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Simulation and Identification of Multiscale Falling Morphology of Fresh Tea Leaves at Different Transport Speeds Based on Discrete Element Method

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***Abstract.* To explore the falling morphology of multiscale fresh tea leaves at different speeds, this study evaluated the multiscale fresh tea leaves (one bud with two leaves, one bud with one leaf, single leaf, and damaged leaf) at different heights (0.7 m, 0.5 m, 0.3 m, and 0.1 m from the ground) during the process of dropping on the conveyor belt at different speeds (0.6 m/s and 1.2 m/s). The motion morphology of fresh tea leaves on multiple scales was analyzed by discrete element simulation, the results showed that the movement patterns of multiscale fresh tea leaves at different positions from the ground were different when the conveyor was dropping at different speeds, and that the multiscale fresh tea leaves all rotated around the long axis, short axis, and root of the fresh tea leaves. When the conveying speed of the conveyor belt was 0.6 m/s, the movement patterns of one bud with two leaves and of one bud with one leaf of fresh tea were near the ground, and the movement patterns of the fresh tea leaves were mostly oriented toward the ground. The leaf tips of the fresh tea leaves were mostly on the side near the ground, the damaged leaves were near the ground, and the movement patterns of the fresh tea leaves were mostly parallel to the ground. When the conveyor belt throwing speed was 1.2 m/s, the roots of one bud with two leaves moved toward the ground when they were close to the ground. When one bud with one leaf was close to the ground, the leaf tip moved toward the ground, and the single leaf and damaged leaf rotated around the root because of the inertia of the conveyor belt throwing.**

Tea is deeply loved by people all over the world. According to its different processing methods, it is divided into primary and refined. With the gradual improvement of people's requirements for tea quality, refined tea has gradually become the mainstream product in the tea industry market and gradually replaced primary tea. Fresh tea leaves sorting is mainly used for refined tea, whereas traditional fresh tea leaves sorting mainly uses the drum type (Luo et al. 2012; Yang et al., 2013), oscillating type (Ren et al. 2013; Xie et al. 2012), air-screened grouping type (Tang et al. 2015; Weng et al. 2014; Zhang et al. 2012, 2013), and modern intelligent sorting based on computer evaluation (Gao et al. 2017; Laddi et al. 2012; Palacios-Morillo et al. 2012). Fresh tea leaves are similar to thin flakes and are more susceptible to the influence of fluid during the falling process, resulting in many complex and interesting motion forms, such as periodic oscillation falling, tumbling falling, disordered falling, and others, and there are instantaneous flow structures such as vortex shedding. With the rapid development of discrete element simulation and computational fluid mechanics, more studies have been conducted to simulate the falling process of flexible thin sheets using a computer. Mittal et al. (Rajat and Veeraraghavan 2004) were the first to conduct computational fluid dynamics numerical simulation of the falling motion of two-dimensional thin sheets, and they adopted the immersed boundary method to simulate the boundary motion. Sun et al. (2020) used the gas–Bhatnagar-Gross-Krook scheme and unified coordinate system method to solve the two-dimensional ellipse and rectangular section falling problem. Bönisch and Heuveline (2007) used the finite element method to simulate the falling problem of two-dimensional rectangular slices. Dmitry and Kai (2010) used the Fourier pseudo-spectrum method to solve the vorticity flow function equation to study the falling of two-dimensional elliptic sections and found that the reduction of the Reynolds number can make the falling of slices more stable. Chrust et al. (2013) conducted a detailed numerical calculation study of the free-falling motion of the disk. The research group used engineering discrete element method (EDEM) to study the falling motion of fresh tea leaves at a fixed speed on a single scale, but the falling motion of fresh tea leaves at different transport speeds on a multiscale has not been studied (Zhang and Zhu 2023).

In summary, scholars using the EDEM discrete element method have not yet analyzed and studied the multiscale fall morphology of fresh tea leaves at different throwing speeds. This study used multiscale fresh tea leaves, including one bud with two leaves, one bud with one leaf, single leaves, and damaged leaves, which were used as research carriers. Under different dropping speeds of the conveyor belt, EDEM discrete element software was used to simulate the falling form of fresh tea leaves. The multiscale discrete element simulation of the falling state of fresh tea leaves was verified by a high-speed camera, and the falling motion form of multiscale fresh tea leaves under different transmission speeds was calibrated.

