agriculture

Article

Gradient Cleaning Method of Potato Based on Multi-Step Operation of Dry-Cleaning and Wet Cleaning

Hongguang Yang [1,2], Jianchun Yan [1,2], Hai Wei [1,2], Huichang Wu [1,2], Shenying Wang [1,2,3], Longlong Ji [1], Xiaowei Xu [1] and Huanxiong Xie [1,2,*]

[1] Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs, Nanjing 210014, China; yanghongguang@caas.cn (H.Y.); yanjianchun@caas.cn (J.Y.); weihai@caas.cn (H.W.); wuhuichang@caas.cn (H.W.); wangshenying@caas.cn (S.W.); 13176435903@163.com (L.J.); 18853855352@163.com (X.X.)
[2] Key Laboratory of on Site Processing Equipment for Agricultural Products, Ministry of Agriculture and Rural Affairs, Hangzhou 310058, China
[3] College of Biosystems Engineering and Food Science, Zhejiang University, Hangzhou 310058, China
* Correspondence: xiehuanxiong@caas.cn; Tel.: +86-25-8434-6223

Abstract: In view of the poor effectiveness of existing potato cleaning methods in China and reflecting the findings of a research analysis of basic sizes and types of impurities on potato tubers, a gradient cleaning method for potato based on a multi-step dry-cleaning and wet cleaning operation was proposed. The method mainly consists of dry-cleaning and wet cleaning. The dry-cleaning stage, which combines vibration and brushing, could effectively remove impurities such as residual rhizomes, peeled potato skin, and large pieces of soil and crushed stone from the surface of potato tubers. The wet cleaning stage adopts the gradient cleaning method of pre-cleaning, rough cleaning and fine cleaning, which could further remove soil and crushed stone attached to the surface and hidden in the sprout eyes of potato tubers. The optimal parameter combination for the gradient cleaning method was determined as follows. The potato feeding amount was 3 t/h, the speed of the rubber chain rod mechanism was 25 r/min, the speed of the first and third brush roller was 40 r/min, the speed of the second and fourth brush roller was 56 r/min, the moving speed of the immersion mechanism conveying net chain was 0.04 m/s, the speed of the brush roller in the high pressure spray and brush roller combination mechanism was 40 r/min, the ultrasonic power was 1200 W, the ultrasonic frequency was 33 kHz, the bubble intensity was 300 L/min, and the moving speed of the conveying net chain in the ultrasonic and bubble combination mechanism was 0.05 m/s. Taking the impurity removal rate and damage rate of potato tuber as the test indexes, a potato cleaning performance test was carried out under the optimal parameters combination. The results showed that the average impurity removal rate and damage rate of potato tubers were 99.05% and 2.48%, respectively. Additionally, the operational performance fully met the requirements for potato cleaning. This study provides a new method for potato cleaning in China and can also provide a reference for cleaning other root and tuber crops.

Keywords: potato; dry-cleaning; wet cleaning; gradient cleaning method; ultrasonic; bubble; impurity removal rate; damage rate

Citation: Yang, H.; Yan, J.; Wei, H.; Wu, H.; Wang, S.; Ji, L.; Xu, X.; Xie, H. Gradient Cleaning Method of Potato Based on Multi-Step Operation of Dry-Cleaning and Wet Cleaning. *Agriculture* **2021**, *11*, 1139. https://doi.org/10.3390/agriculture11111139

Academic Editor: María Gloria Lobo

Received: 13 October 2021
Accepted: 4 November 2021
Published: 13 November 2021

1. Introduction

Potato (*Solanum tuberosum* L.) is an important crop worldwide and is widely cultivated in China because of its rich nutritional value [1]. According to statistics of the Food and Agriculture Organization of the United Nations (FAO), in 2019, China's potato harvest area was 4.91 million hectares, and the total output was 91.88 million tons, accounting for 28.34% and 24.80% of the world's potato harvest area and total output, respectively, ranking first in the world. Although China is a large potato producer, the level of post-harvest processing mechanization is low, which seriously restricts the development of China's potato industry [2]. In recent years, against the background of the implementation of China's potato main grain strategy and adjustment of crop planting structure, China's mechanized potato production is no longer limited to the two links of planting [3] and harvesting [4] and has gradually extended to post-harvest processing [5,6].

Cleaning is one of the key links in post-harvest primary processing of potato, and its performance has an important impact on the quality of subsequent intensive processing products. At present, mechanized potato cleaning technology is mainly divided into dry-cleaning and wet cleaning according to different operational modes [7]. The dry-cleaning operation is completed using specific equipment without water treatment, which can effectively avoid the perishable problem caused by water immersion of potatoes after cleaning, and can be used for sales of fresh potatoes. Wet cleaning, which is used to complete the impurity cleaning operation with specific equipment and high-pressure water, is mainly used in the field of potato edible processing and intensive processing. Research on mechanized potato cleaning in European countries and the United States has already been initiated and the relevant technical equipment in those countries is relatively mature. The representative companies include Bijlsma Hercules and Tolsma Grisnich in the Netherlands and Vanmark in the United States, which have achieved standardized production [7]. The research on mechanized potato cleaning technology and equipment in China started late and the overall level of development has been low [8,9]. Cai Wei et al. [10] designed a potato cleaning machine based on water jet, and the test results showed that it achieved an average potato cleaning rate of 88.86%. Feng Zhuoran [11] designed a squirrel cage potato cleaning machine, the test results of which showed a potato cleaning rate of 94.95%. Ji Longlong [12] experimentally optimized the parameters of a potato dry-type brush roller cleaning device, which was shown on the basis of test results to have achieved a potato cleaning rate of 91.11%. The research by the above scholars has further advanced the potato cleaning technical equipment in China, but the above methods all use a single mechanism to complete the potato cleaning operation. However, these single cleaning mechanisms and methods have problems such as poor cleaning effectiveness or intensive water consumption. In China, the types of potato processing can be subdivided into potato chip processing, French fries processing, whole powder processing and starch processing. With the rapid development of the potato processing industry in China, the existing cleaning methods cannot meet the needs of potato cleaning, and there is an urgent need for new technologies and methods to replace them.

