems, the J-C model can be simplified as Equation 6 (J Liu et al. 2020).

$$\sigma = (A + B\varepsilon^N)(1 + C\ln\dot{\varepsilon}^*) \quad [6]$$

Because the J-C model does not indicate the failure of the material, the J-H constitutive model is proposed as better

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predicting the behavior and failure of brittle materials (Holmquist and Johnson 2011; Johnson and Holmquist 1994), which can also reflect the behavior of materials under large deformation and high strain rate conditions. The J-H model can be described by Equation 7.

$$\sigma^* = \sigma_i^* - D\left(\sigma_i^* - \sigma_f^*\right) \quad [7]$$

Here, σ^* is equivalent normalized strength of materials (Pa); σ_i^* is normalized strength of intact materials (Pa); σ_f^* is normalized fracture stress (Pa), and σ_f^* is not greater than $\sigma_f^*{}_{max}$; $\sigma_f^*{}_{max}$ is a dimensionless fracture strength of sample; D is the damage factor of the material ($0 \leq D \leq 1$), and when the material is intact, $D = 0$. The dimensionless expression of σ^* is shown in Equation 8.

$$\sigma^* = \frac{\sigma}{\sigma_{HEL}} \quad [8]$$

Here, σ_{HEL} is the equivalent stress at Hugoniot elastic limit (Pa).

The expression of normalized strength of intact materials σ_i^* is shown in Equation 9, and the expression of normalized fracture stress σ_f^* is shown in Equation 10.

$$\sigma_i^* = a(p^* + t^*)^n(1 + c\ln\dot{\varepsilon}^*) \quad [9]$$

$$\sigma_f^* = b(p^*)^m(1 + c\ln\dot{\varepsilon}^*) \quad [10]$$

Here, a, b, c, m, and n are the material constants to be determined; $\dot{\varepsilon}^*$ is the dimensionless strain-rate; p^* is dimensionless pressure; t^* is dimensionless maximum tensile strength. The expressions of dimensionless pressure p^* and dimensionless maximum tensile strength t^* are shown in Equations 11 and 12.

$$p^* = \frac{P}{P_{HEL}} \quad [11]$$

$$t^* = \frac{t}{P_{HEL}} \quad [12]$$

Here, P is actual pressure (Pa); P_{HEL} is the pressure at Hugoniot elastic limit (Pa); and t is the maximum tensile strength of sample (Pa).

Wedge Angle and Sliding Cutting Angle

The sharpness of the blade is an important factor affecting the cutting process and has a significant impact on cutting force, cutting energy, cutting quality, and blade life (McCarthy et al. 2007; Schuldt et al. 2016). As shown in Figure 6, the wedge angle γ is the angle between the front and rear cutting surfaces of the cutting edge. As the wedge angle decreases, the sharpness of the blade increases (McCarthy et al. 2010). However, an excessively small wedge angle can lead to insufficient strength at the blade tip, resulting in cutting stability issues (McCarthy et al. 2010). One other factor that significantly affects the sharpness of the blade is the radius of the blade tip (Schuldt et al. 2016). The blade would be sharper when the radius of the blade tip is smaller. Due to the significant variation in blade tip radius with blade wear in practical operations, this article will not discuss the impact of blade tip radius on cutting plant stems.

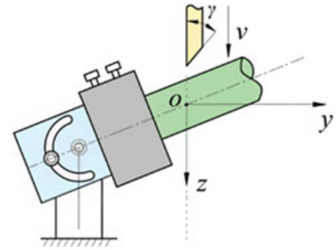

Figure 6. Schematic diagram of sliding angle (Song et al. 2022a).

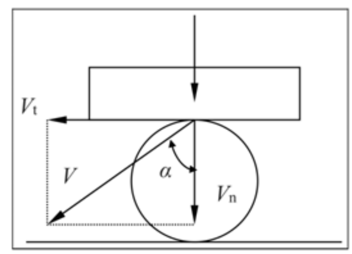

Figure 7. Schematic diagram of sliding angle (Tian et al. 2021).