Materials and Methods

Multiscale measurement of physical parameters of fresh tea leaves. Because of the influence of tea tree growth, environment, and size of mechanical tea picking, the outline shape of fresh tea leaves of the same variety is different, and the bud length and leaf length are different. During this study, 50 samples were selected for each scale of fresh tea leaves to measure the leaf size. It was found that the length of one bud with two leaves ranged from 20 mm to 35 mm, with an average of 28 mm; the length of one bud with one leaf ranged from 15 to 25 mm, and the mean value was 21 mm; the length of the single blade ranges from 19 to 35 mm, with an average value of 30 mm; and the blade length of the damaged leaf ranges from 9 to 15 mm, with an average value of 13 mm. The toughness, ductility, and mechanical properties of fresh tea leaves were tested by a texture

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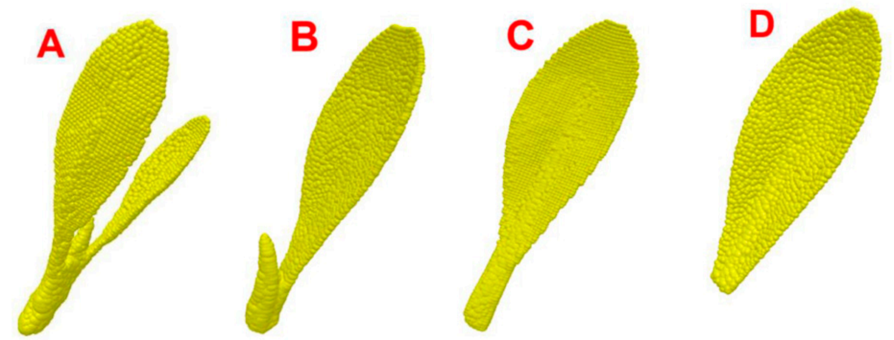

Fig. 1. Multiscale fresh tea leaves. (**A**) One bud with two leaves of fresh tea leaves. (**B**) One bud with one leaf fresh tea leaves. (**C**) Simple leaf fresh tea leaves. (**D**) Damaged leaf.

analyzer. The average elasticity modulus and shear modulus of tea leaf were 9.3 MPa and 3.3 MPa, respectively (Zhang and Zhu 2023).

Establishment of discrete element particle model of scale fresh tea leaves. A three-dimensional scanner was used to conduct three-dimensional scanning of multiscale fresh tea leaves, and a three-dimensional model was established. The obtained 1:1 three-dimensional model was imported into discrete element software EDEM, and discrete element particles were filled in the three-dimensional model. Figure 1A shows one bud with two leaves filled with 2384 spherical particles of different scales (Zhang and Zhu 2023). Figure 1B shows one bud with one leaf filled with 1907 spherical particles of different scales. Figure 1C shows a single leaf filled with 1455 spherical particles of different scales. Figure 1D shows damaged leaves filled with 1023 spherical particles of different scales.

Discrete element simulation method based on EDEM. The discrete element method was used to simulate multiscale motion characteristics of fresh tea leaves falling from the conveyor belt. The basic model of this study was the Hertz-Mindlin (no slip) model, which is accurate and efficient for force calculations. In the model, the normal force component is based on Hertzian contact theory, and the tangential force model is based on Middlin-Deresiewicz's research theory. The normal force and tangential force both have damping components and are related to the damping coefficient and recovery coefficient. The tangential friction force follows the Coulomb friction law, and the rolling friction force is independently directed by the constant torque model through contact (Ai et al. 2010; Oka et al. 2005; Potyondy and Cundall 2004; Sakaguchi 1993). Zhang and Zhu (2023) have explained that the Bonding V2 model in EDEM should also be loaded because fresh tea leaves belong to a flexible sheet and have certain bending deformation behavior, and the bonding force/torque in the model is complementary to the basic contact model. Because the bonds involved in this model can function when the particles are no longer in physical contact, the contact radius should be set higher than the actual radius of the sphere, and the bond will break when the normal and tangential shear stresses exceed a certain predetermined value. Because the weight of fresh tea leaves is relatively light, it is necessary to consider the influence of air resistance during falling on the motion state of fresh tea leaves. The air resistance contact model is added to EDEM. The resistance model is applied to fresh tea leaf particles and the direction of movement is opposite to that of fresh tea leaves.