In view of the above problems, and to provide new technologies and methods that support the potato cleaning and production industry, this study proposes a gradient cleaning method for potato based on a multi-step operation of dry-cleaning and wet cleaning that first performs preliminary cleaning through dry-cleaning and then performs fine cleaning through multi-step wet cleaning.

2. Materials and Methods

2.1. Determination of Basic Sizes and Types of Potato Tuber Impurities

The three-dimensional size of potato tubers and the types of impurities contained in potato tubers have an important influence on the selection of cleaning methods and the design of cleaning mechanisms. The basic sizes and types of impurities of potato tubers were determined. The potato samples originated from Yancheng City, Jiangsu Province, China, the variety was Netherlands No. 15, and the harvest season ranges from May to June every year. The potato tuber moisture content was 80.12%, and the moisture content in impurities of soil and crushed stone was 9.23%.

The three-dimensional length, width, and height of 100 potato tubers, as shown in Figure 1, were measured with a digital vernier caliper (Model: MNT-150T, manufacturer: Shanghai meinaite Industrial Co., Ltd., measurement accuracy: 0.01 mm). Ten potatoes were randomly selected as a group to determine their types of impurities and mass ratio with an electronic balance (Model: HC60001XG, manufacturer: Shanghai Huachao Electric Appliance Co., Ltd., China, measurement accuracy: 0.1 g).

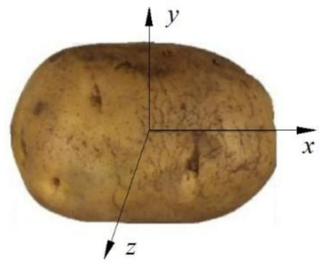


Figure 1. Schematic diagram of three-dimensional size. Note: the x axis represents the length direction, the y axis represents the height direction, and the z axis represents the width direction.

2.2. Overall Process Flow and Selection of Key Operation Parameters for Cleaning Method

2.2.1. Overall Process Flow of Cleaning Method

The gradient cleaning method is carried out through dry-cleaning and wet cleaning equipment. Firstly, dry-cleaning equipment is used to remove impurities such as peeled potato skin, residual rhizome and large pieces of soil and crushed stone on the surface of potato tubers. Then, the wet cleaning equipment is used to remove the soil and crushed stone attached to the surface and hidden in the sprout eyes of potato tubers after the dry-cleaning operation through a multi-step operation of pre-cleaning, rough cleaning and fine cleaning. The dry-cleaning and wet cleaning combination can effectively solve the problem of low impurity removal rates in potato cleaning. The overall process flow of the gradient cleaning method for potato is shown in Figure 2.

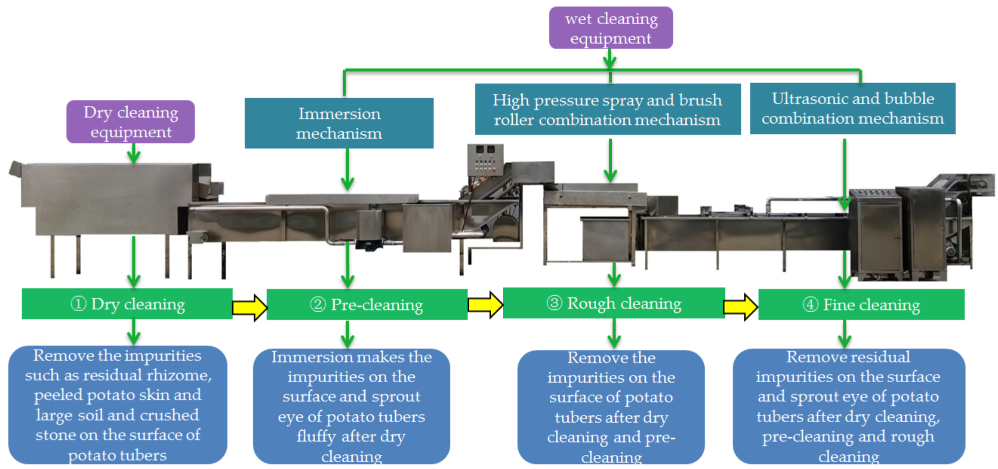


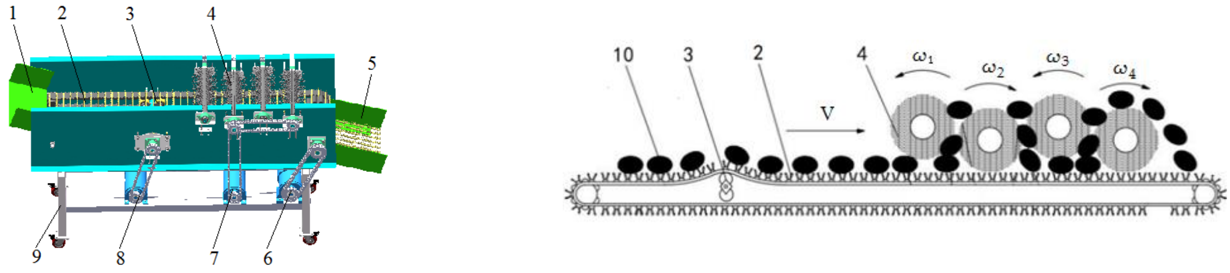
Figure 2. Overall process flow of cleaning method.