During the cutting process, the sliding cutting angle is a crucial parameter affecting cutting resistance. The sliding cutting angle has been widely used in agricultural production related to cutting, and it is an important performance index of some agricultural machinery (Huang et al. 2023).

The sliding cutting angle is defined as the angle between the absolute velocity direction of the blade motion and the normal velocity direction, as shown in Figure 7 (Tian et al. 2021), where V is actual velocity of blade motion, V_n is normal velocity of blade motion, V_t is tangential velocity of blade motion, and α is the sliding cutting angle. Angle α shall be between 0° and 90°, and when angle α is 0°, the cutting method is considered to be cross-cutting (Song et al. 2022b).

Sliding cutting can effectively reduce the ultimate stress of material tension, tensile fracture, and shear failure (Qian et al. 2023). Some studies suggest that a larger sliding cutting angle leads to lower cutting resistance (Hu et al. 2023; Rabbani et al. 2015; W Wang et al. 2022b), while other studies indicates that the relationship between them is not linear (Cao et al. 2023; Huan et al. 2024; Zhang et al. 2024). An increase of sliding cutting angle would reduce the actual wedge angle of the blade, making the blade sharper and reducing the normal stress during cutting, which is conducive to reducing the cutting force. On the other hand, an increase of the sliding cutting angle would increase the cutting displacement of the blade and the length of the blade put into cutting work, which is not conducive to reducing the cutting energy. When the sliding cutting angle is small, reducing the cutting force in the cutting process has a greater impact on the total cutting energy than reducing the cutting displacement. However, when the sliding cutting angle is large, although the ultimate shear stress decreases, the cutting will consume more energy due to the friction resistance between the blade surface and the stem (Song et al. 2022a). This is essentially a comparison between two effects caused by reducing cutting angle, and the values of both sides change with the cutting object.

Moisture Content

Because the stem is considered to be a composite material composed of cells (Du et al. 2020), the lack of water would affect the

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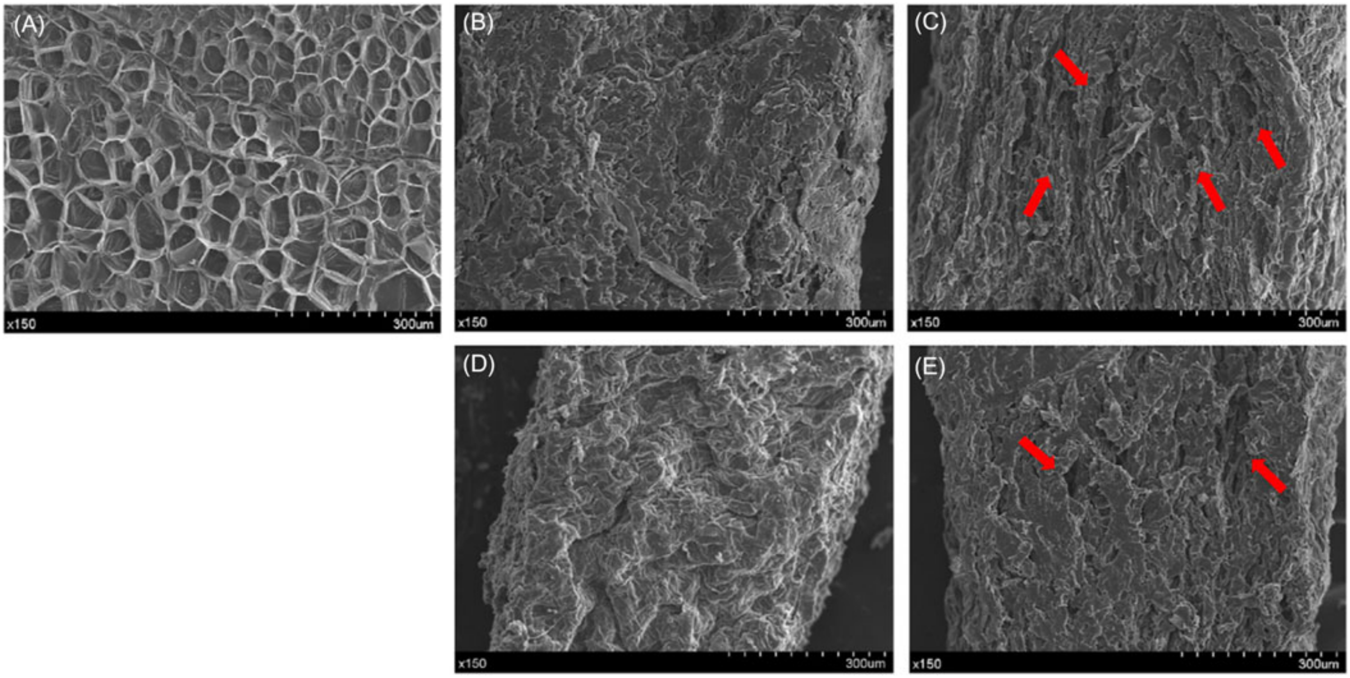