Multiscale Tea Leaf Movement Identification and Simulation Verification Based on EDEM

Transfer rate selection. No matter the separation method of fresh tea leaves used, such as drum type, vibration type, or pneumatic type, during the process, the transmission belt is required to transport, and the speed of the transmission belt directly affects the accuracy of the separation of fresh tea leaves. The slow transmission speed affects the sorting efficiency of fresh tea leaves, and the fast transmission speed leads to the low sorting accuracy of fresh tea leaves. Combined with the actual production characteristics, this study selected the velocity values of 0.6 m/s and 1.2 m/s as the velocity variation of the transmission belt, analyzed the changes of the multiscale falling motion patterns of fresh tea leaves under different transmission speeds, and laid the foundation for the movement characteristics of fresh tea leaves by air suction sorting.

Multiscale morphological identification of fresh tea leaves. According to the research group's previous research basis, the transmission belt is 0.8 m above the ground, and the intervals for the analysis of the falling motion pattern of fresh tea leaves selected for this study were as follows: the critical position of fresh tea leaves falling from the belt to 0.7 m, 0.7 to 0.5 m, 0.5 to 0.3 m, and 0.3 to 0.1 m. The position morphology of fresh tea leaves before falling from the belt is shown in Fig. 2A; the fresh tea leaves are parallel to the conveyor belt and the roots of the fresh tea leaves are perpendicular to the edge of the conveyor belt. The motion patterns of fresh tea leaves in the falling process include turning the fresh tea leaves around the short axis, turning the fresh tea leaves around the long axis, and rotating around the tea root, as shown in Fig. 2B.

Simulation verification. During previous basic research, Zhang and Zhu (2023) established the fresh tea discrete element motion model of one bud with two leaves based on EDEM and photographed the falling motion state of the fresh leaves of one bud with two leaves by using high-speed cameras. By comparing with the model and adjusting the parameters, the discrete element falling motion model of the fresh tea leaves of one bud with two leaves based on EDEM was established. The fitting degree was higher than 95%. Based on the model, the motion states of one bud with two leaves, one bud with one leaf, a simple leaf, and a damaged leaf with different transmission speeds were analyzed.

Simulation Analysis of Falling Morphology of Fresh Tea Leaves at Different Transport Speeds Based on EDEM Multiscale

Movement patterns of one bud with two leaves of fresh tea at different speeds. Figure 3A shows the falling motion pattern of fresh tea leaves of one bud with two leaves when the conveyor belt is running at a speed of 0.6 m/s. The changing law of its falling motion is as follows: the fresh tea leaves of one bud with two leaves fall 0.7 m away from the ground at the belt, and the fresh tea leaves rotate around the long axis and short axis at the same time; at 0.7 m away from the ground, the fresh tea leaves move toward the right side of the conveyor belt and upward (Fig. 2A is the orientation change diagram of the fresh tea leaves). At 0.7 to 0.5 m from the ground, the fresh tea leaves of one bud with two leaves are mainly turned around the short axis, and the turning angle around the long axis is small; at 0.5 m from the ground, the fresh tea leaves have turned 90° around the short axis, which is consistent with the critical position of falling. At 0.7 m from the ground, the fresh tea leaves have turned 90° around the long axis. At 0.5 to 0.3 m from the ground, the fresh tea leaves continue to rotate around the long axis and short axis at the same time, and the rotation pattern of the fresh tea leaves around the long axis is consistent with that at the critical point of the belt drop. At 0.3 to 0.1 m from the ground, the fresh tea leaves also rotate around both the long axis and short axis, where the root of the fresh tea leaves faces down.