2.2.2. Constructional Features, Operating Principle, and Parameters Selection of Dry-Cleaning Equipment

(1) Constructional features and operating principle

As shown in Figure 3a, in light of the potato tubers three-dimensional size and its characteristics of mainly containing impurities such as residual rhizomes, peeled potato skin and soil and crushed stone, the dry-cleaning equipment is mainly composed of a feed port, a rubber chain rod mechanism, shaking mechanism, four groups of brush roller mechanism, a drive system, and a discharge port. The equipment can be used to complete the impurity removal of potato tubers independently and it can be arranged in front of the wet cleaning equipment for impurity removal by combined types. The overall dimension of dry-cleaning equipment (length × width × height) is 2810 × 830 × 1450 mm. Among them, the rubber chain rod mechanism adopts a flexible rubber finger with an effective working width of 470 mm. The shaking mechanism adopts a double wheel eccentric type.

The four groups of brush roller mechanisms adopt flexible long nylon brush wire, and the brush wire length is 50 mm.



(**a**) (**b**)

Figure 3. Constructional features and operating principle of dry-cleaning equipment; 1. Feed port; 2. Rubber chain rod mechanism; 3. Shaking mechanism; 4. Four groups of brush roller mechanism; 5. Discharge port; 6. Drive system of the rubber chain rod mechanism; 7. Drive system of the four groups of brush roller mechanisms; 8. Drive system of the shaking mechanism; 9. Frame; 10. Potato. (**a**) Structure of dry-cleaning equipment; (**b**) Principle of dry-cleaning equipment. Note: the ω_1, ω_2, ω_3, ω_4 is the rotation direction of brush roller, and V is the movement direction of potatoes and rubber chain rod mechanism.

As shown in Figure 3b, the dry-cleaning equipment adopts the principle vibration and brushing combination. The working process can be divided into two stages. The first is mainly to remove some impurities mixed in potatoes, and the second is mainly to remove impurities attached to the surface of potato tubers. The specific working principle is that the mixture of potatoes and impurities falls into the rubber chain rod mechanism through the feed port and the soil blocks, crushed stone and other large particle impurities are removed under the joint action of the rubber chain rod mechanism and shaking mechanism. Then, the potatoes continue to move forward under the joint action of the four groups of the brush roller mechanism and rubber chain rod mechanism. The impurities attached to the surface of potato tubers can be removed by the circumferential rolling brushing operation. Finally, the cleaned potato is output from the discharge port.

(2) Parameter selection

The potato feeding amount, and both the speed of the rubber chain rod mechanism and the brush roller, have great influence on the effectiveness of dry-cleaning. Through simulation and experimental verification, the single factor test was carried out. The conditions of the test included a potato feeding amount of 3 t/h, 4 t/h and 5 t/h, a rubber chain rod mechanism speed of 15 r/min, 25 r/min and 35 r/min, the speed of the first and third brush rollers of 30 r/min, 40 r/min and 50 r/min, and the speed of the second and fourth brush rollers of 42 r/min, 56 r/min and 70 r/min. Through this process, the test analyzed the force, collision characteristics and cleaning quality of potatoes during cleaning operation [13].

2.2.3. Constructional Features, Operating Principle, and Parameters Selection of Wet Cleaning Equipment

(1) Constructional features and operating principle

Because the dry-cleaning operation removal rate of impurities attached to the surface and hidden in the sprout eye of potato tubers is poor, the impurities of potatoes after the operation of dry-cleaning equipment are mainly concentrated on the attached soil on the surface and the hidden soil and crushed stone in the sprout eyes. According to these characteristics, the structure of wet cleaning equipment is determined as shown in Figure 4, which is mainly composed of the water immersion mechanism, high pressure spray and the brush roller combination mechanism, and the ultrasonic and bubble combination mechanism. The immersion mechanism is composed of conveying net chain and immersion tank. The high-pressure spray and brush roller combination mechanism is composed of short filament brush roller, high pressure spray assembly and water tank. The ultrasonic and bubble combination mechanism is mainly composed of an ultrasonic vibration plate, ultrasonic generator and bubble spray tube assembly.

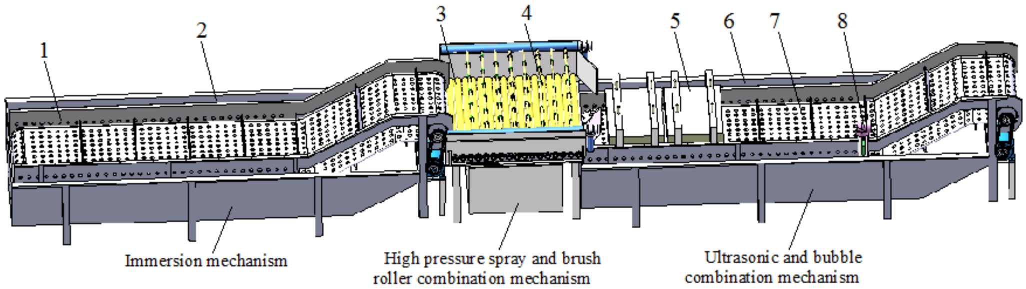


Figure 4. Constructional features and operating principle of wet cleaning equipment. 1. Conveying net chain of immersion mechanism; 2. Immersion tank; 3. Short filament brush roller; 4. High pressure spray assembly; 5. Ultrasonic vibration plate; 6. Cleaning tank; 7. Conveying net chain of ultrasonic and bubble combination mechanism; 8. Bubble spray tube assembly.