Figure 8. Longitudinal microstructure of carrot (*Daucus carota* L.). (A) Fresh; (B and D) infrared drying; (C and E) ultrasound-assisted infrared drying (Guo et al. 2020b).

structure and the physical properties of the cells, thus impacting the physical properties of the stem (Rabbani et al. 2015). Moisture content would have a significant impact on the toughness and strength of the stem and would greatly impact the cutting process (Cao et al. 2023; Tang et al. 2020, 2021). Moisture content is among the characteristics of the cutting object, the stem itself, but moisture content is relatively easy to predict and control in agricultural production.

The influence trend of stem moisture content on cutting resistance can be divided into two types. First, when the stem is fresh and the plant cells do not die in a large range during cutting, the cutting resistance decreases with the increase of moisture content (Chandio et al. 2021; Du et al. 2020; Kumar et al. 2023; Taghinezhad et al. 2013). Second, when the stem has been dried or the plant cells have died in a large range before the experiment, the cutting resistance increases with the increase of moisture content (Charee et al. 2021; Galedar et al. 2008; Oyefeso et al. 2021).

The increase of water content would make the fresh plant cells fuller and would further increase the Young's modulus of the stem. The increase of water content would also reduce the ultimate shear stress of fresh stems. In summary, increasing the moisture content would increase the brittle material characteristics of fresh stems.

Generally, there are several ways to dry plants, including freeze drying, relative humidity convective drying, infrared drying, microwave drying, and ultrasonic drying. All these drying methods would create a porous microstructure in the dried product and have great effects on plant cells and tissues (Guo et al. 2020b; Osae et al. 2020; Rashid et al. 2019). The effects can be seen in Figure 8: the arrows refer to the pores and cavities caused by drying. Freeze drying can produce ice crystals in cells, resulting in voids in the cell structure and cell collapse. In relative humidity convective drying, the synergistic effect of temperature and relative humidity will make plants create micropores, and the dried product will be softer than the non-dried one (Xu et al. 2022). Infrared drying and microwave drying will lead to irreversible cell rupture and destruction of cell structure, which will lead to the loss of plant tissue integrity and severe cell collapse (Osae et al. 2020; Wu et al. 2021). It can be determined that ultrasonic drying can change the five textural properties of the target: hardness, elasticity, cohesion, adhesion, and stickiness (Xu et al. 2022). In summary, drying can reduce the material strength of plant stems by altering their cell and tissue structure.

Material Preparation and Test Methods

Plant cutting is a complex process that involves many variables. To measure whether a cutting process meets the indicators required by the operation, it is necessary to select some variables to characterize important characteristics of the cutting process.