Figure 3B shows the falling motion pattern of the fresh leaves of one bud with two leaves of tea when the conveyor belt is running at a speed of 1.2 m/s. The changing law of its falling motion is as follows: when the fresh tea leaves of one bud with two leaves fall near the conveyor belt to 0.7 m from the ground, the fresh tea leaves turn around the short axis, and the turning angle is close to 180°, compared with the running speed of the conveyor belt, the fresh tea leaves in this area have a larger turning angle around the short axis. In the interval of 0.7 to 0.5 m from the ground, the fresh tea leaves mainly turn around the short axis, and the turning angle is ∼90°, where the tip of the fresh tea leaves faces the ground. At 0.5 to 0.3 m from the ground, the fresh tea leaves are mainly turned around the short axis, and the turning angle is ∼45°. At 0.3 to 0.1 m from

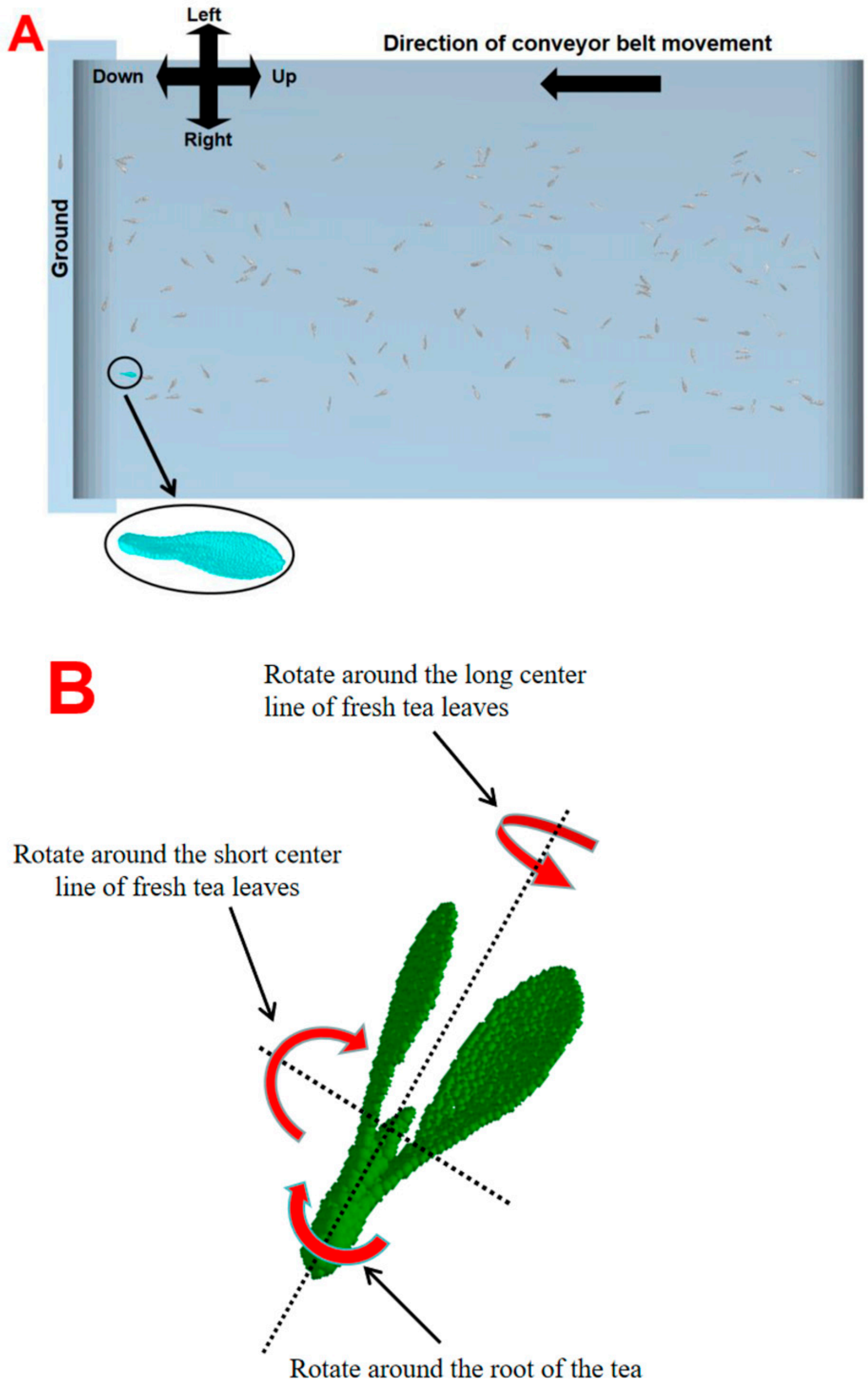

Fig. 2. Position of fresh tea leaves before falling and the main form of motion in the falling process. (**A**) The position of the fresh tea leaves before falling. The root is toward the direction of the transmission belt and the leaves are parallel to the transmission belt. (**B**) There are three movement trends of fresh tea leaves: rotation around the long axis, rotation around the short axis, and rotation around the root.

the ground, the fresh tea leaves mainly turn around the short axis, and the turning angle is greater than 45°, the movement of the fresh tea leaves here is manifested as the root movement toward the ground. In conclusion, when the fresh tea leaves of one bud with two leaves were transferred at different speeds on the conveyor belt, the falling forms of the fresh tea leaves were different in each interval of distance from the surface.

Movement patterns of one bud with one leaf of fresh tea at different speeds. Figure 4A shows the falling motion pattern of fresh tea leaves of one bud with one leaf when the conveyor belt is running at a speed of 0.6 m/s. The changing law of its falling motion is as follows: one bud with one leaf of fresh tea leaves falls near the belt to 0.7 m from the ground, and the fresh tea leaves turn around the short axis; the rotation angle around the long axis is close to 90°. At 0.7 to 0.5 m from the ground, the fresh tea leaves still rotate around the short axis, and the rotation angle is much larger than 90° compared with the position of 0.7 m; at this position, the tip of the fresh tea leaves faces the ground, and the fresh tea leaves are in