The wet cleaning equipment adopts the method of pre-cleaning, rough cleaning, and fine cleaning to remove the residual impurities on the potato tubers. The specific working principle was that once the potatoes enter the immersion mechanism after dry-cleaning the impurities on the surface, the sprout eyes will become fluffy through the water immersion operation. Secondly, the potatoes entered the high-pressure spray and brush roller combination mechanism to roughly clean the impurities on the surface under the joint action of high-pressure water spray and brush rotation. Then, the potatoes entered the ultrasonic and bubble combination mechanism for fine cleaning, in order to remove the residual impurities on the surface and sprout eyes through ultrasonic cavitation and bubble scouring. Finally, the cleaned potatoes fell into the collection basket from the outlet.

The overall dimension of wet cleaning equipment (length $\times$ width $\times$ height) is 11,550 $\times$ 1780 $\times$ 1850 mm. On the basis of the structural size of the whole machine and the actual operation requirements, the length of the immersion mechanism is 4 m, and the width is 0.8 m. According to the structural form and size of the brush roller of the existing high-pressure spray and brush roller combined cleaning machine, the working length of the high-pressure spray and brush roller combined mechanism is designed to be 1.5 m, and the brush roller eqipment is mainly composed of 22 short brush rollers with a diameter of 65 mm. The ultrasonic cleaning and bubble cleaning of the combination mechanism share the same cleaning tank. Based on the impurity containing characteristics of rough cleaned potato tubers, in order to facilitate processing, the length of the cleaning tank was 4 m, and the width is 0.8 m.

At the same time, according to the structure of the cleaning tank and the conveying net chain, in order to ensure the fluidity of potatoes and avoid the influence of the conveying net chain on the ultrasonic cavitation effect, the ultrasonic vibration plate adopted the top vibration installation mode. The vertical distance (H) between the bottom surface of the vibration plate and the upper surface of the conveying net chain was 13 cm.

(2) Parameter selection

The key working parameters of the immersion mechanism, high pressure spray and brush roller combination mechanism, and the ultrasonic and bubble combination mechanism of wet cleaning equipment were determined through further experiment.

1. Selection of key parameters of immersion mechanism

The movement speed of the immersion mechanism conveying the net chain, namely the immersion time, was the key operation parameter affecting the immersion quality. As shown in Figure 5, selecting potatoes with more than 90% of the surface covered with impurities was the research object. When there were still two or more impurities with a size of more than 1.5cm in a potato tuber after cleaning, it was regarded as unclean. Comparing the high-pressure spray and brush roller combined cleaning after immersion in the water to measure the different effects. At the same time, the cleaning effectiveness of the high-pressure spray and brush roller under different immersion time of 30 s, 60 s, 90 s and 120 s were studied.

Figure 5. Test object of immersion cleaning.

2. Selection of key parameters of high-pressure spray and brush roller combination mechanism

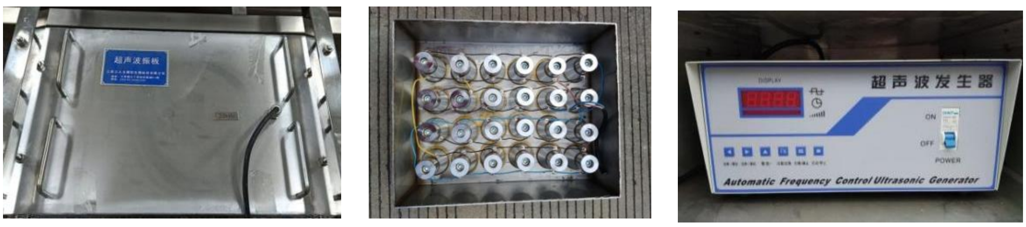
According to relevant research [14,15], the speed of the brush roller in the high-pressure spray and brush roller combination mechanism is the key factor. Therefore, taking the potatoes after immersion as the object, the combined cleaning effects of high pressure spray and brush roller under the conditions of brush roller speed of 30 r/min, 40 r/min and 50 r/min were studied.

3. Selection of key parameters of ultrasonic and bubble combination mechanism

The ultrasonic and bubble combination mechanism is mainly composed of ultrasonic cleaning and bubble cleaning. During the operation, it is first treated to make the residual impurities on the surface and in the sprout eyes by ultrasonic, and then cleaned by bubbles.

(a) Selection of key parameters of ultrasonic cleaning equipment

The ultrasonic cleaning was mainly composed of an ultrasonic vibration plate and generator [16]. The residual impurities on the surface and in the sprout eyes were made fluffy by the ultrasonic cavitation [17]. Based on the application status of ultrasonic in cleaning, the selected ultrasonic vibration plate and generator is shown in Figure 6. Among them, the ultrasonic vibration plate is composed of 24 oscillators with a power of 50 W. If increasing or decreasing 150 W each time through the keys on the panel, the ultrasonic generator will be adjusted along with the power.



(**a**) (**b**) (**c**)

Figure 6. Ultrasonic vibration plate and generator. (**a**) Ultrasonic vibration plate; (**b**) Ultrasonic vibrator. (**c**) Ultrasonic generator.

The frequency, the power, and the cleaning time of ultrasonic have an important influence on cleaning quality [18–20]. As shown in Figure 7, using the aluminum foil corrosion [21] for testing, the ultrasonic cavitation effects at the bottom of the ultrasonic vibration plate, under the conditions of frequencies of 20 kHz, 33 kHz and 50 kHz, generates a power of 1200 W and cleaning time of 1 min. Under the same conditions the testing effects were 5 cm away from the bottom of the vibration plate and 10 cm, respectively.