The cutting process evaluation indices shown in this paper are ultimate cutting stress, specific cutting energy, and cutting quality. Ultimate cutting stress represents the maximum resistance received by the blade when cutting, and the cutting resistance is one of the core indicators of much cutting equipment (Tian et al. 2023). Because cutting resistance is affected by the diameter of the plant stem, the effect of diameter can be removed by using shear stress compared with shear resistance. Specific cutting energy represents the work done by the cutting system during the cutting process and the resistance of the blade in the cutting process. Similar to the ultimate cutting stress, specific cutting energy also removes the influence of diameter. Cutting quality is the evaluation index for the flatness of the section produced by cutting when harvesting crops, such as sugarcane (*Saccharum officinarum* L.), which can be seen in Figure 9. Improving the cutting quality can reduce the harvest losses and stubble damage rates of crops. Moisture content, which is an important physiological and mechanical index of plant cannot be used directly to represent the cutting process, but can indirectly affect the process by affecting the mechanical properties of plant stems. The moisture content of fresh plant stems can vary, but the variation range is small.

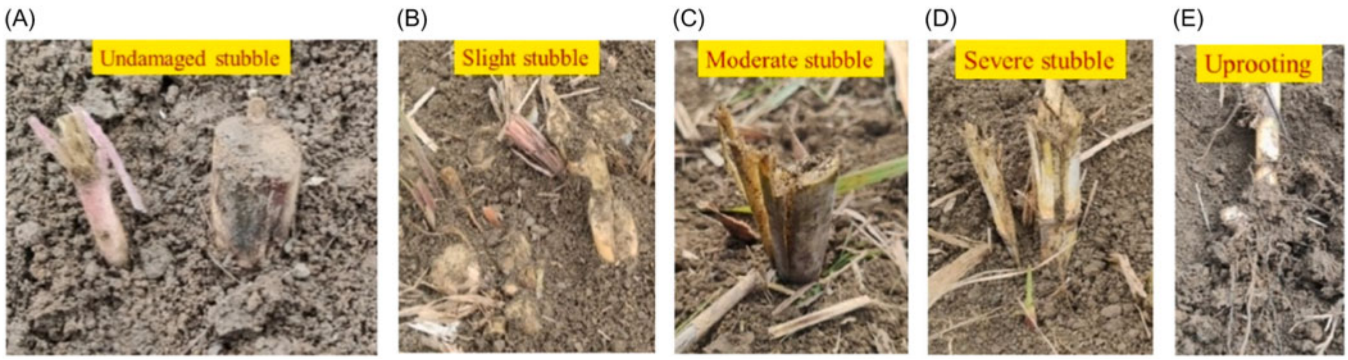

Figure 9. The sugarcane stubble damage condition: (A) undamaged stubble; (B) slight damage; (C) moderate damage; (D) severe damage; and (E) uprooting (Qian et al. 2024).

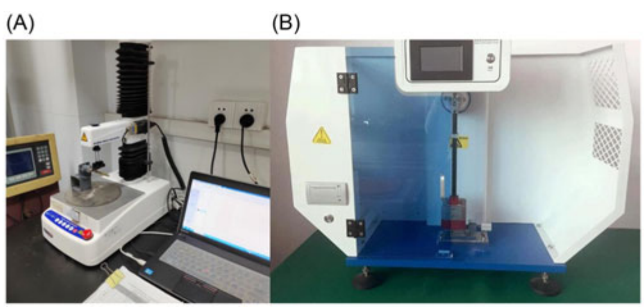

Figure 10. Test instruments: (A) texture analyzer and (B) pendulum-based cutting test setup.