vertical downward movement. At 0.5 to 0.3 m from the ground, fresh tea leaves still rotate around the short axis. Compared with 0.5 m, the rotation angle of fresh tea leaves around the short axis is nearly 90°, and the leaves are parallel to the ground. At 0.3 to 0.1 m from the ground, the fresh tea leaves rotate around the short axis, and the rotation angle is less than 90°. At 0.1 m from the ground, the roots of the fresh tea leaves move downward.

Figure 4B shows the falling motion pattern of fresh tea leaves of one bud with one leaf when the conveyor belt is running at a speed of 1.2 m/s, the changing law of its falling motion is as follows: one bud with one leaf of fresh tea leaves falls near the belt to 0.7 m from the ground, and the fresh tea leaves turn around the short axis; the turning angle is ∼90°. At 0.7 to 0.5 m from the ground, fresh tea leaves are still mainly turned around the short axis, and the turning angle is close to 45°; compared with the conveyor belt running at 0.6 m/s, the movement pattern of fresh tea leaves here is opposite. At 0.5 to 0.3 m from the ground, the fresh tea leaves still rotate around the short axis, and the turning angle is less than 45°. At 0.3 to 0.1 m from the ground, the fresh tea leaves are still mainly turned around the short axis, and the turning angle is close to 30°; the movement pattern of the fresh tea leaves here tends to be parallel to the ground.

Movement patterns of simple leaf of fresh tea at different speeds. Figure 5A shows the falling motion pattern of fresh tea leaves of simple leaf when the conveyor belt is running at a speed of 0.6 m/s. The changing law of its falling motion is as follows: the fresh tea leaves of a simple leaf fall near the belt to 0.7 m from the ground, and the fresh tea leaves rotate around a short axis with a rotation angle greater than 90°. At 0.7 to 0.5 m from the ground, the fresh leaves of simple leaf tea still rotate around the short axis, and the rotation angle is ∼90°; compared with the aforementioned region, the rotation angle of fresh leaves of single-leaf tea around the short axis in this region is smaller. At 0.5 m to 0.3 m from the ground, the fresh leaves of single-leaf tea still rotate mainly around the short axis, and the rotation angle is nearly 60°. At 0.3 to 0.1 m from the ground, the rotation angle of fresh tea leaves around the short axis is small, and the fresh tea leaves at 0.3 m and 0.1 m from the ground face down; from 0.3 m from the ground, the rotation angle of fresh tea leaves tends to be stable.