Under the conditions of 33 kHz frequencies, the cleaning effects of rough cleaned potatoes in 20 s, 40 s and 1 min was compared.

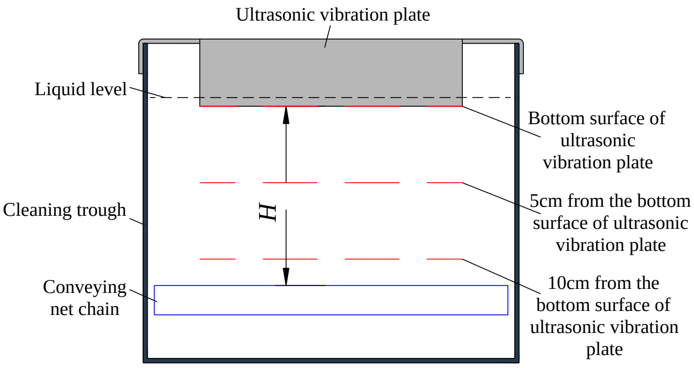
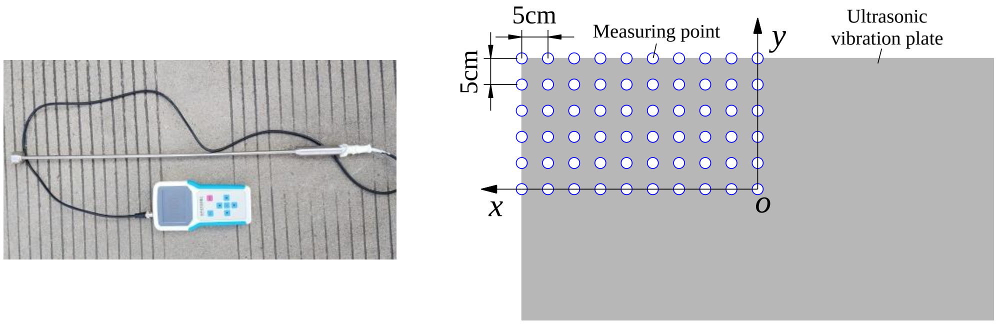


Figure 7. Schematic of position relationship of ultrasonic cleaning.

At the same time, based on the adjustment range of the ultrasonic generator, the aluminum foil corrosion on the bottom position of the vibration plate was used. Under the frequency of 33 kHz, the influence of power on the ultrasonic cavitation when the generator power was in the range of 300–1200 W in 40 s was determined.

In order to explore the sound field distribution between the ultrasonic vibration plate and the conveying net chain, the digital ultrasonic sound intensity measuring instrument (Figure 8a) was used for testing the sound intensity on the bottom surface of the vibration plate, 5 cm away from the bottom surface of the vibration plate and 10 cm respectively, under the conditions of 33 kHz frequency of the ultrasonic vibration plate and the 1200 W power of the generator. As shown in Figure 8b, where the quarter plane of the ultrasonic vibration plate is measured [22], the side length of the effective range was 45 × 25 cm, and a dot was placed at an interval of 5 cm on each side. Finally, a total of 60 points were measured.



(**a**) (**b**)

Figure 8. Ultrasonic sound intensity measurement. (**a**) Ultrasonic sound intensity measuring instrument; (**b**) Distribution of sound intensity measurement points.

(b) Selection of key parameters of the bubble cleaning equipment

The bubble cleaning equipment is composed of a bubble nozzle device and an air pump. It mainly uses high pressure air flow to the water in the cleaning tank to produce bubbles, and then roll the water to clean the potatoes. In this process, the cleaning quality is affected significantly by the bubble strength (gas flow) and cleaning time. Concerning the types of impurities after rough cleaning and ultrasonic cleaning, the two parts share a cleaning tank and therefore cannot achieve good cleaning when the bubble intensity is small, while the ultrasonic cavitation effect will be ruined if the intensity is too large. Therefore, in light of previous studies on bubble strength during cleaning operations [23,24], taking the impurity containing potatoes after rough cleaning and ultrasonic treatment as the research object, this method was compared with the effect under the conditions of bubble strength of 250 L/min, 300 L/min and 350 L/min.

2.3. Gradient Cleaning Test of Potato

2.3.1. Test Conditions

The gradient cleaning test was conducted from 28 October to 5 November 2020, in Jiangsu Li gong fruit and vegetable Machinery Co., Ltd. (Address: No. 6, Nanshan Road, Xinghua City, Jiangsu Province, China). The basic parameters and types of impurities in the test were similar to those of the above measured potato tubers. The test instruments and equipment mainly included gradient cleaning equipment of potato (Developed by the author's team), ultrasonic sound intensity measuring instrument (Model: GBS-UEC300P, manufacturer: Beijing Zhongxi Yuanda Technology Co., Ltd., measurement accuracy: 0.1%), electronic tachometer (Model: FLUKE931, manufacturer: Fluke testing instruments (shanghai) co., ltd., measurement accuracy: +0.02%), electronic platform scale (Model: TCS, manufacturer: Zhejiang Jinhua Nantian post and Telecommunications Equipment Manufacturing Co., Ltd., China, measurement accuracy: 0.01 kg).