Ultimate Cutting Stress and Specific Cutting Energy

To calculate ultimate cutting stress and specific cutting energy, it is necessary to select the data acquisition instrument according to the cutting speed. To obtain a quasi-static response, the texture analyzer can be used for the cutting test, as shown in Figure 10A (Liu et al. 2022; Tang et al. 2022). The cutting displacement cutting resistance curve can be obtained with a cutting test using the texture analyzer; the ultimate cutting stress can be obtained using Equation 13, and specific cutting energy can be obtained using Equation 14. To obtain dynamic response, a pendulum-based cutting test setup or other homemade cutting test machine can be used. A pendulum-based cutting test setup can be seen in Figure 10B. The calculation of ultimate cutting stress and specific cutting energy is the same as that used for quasi-static cutting.

$$\tau = \frac{F_{\max}}{A} \quad [13]$$

$$E_p = \frac{1}{A}\int_0^s F ds \quad [14]$$

Here, τ is ultimate cutting stress (MPa); $F_{\max}$ is the maximum force the blade received (N); A is the area of the section caused by cutting (mm^2); E_p is specific cutting energy ($\times 10^{-3}$ J mm^{-2}); s is blade displacement during the cutting process (m); F is instantaneous force received by the blade during the cutting process (N).

Cutting Quality

When measuring cutting quality, taking sugarcane as an example, if the crack on a stem stub exceeds one node of sugarcane or the stub is pushed down or pulled out, the stub should be considered damaged. If the section of a stem stub is flat and exhibits no tearing, the stub can be considered to be qualified stub. The damage rate for measuring cutting quality can be calculated according to Equation 15 (Qian et al. 2023).

$$C_P = \frac{N_P}{N_A} \quad [15]$$

Here, C_P is stubble damage rate (%); N_P is the number of damaged stem stubs produced by the test; N_A is the number of stem stubs produced by the test.

Moisture Content

Moisture content is an important physical parameter that needs to be measured using instruments. Many devices can be selected to assist in the measurement of moisture content. The use of hyperspectral technology is efficient and nondestructive and has been widely used in the measurement of agricultural products (Lu et al. 2018). However, to improve accuracy, the moisture content of the test points needs to be the same as that of the whole plant sample (Sun et al. 2020). Hyperspectral technology is suitable for measuring the moisture content of smaller parts such as leaves, seeds, or slender stems (Lu et al. 2018; X Zhou et al. 2018). The use of a constant-temperature oven is accurate, but time-consuming, destructive, and cumbersome (Sun et al. 2020). The constant-temperature oven would use convective air or infrared or microwave to promote the loss of moisture in plant samples and finally end the drying when the sample mass no longer decreases. The moisture content measured with a constant-temperature oven can be calculated using Equation 16.

$$M_C = \frac{m_A - m_P}{m_A} \quad [16]$$

Here, M_C is moisture content (%); m_P is the mass after drying (g); and m_A is the mass before drying (g).

Weeding Blade Design

In mechanical weeding, the core goal has always been to improve weeding efficiency or weeding performance, which means the

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blade can cut weeds with less resistance and dragging. In summary, the core goal is increasing weeding rate and reducing weeding power.

There are many types of designs for cutting blades, include bionic cutting blade design and serrated cutting blade design. They all can achieve the goal of improving cutting performance but neglect the intrinsic design of the blade edge curve which bases on the force analysis and material mechanics (J Wang et al. 2021; Zhang et al. 2018). Therefore, there are blades designed with equal sliding cutting angle to keep cutting resistance on blade constant; but these neglect the influence of speed on cutting resistance, as higher speed leads to lower resistance during cutting and impact (Song et al. 2022a; Zhang et al. 2018), rendering such designs unsuitable for rotary mowers.

Bionic Cutting Blade Design

In recent years, the application of physiology as well as morphology in agriculture has been increasing. Different biological characteristics have been incorporated into the design of cutting tools based on observing cutting processes in nature and analyzing low-resistance, anti-wear, and anti-friction characteristics,. These characteristics are successful examples of the cutting mechanisms evolved by various organisms. This effectively enhances the performance of cutting tools and the quality of the cutting process (Yu et al. 2021). The use of bionics in agricultural components includes the design of openers, plows, and cutting blades to reduce resistance and power consumption (Tian et al. 2017).