Figure 5B shows the falling motion pattern of fresh tea leaves of a simple leaf when the conveyor belt is running at a speed of 1.2 m/s. The changing law of its falling motion is as follows: the fresh tea leaves of a simple leaf rotate around the short axis and long axis from the belt to 0.7 m from the

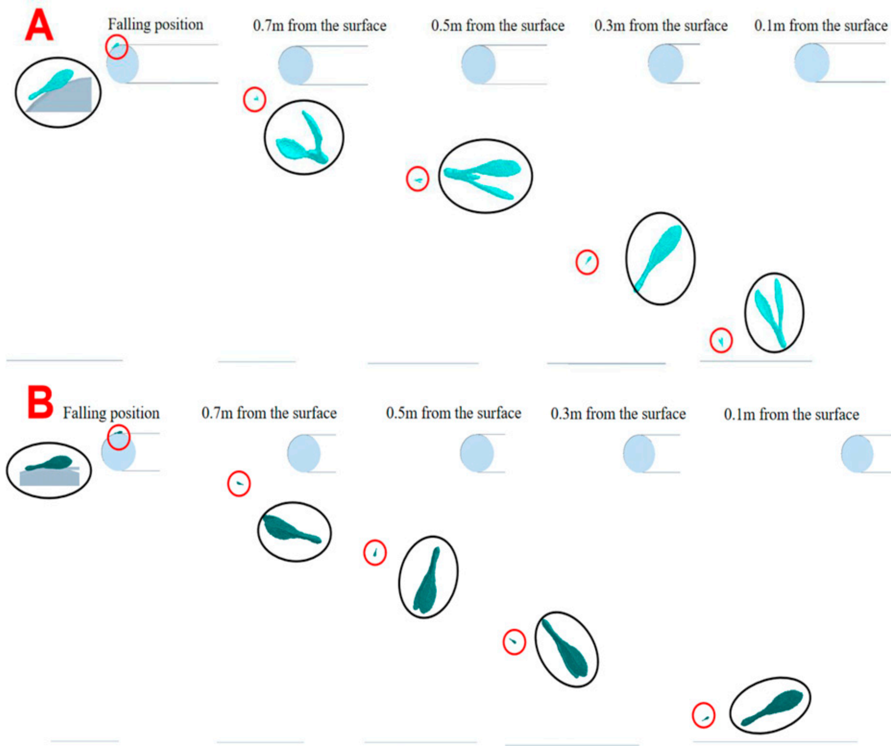

Fig. 3. The movement pattern of fresh leaves of one bud with two leaves falling at different distances from the ground. (**A**) The conveyor speed is 0.6 m/s. The movement pattern of fresh tea leaves falling. (**B**) The conveyor speed is 1.2 m/s. The movement pattern of fresh tea leaves falling.