2.3.2. Test Factors and Indicators

(1) Test factors

During the test, the main operating parameters of dry-cleaning and wet cleaning equipment were obtained from previous research, together with the test optimization in this paper. Specifically, the potato feeding amount was 3 t/h. In the dry-cleaning, the speed of the rubber chain rod mechanism was 25 r/min, the speed of the first and third brush roller was 40 r/min, and the second and fourth was 56 r/min. In the wet cleaning, the moving speed of the immersion mechanism conveying net chain was 0.04 m/s, the speed of brush roller in the high pressure spray and brush roller combination mechanism was 40 r/min, the ultrasonic power is 1200 W, the ultrasonic frequency is 33 kHz, the bubble intensity was 300 L/min, and the moving speed of the conveying net chain in the ultrasonic and bubble combination mechanism was 0.05 m/s.

(2) Test indicators

According to the requirements for impurity and mechanical damage indexes in the grading of commercial potatoes, as stipulated in the Chinese national standard code of practice for the grading and inspecting of commercial potatoes: GB/T 31784-2015 [25], the performance test was carried out with the impurity removal and damage rate of potato tubers. Based on the relevant contents of identification standard for the vegetable washing machine: DG/T 125—2019 [26], it is defined that the impurity removal rate of potato tuber is the percentage of the weight of potato cleaned after the cleaning equipment operation among the sampled potato. When the cleaning equipment began, the potato tubers with more than 1.0 cm impurities diameter and less than 2 sides were cleaned. The damage rate of potato tubers is defined as the percentage of mechanical damage potatoes in the sampled after the cleaning equipment operation. The mechanical damage is defined as the damaged potato interior or if the potato tuber skin has scratches of more than 1.5 cm, or the area of a single scratch and skin breaking point exceeds 200 mm^2. The calculation equations of impurity removal rate T_1 and damage rate T_2 of potato tubers are as follows:

$$T_1 = \frac{M - M_1}{M} \times 100\% \tag{1}$$

$$T_2 = \frac{M_2}{M} \times 100\% \tag{2}$$

Among them, M is the weight of potato samples, kg; M_1 is the weight of uncleaned potatoes, kg; M_2 is the weight of potatoes with new mechanical damage, kg.

2.3.3. Test Methods

During the test, three samples were taken at equal intervals at the discharge port of the cleaning equipment, and the weight of each sample was about 50 kg. In each sample received, the uncleaned potatoes with new mechanical damage were picked manually. Then, they were weighed respectively and the impurity removal rate and damage rate of potato tuber were calculated according to Equations (1) and (2). The average value of three tests were taken as the final result. Figure 9 shows the test equipment of dry-cleaning and wet cleaning.

Figure 9. Equipment of cleaning test.

3. Results

3.1. Determination of Basic Sizes and Types of Potato Tubers Impurities

As shown in Figure 10, the value and range of three-dimensional potato tubers are displayed. The length of the potato tubers ranges from 90 to 120 mm, accounting for 76% of the statistical quantity. The average value of the length direction is 105.58 mm, and the standard deviation is 12.87. The width ranges from 55 to 85 mm, accounting for 88% of the statistical quantity. The average value of the width direction is 71.19 mm, and the standard deviation is 9.88. The height ranges from 45 to 75 mm, accounting for 88% of the statistical quantity. The average value of the height direction is 63.04 mm, and the standard deviation is 8.74.

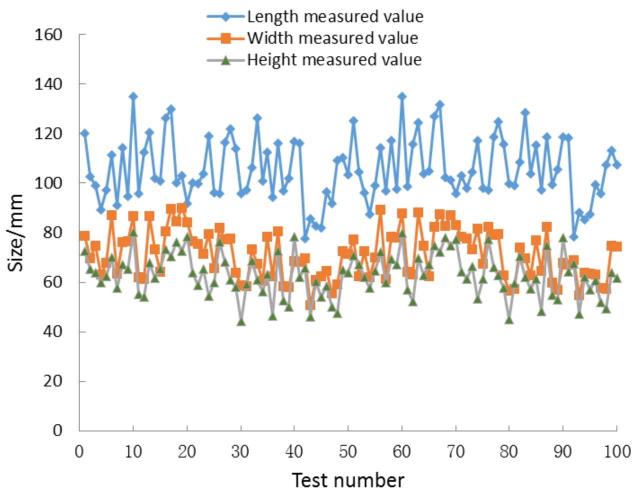


Figure 10. Three-dimensional size of potato tubers.

As shown in Figure 11a, potato tubers mainly contain impurities such as residual rhizome, peeled potato skin and soil and crushed stone. The proportion of various impurities contained in potato tubers are shown according to their weight in Figure 11b. Among them, soil and crushed stone mostly account for about 85%.

(**a**) (**b**)

Figure 11. Type and proportion of impurities in potato tubers. (**a**) Type of impurities; (**b**) Proportions of impurities.

3.2. Selection of Key Operation Parameters of Cleaning Method

3.2.1. Parameter Selection of the Dry-Cleaning Equipment

According to the parameter optimization test of dry-cleaning equipment conducted by the author's research group in the early stage [13], it was obtained that the potato cleaning quality of dry-cleaning equipment is better when the potato feeding amount is 3 t/h, the speed of the rubber chain rod mechanism is 25 r/min, the speed of the first and third brush roller is 40 r/min, and the second and fourth brush roller is 56 r/min. This provides a foundation for the selection of operation parameters of dry-cleaning equipment in the follow-up test of this study.