In bionic cutting blade design, the first step is to determine the required cutting blade features and the suitable bionic prototype. Especially for the blade design for plant cutting, the blades need to be low resistance and anti-friction. The material properties and cutting mechanisms of different materials vary from one another, and different bionic prototypes need to be selected according to the cutting object requirements (Yu et al. 2021). For example, the common pest *Locusta migratoria manilensis*, which mainly feeds on plants, has highly developed chewing mouthparts. The mandibles of the Oriental migratory locust are an important and efficient tool for cutting plants and a suitable bionic prototype (Hu et al. 2023). *Otidognathus davidis* larvae feed on bamboo (*Bambusa* spp.), which has high strength and hardness. Bamboo weevil larvae can easily cut the thick, tough fibers bamboo. The cutting ability mainly comes from the larva's sturdy and sharp mandibles and can serve as a good bionic prototype in the design of plant cutting blades (Tong et al. 2017).

It is necessary to extract features from bionic prototypes, usually insect mandibles or animal claws. First, observe and record bionic prototypes through scanning electron microscopy, 3D microscopy, or nano-computed tomography (CT) scanners. Then, extract contour data from raw images through image post-processing software (Moyer and Bemis 2017; J Wang et al. 2020; Zhang et al. 2024). In the end, based on actual needs, the extracted data should be reproduced on the cutting blade in a specific size. This can be the reproduction of the cutting part curve of the bionic prototype by the blade edge curve design in a two-dimensional perspective (Cao et al. 2023; Guan et al. 2022), or the reproduction of the cutting part curve of the bionic prototype by the blade specific design in a three-dimensional perspective (Li et al. 2016).

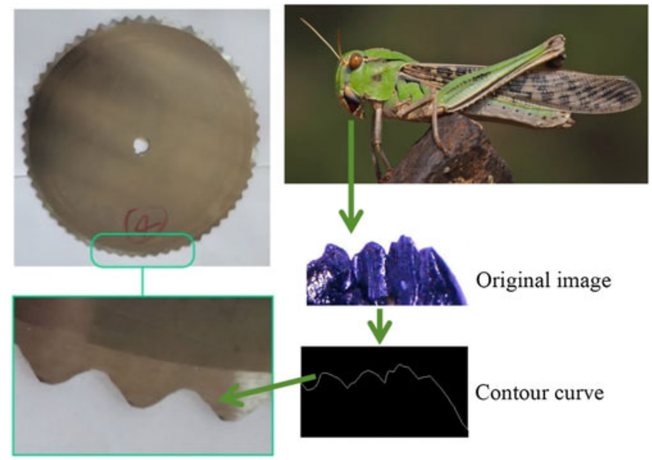

Figure 11. The design process for a bionic cutting blade inspired by Oriental migratory locust (Cao et al. 2023).

The design process for a bionic cutting blade can be seen in Figure 11.

Serrated Cutting Blade Design

The design of serrated blade is a common improving design scheme for ordinary blade. A serrated blade design would not change the blade curve of the original blade design but would replace the original blade edge with a row of serrations.

The design of a serrated blade is similar to that of a saw. The serrations will produce local high-pressure points on the cutting object, which will produce cutting object failure (Gan et al. 2018). After the stem fails at high-pressure points, the displacement of serrations, which would already be embedded in the stem, would strengthen the tensile stress and shear stress of the blade on the stem. Because shear and tensile failure of stem fibers are the main sources of stem failure (Tang et al. 2022), strengthening tensile stress during cutting can encourage stem failure and reduce energy consumption (Gan et al. 2018).