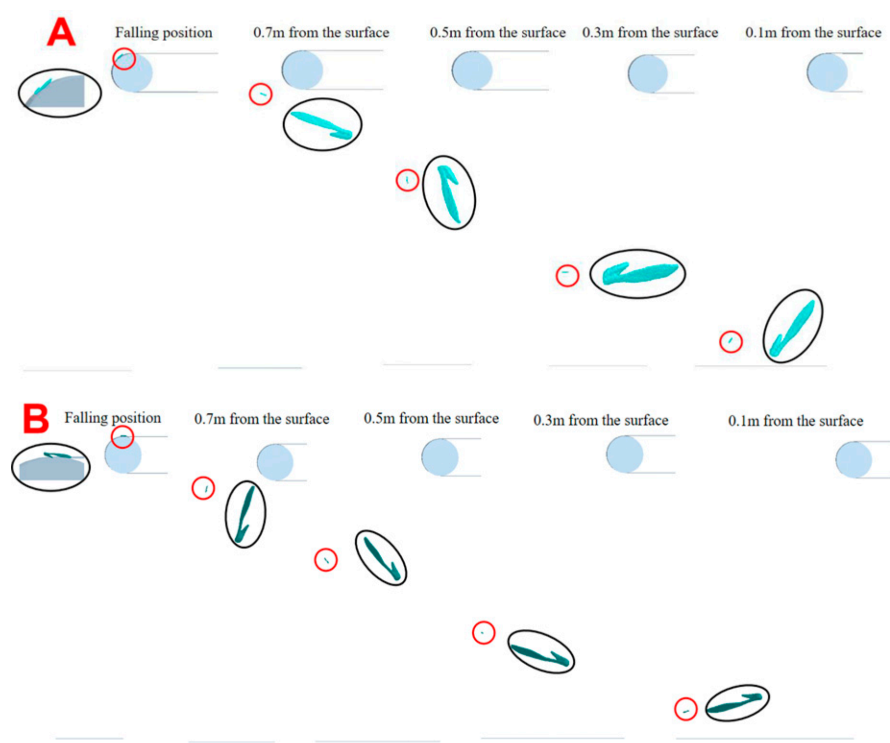

Fig. 4. The movement pattern of fresh leaves of one bud with one leaf falling at different distances from the ground. (**A**) The conveyor speed is 0.6 m/s. The movement pattern of fresh tea leaves falling. (**B**) The conveyor speed is 1.2 m/s. The movement pattern of fresh tea leaves falling.

ground, and the rotation angle around the short axis is ∼90°; at the same time, the fresh tea leaves rotate around the root of the tea leaves, and the tip of the leaves faces the right side of the running direction of the conveyor belt (marked in the direction of Fig. 2A). At 0.7 to 0.5 m from the ground, the change law of fresh tea leaves is similar to that of the previous stage, rotating around the long axis, short axis, and root of fresh tea leaves. At this position, the fresh tea leaves rotate around the root, and the rotation direction is opposite to that of the previous stage. At 0.5 to 0.3 m from the ground, the fresh tea leaves mainly rotate around the root, and the rotation angle around the short axis is ∼45°. At 0.3 to 0.1 m from the ground, the fresh tea leaves mainly rotate around the short axis and long axis, and the rotation angle around the short axis is less than 45°. The spatial position of the fresh tea leaves at this position is relatively parallel to the ground, but the root movement trend is downward.

Movement patterns of damaged leaves of fresh tea at different speeds. Figure 6A shows the falling motion pattern of fresh tea leaves of damaged leaf when the conveyor belt is running at a speed of 0.6 m/s. The changing law of its falling motion is as follows: the damaged fresh tea leaves fall near the belt to 0.7 m from the ground, and the fresh tea leaves turn around the short axis at an angle of 90°; at this time, the fresh tea leaves are vertically downward with the tip of the leaves facing upward. At 0.7 to 0.5 m from the ground, the damaged fresh tea leaves rotate counterclockwise around the short axis, and the rotation angle is ∼45°. At 0.5 to 0.3 m from the ground, the damaged fresh tea leaves rotate counterclockwise around the short axis, the rotation angle is less than 45°, and the damaged fresh tea leaves are in a parallel position to the ground. At 0.3 to 0.1 m from the ground, the fresh tea leaves still rotate around the short axis, but the rotation angle is small, and the tip of the fresh tea leaves shows a trend toward the ground at 0.1 m.

Figure 6B shows the falling motion pattern of fresh tea leaves of damaged leaf when the conveyor belt is running at a speed of 1.2 m/s. The changing law of its falling motion is as follows: the damaged fresh tea leaves fall to 0.7 m from the ground near the conveyor belt, the damaged fresh tea leaves rotate around the short axis, long axis, and root; the rotation angle of the damaged leaves around the root and short axis is close to 90°. At 0.7 to 0.5 m from the ground, the fresh tea leaves continue to rotate around the long axis, short axis, and root; at 0.5 m from the ground, the tip of the damaged fresh tea leaves faces the ground and slopes upward. At 0.5 to 0.3 m from the ground, the damaged fresh tea leaves rotate around the long axis and short axis, where the rotation around the long axis is ∼90°, and the rotation angle around the short axis is less than 30°. At 0.3 to 0.1 m from the ground, the movement pattern of the damaged fresh tea leaves is still the same as that in the previous stage. At 0.1 m from the ground, the damaged fresh tea leaves are close to and parallel to the ground, and the roots of the damaged leaves tend to move toward the ground.