3.2.2. Parameter Selection of Wet Cleaning Equipment

(1) Selection of key parameters of immersion mechanism

Tests have proved a cleaning rate of more than 10% after water immersion compared to no water. Additionally, the results show that immersion time has an important influence on cleaning effectiveness. In the test range, the more time spent on immersion, the higher the corresponding cleaning rate. In light of factors such as the productivity of the whole machine and the influence of too long immersion time on the quality of potato tubers, the optimal immersion time was finally selected as 90 s. At this time, the movement speed of the immersion mechanism conveying net chain is 0.04 m/s.

(2) Selection of key parameters of high-pressure spray and brush roller combination mechanism

The results show that the cleaning quality is best when the speed of the brush roller is 30 r/min, but the efficiency is low. When it is 50 r/min, the tubers surface could not be fully cleaned because the potatoes moved too fast, and the cleaning effect is poor; When it is 40 r/min, the cleaning effect is better, and the operation efficiency also meets the requirements. Therefore, the speed of the brush roller is finally selected as 40 r/min. At the same time, as shown in Figure 12, the types of impurities of potato tubers cleaned by high pressure spray and brush roller combination mechanism are mainly concentrated at both end faces and sprout eyes, which provides a basis for the study of subsequent fine cleaning.

(3) Selection of key parameters of ultrasonic and bubble combination mechanism

a. Selection of key parameters of ultrasonic cleaning equipment

In terms of the ultrasonic frequency, the results show that the corrosion of aluminum foil is relatively uniform under the action of 33 kHz. In terms of the ultrasonic power, it shows that the sound field is strong under the action of 1200 W. In terms of the ultrasonic cleaning time, the results reflect that the impurities at the end face and sprout eye of potato tubers become fluffier when the ultrasonic action time is 40 s. Even if the ultrasonic action time is increased, the effect on stubborn impurity is not obvious. Therefore, the optimal ultrasonic frequency, power and cleaning time are 33 kHz, 1200 W and 40 s, respectively.

Additionally, the ultrasonic sound intensity measurement results are shown in Figure 13. The results show that the ultrasonic sound intensity is in the range of 0.30~0.55 w/cm^2, and the overall distribution is relatively uniform, which can meet the needs of potato cleaning.

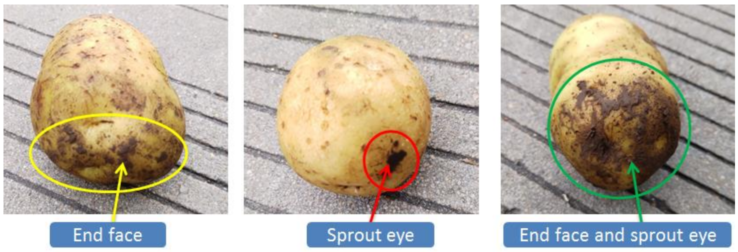


Figure 12. Characteristics of impurity in potato tubers after pre-cleaning and rough cleaning.

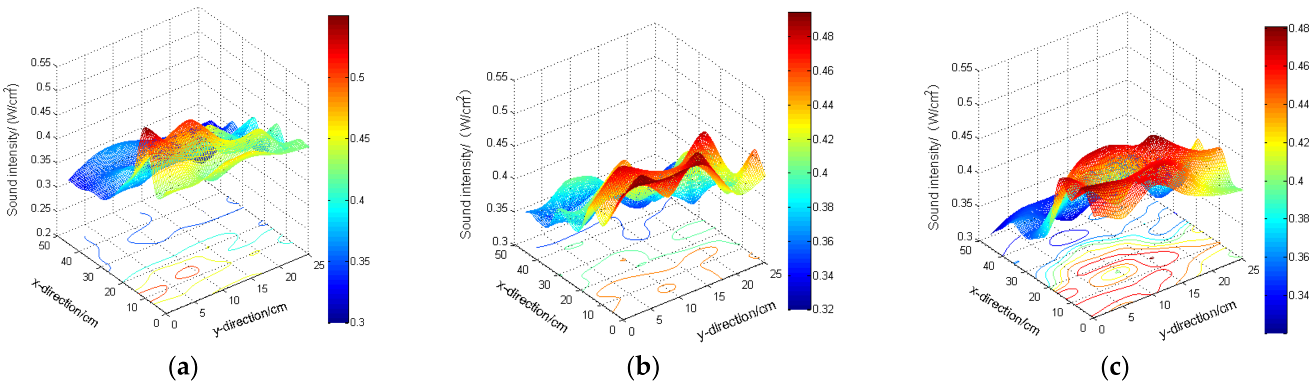


Figure 13. Ultrasonic sound intensity distribution. (**a**) Bottom surface of ultrasonic vibration plate; (**b**) 5 cm from the bottom surface of ultrasonic vibration plate; (**c**) 10 cm from the bottom surface of ultrasonic vibration plate.

b. Selection of key parameters of bubble cleaning equipment

The results show that when the bubble strength is 300 L/min, the residual impurities of potato tubers have been cleaned basically. For some impurities that have not been cleaned off, it is still unable to wash off them by continuously increasing the bubble strength. Therefore, the bubble strength is finally selected as 300 L/min. At the same time, since ultrasonic cleaning and bubble cleaning share a set of conveying net chains, in order to realize the effective connection and matching of the two parts, the cleaning time of the bubble eqipment is 40 s. At this time, the movement speed of the conveying net chain in the ultrasonic and bubble combination mechanism is 0.05 m/s.

3.3. Gradient Cleaning Test of Potato

The gradient cleaning process of potatoes is shown in Figure 14. The potato tubers are subjected to the process of vibrating chain rod and dislocation brush roller dry-cleaning, water immersion pre-cleaning, high pressure spray and brush roller rough cleaning, and ultrasonic and bubble fine cleaning. The results are shown in Table 1. According to the results, the average impurity removal rate and damage rate of potato tubers were 99.05% and 2.48% respectively, which can fully satisfy the requirements of potato cleaning operations in China.