There are many specific designs for serrations, including designs with triangular protrusions like saws (Mello and Harris 2003; J Wang et al. 2021), designs with strip-shaped serrations (Liu et al. 2012; Momin et al. 2017), and designs that use the curve obtained from a bionic prototype as the blade curve at the serrated gap (X Chen et al. 2024). A blade with strip-shaped serrations is shown in Figure 12.

Equal Sliding Cutting Angle Blade Design

The influence of sliding cutting angle on the cutting process has been described earlier. To solve the problem of uneven force and large fluctuations on the blade during the cutting of rattan straw, an equal sliding angle cutting blade design has been proposed (Guo et al. 2014). The equal sliding angle cutter not only reduces cutting power consumption and improves cutting efficiency but also extends blade life (Song et al. 2024; Zheng et al. 2016).

As shown in Figure 13, a polar coordinate system is established with point O as the pole, and the blade rotates around point O as the center. When the blade curve AB rotates dδ, any point D on the blade curve would changes to point M, and vector **r** would become **r**′. Set dr as the difference between **r** and **r**′. When dδ approaches 0, arc MD can be regarded as a straight line, and the lengths of arc ND can be regarded the same as line MN. According to the definition of a

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Figure 12. Serrated blade design with strip-shaped serrations (Gan et al. 2018).

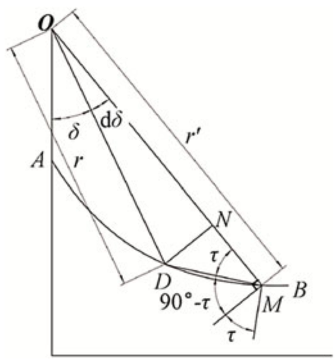

Figure 13. Schematic diagram of the equal sliding cutting angle blade curve (P Liu et al. 2020).

sliding angle, in triangle ABC, the relationship between sliding angle τ and polar angle δ can be expressed by Equation 17:

$$\tan\tau = \frac{ND}{MN} = \frac{rdr}{dr} \quad [17]$$

If the sliding angle is constant, the polar coordinate equation of the blade curve is shown in Equation 18).

$$r = Ce^{\frac{\delta}{\tan\tau}} \quad [18]$$

Here, C is constant.

The polar coordinate equation is a logarithmic spiral equation. In a logarithmic spiral curve, if any ray passing through the pole O intersects with a curve, the angle between the tangent of the curve at the intersection and the ray is a fixed value, which is the slip angle τ. Therefore, the equal sliding angle blade can also be referred as a logarithmic spiral blade.

The equal sliding angle cutting blade has a significant effect on cutting stems with low fiber content. However, banana (*Musa acuminata* Colla) straw has a large amount of fiber. If the equal sliding angle cutting blade is used to cut banana straw, due to inertia, the fiber of the banana straw easily slides from the high cutting speed blade tip to the low cutting speed blade base and then wraps around the blade shaft. Therefore, in this case, the variable sliding cutting angle blade is needed (Zhang et al. 2018).

Discussion

Cutting plant stems is a complex process, and its mechanism is currently unclear. The factors that affect the process of cutting plant stems can be roughly divided into two categories: one factor is the physical characteristics of the plant stem, and the other factor is the behavior and properties of the cutting components. Because plant stems are composite materials composed of cells, the morphology and physical properties of cells directly affect the physical characteristics of plant stems. During the cutting process, the blade would first contact the cells of the plant stem. Based on the cutting speed and sharpness of the blade, the cells and tissues of the stem would have different reactions. When the cutting speed and the sharpness of the blade are reduced, and the stem skin cells lack moisture, the material strength of the stem is low. In this case, the deformation of the stem skin caused by the stem epidermal cells and tissues being cut would be significant, with plant stems exhibiting characteristics of ductile materials. However, when the cutting speed and the blade sharpness is large, and the stem cells have moisture, the strength of the stem material would be high, leading to less deformation of the skin cells and tissues when the blade comes into contact. The strain rate strengthening effect of plant stems is significant, and plant stems exhibit brittle material characteristics. This reduces the cutting resistance and energy consumption. To reduce the cutting resistance and energy consumption, it is recommended to choose a cutting blade with a larger sliding angle and a smaller wedge angle for high-speed weeding when the weed moisture content is high.