Discussion and Conclusion

According to this analysis, when the conveyor belt is running at a speed of 0.6 m/s, the multiscale fresh tea leaves fall in different motion forms but mainly rotate around the rotating axis. As the distance from the ground gets

Fig. 5. The movement pattern of fresh leaves of simple leaves falling at different distances from the ground. (**A**) The conveyor speed is 0.6 m/s. The movement pattern of fresh tea leaves falling. (**B**) The conveyor speed is 1.2 m/s. The movement pattern of fresh tea leaves falling.

closer, the rotation angle of the multiscale fresh tea leaves gradually decreases. The characteristics of one bud with two leaves, one leaf with one leaf, simple leaf, and damaged leaf gradually weaken. One bud with two leaves and one bud with one leaf of tea were near the ground, and their movement patterns were mostly the root of the fresh tea leaves toward the ground; the leaf tips of the fresh tea leaves were near the ground, the damaged leaves were near the ground, and the movement patterns were mostly parallel to the ground. When the conveyor belt is running at the speed of 1.2 m/s, the movement of multiscale fresh tea leaves has a completely different movement form than that when it is transmitted at 0.6 m/s, which is mainly manifested as simple leaves and damaged leaves. When the transmission speed is large, the single leaf and damaged leaf are rotated around the root by the inertia of the conveyor belt. By comparing the changes in the falling movement of fresh tea leaves under different transmission speeds, it was found that under the influence of conveyor belt speed, the transverse distance between the falling time of fresh tea leaves and the conveyor belt was different. The greater the speed, the farther the fresh tea leaves were thrown. Using one bud with one leaf of fresh tea leaves as an example, Fig. 7A shows the falling trajectory of one bud with one leaf of fresh tea leaves at 0.6 m/s, and Fig. 7B shows the falling trajectory of one bud with one leaf of fresh tea leaves at 1.2 m/s.

In summary, when multiscale fresh tea leaves fall from the conveyor belt at different speeds, the movement forms of falling are different from the surface at different positions. The movement forms are mainly rotating around the short axis, rotating around the long axis, and rotating around the root of the fresh tea leaves. During this study, the motion morphology of multiscale fresh tea leaves falling at different speeds was analyzed, which laid a foundation for the subsequent research of multiscale fresh tea leaves by negative pressure adsorption.

Fig. 6. The movement pattern of fresh leaves of damaged leaves falling at different distances from the ground. (**A**) The conveyor speed is 0.6 m/s. The movement pattern of fresh tea leaves falling. (**B**) The conveyor speed is 1.2 m/s. The movement pattern of fresh tea leaves falling.

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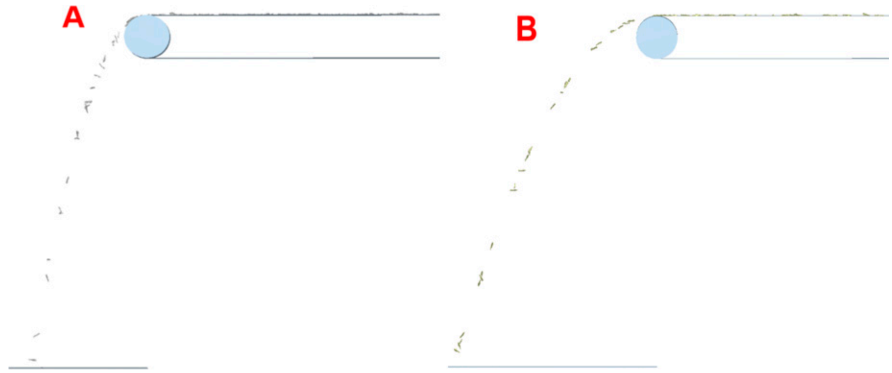

Fig. 7. The trajectory of fresh tea leaves thrown by one bud with one leaf under different transmission speeds. (**A**) Conveyor speed of 0.6 m/s. (**B**) Conveyor speed of 1.2 m/s.

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