Based on our review and summary, potential research directions can be focused on these areas:

1. The influence of friction on the cutting process: Due to the unclear cutting mechanism of plant stems, there are some important factors that affect cutting that have not been thoroughly understood. Friction has been mentioned several times in the preceding text and can actually affect the cutting process (He et al. 2020), but there is still no explanation or application of the friction mechanism in cutting fresh plant stems. Therefore, friction during the cutting process of fresh plant stems is a possible research subject. Coatings can be added to blades to solve the friction problem of rotary tillage blades (Guan et al. 2021), which could be a possible solution.
2. The comprehensive application of factors affecting the cutting process: Cutting blade design is an application based on the influence of specific factors on the cutting process, but the more common cutting blade designs mentioned earlier only utilize the influence of blade wedge angle and sliding cutting angle on the cutting process. Designing a cutting blade based on the comprehensive application of cutting speed, blade wedge angle, and sliding cutting angle on the cutting process is a valuable research direction.
3. The application of influence moisture content on the cutting process: The moisture content of plants is easily altered. However, due to the high cost of quickly changing the moisture content of plants through manpower, there are few designs based on the influence of moisture content on the cutting process in practical operations. Meanwhile, cutting speed is a very controllable influencing factor. Therefore, working standards or cutting methods based on the influence of moisture content and cutting speed on the cutting process are a direction that can be studied.

The methods proposed in this review can be applied not only to weed control, but also more generally to cutting plant stems. Cutting is an important part of harvesting work (Chen et al. 2017; Liang et al. 2016), and the cutting theory for plant stems contributes to the development of harvesting technology. For example, cutting can cause vibration, with structural parts' stress changing within the harvester (Liu et al. 2019; Pang et al. 2019), and a deeper understanding of the cutting theory may help solve this problem. Cutting is also one of the important steps in processing straw (Bai et al. 2021). It is very important to remove straw from farmland to avoid breeding crop pests, poor sowing quality, and serious weeds during the seedling stage (Huang et al. 2019; Tang et al. 2017). In areas like these, the theory of cutting plant stems can play an important role.

Conclusions

This review provided directions for potential weed cutting techniques by reviewing the research progress of plant stem cutting technology. It listed evaluation indicators that can characterize the cutting process, summarized the factors that can significantly affect the cutting process based on these evaluation indicators, and finally, listed cutting blades designed based on the influences of these factors. It also elaborated on the possible plant stem cutting processes at different cutting speeds based on the impact of influences of the factors described. Potential research directions for plant stem cutting were discussed.

The main conclusions obtained are as follows:

1. The cutting of plant stems is a complex process that can be measured using ultimate shear stress, shear energy, and cutting quality. Among the easily modifiable parameters, factors that can significantly affect the cutting process are cutting speed; blade sharpness, including the wedge angle and the sliding cutting angle; and stem moisture content.
2. When the moisture content of plant stems is high, the stem cells would be full, the stem would be stronger, and the stem would be less likely to deform. When the cutting speed is high, the deformation of the plant stem would be insufficient, and the degree of deformation would be lower during the cutting process. Both of these factors can lead to brittle behavior of plant stems during the cutting process, reducing resistance and energy consumption during the cutting process.
3. Reducing the wedge angle and increasing the sliding cutting angle within a range can increase the sharpness of the blade, which can reduce cutting resistance and cutting energy consumption. However, excessive reduction of the blade wedge angle would lead to insufficient strength of the cutting edge. Excessive increase of the sliding cutting angle would increase the blade length put into operation and increase frictional power consumption, which would increase cutting resistance and energy consumption.

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