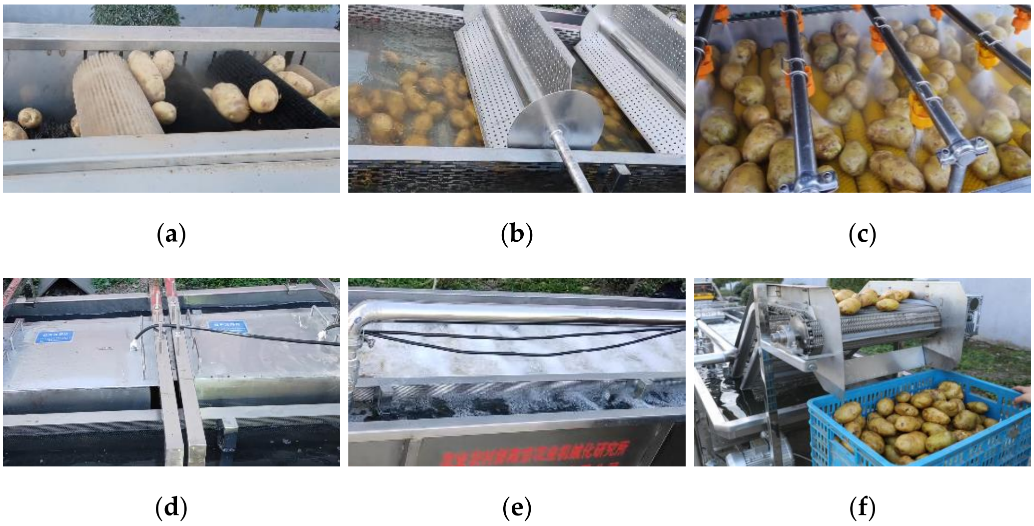


Figure 14. The gradient cleaning process of potato. (**a**) Dry-cleaning; (**b**) Pre-cleaning; (**c**) Rough cleaning; (**d**) Fine cleaning of ultrasonic; (**e**) Fine cleaning of bubble; (**f**) Cleaning effect.

Table 1. Results of cleaning test.

Test No.	Impurity Removal Rate/%	Damage Rate/%
1	99.13	2.25
2	99.36	2.71
3	98.67	2.49
Mean	99.05	2.48

4. Discussion

In China, the potatoes of post-harvest are mainly divided into fresh food (for cooking) and processing according to their uses [25]. Both of them need cleaning [7]. Because the edible parts (tuber) of a potato grows under the soil, it is easy for them to suffer a large number of impurities after harvest. Additionally, the shape and size of potato tubers are different, making them difficult to clean mechanically. The existing potato cleaning methods in China commonly use a single mechanism, such as a water jet [10], squirrel cage [11] and a dry brush roller [12]. However, these methods have many problems such as poor cleaning effect or large water consumption, which cannot meet the needs of production and water resource conservation [8,9]. In consideration of the requirements of high impurity removal rate of raw potato for processing products such as potatoes, fresh-cut vegetables, potato chips, potato flakes and starch in China, this study proposed a gradient cleaning method of potato. The potato cleaning operation is carried out by the combination of dry-cleaning and wet cleaning.

Compared with the water jet, squirrel cage and dry brush roller cleaning structures, the gradient cleaning method proposed in this study can improve the cleaning effect and reduce damage and water consumption effectively. During the test, the dry-cleaning link was able to effectively remove impurities such as residual rhizomes, peeled potato skin, large pieces of soil and crushed stone of potato tubers [13]. Through multi-step cleaning, the wet cleaning link is used to remove the impurities attached to the surface and hidden in the sprout eyes which are uncleaned by dry-cleaning [7]. For potato cleaning, short-term cleaning cannot ensure the effectiveness, and long-term cleaning will put the potato in contact with the brushing mechanism continually, damaging tubers' skin [9]. In this study, the dry-cleaning link can pave the way for wet cleaning, and most impurities can be cleaned in advance by combining vibration and brushing, which can not only effectively reduce the burden of wet cleaning and improve the final cleaning effect, but also reduce the discharge of high concentration wastewater [10,11]. Additionally, because the key components of each operation mechanism adopt flexible rubber and nylon brush wire, it will have little impact damage on potato tubers.

In the general, while the gradient cleaning method proposed in this study includes many operation links, compared with a single cleaning mechanism, it can effectively remove the large particle impurities contained in the potato tubers and reduce the burden for the subsequent wet cleaning by the dry-cleaning. Practice has proved that cleaning efficiency and quality can be significantly improved when large particle impurities are removed by dry-cleaning and then cleaned by wet cleaning.

In the follow-up, we will further take other root and tuber crops such as sweet potato, carrot, and white radish as the test objects, to test the cleaning effect and quality of the gradient cleaning method proposed in this study on different crops, so that this technical method can be better popularized and applied.

5. Conclusions

This study proposed a gradient cleaning method of potato based on multi-step operation. The method was carried out through dry-cleaning and wet cleaning, respectively. Firstly, dry-cleaning was used to remove impurities such as peeled potato skin, residual rhizome and large pieces of soil and crushed stone contained in the potatoes. Then, wet cleaning was used to remove the impurities attached to the surface and hidden in the sprout eye of potato tubers.

According to the previous research and the parameter optimization test, the optimal parameter combination of the gradient cleaning method is obtained as follows. The potato feeding amount is 3 t/h, the speed of the rubber chain rod mechanism is 25 r/min, the speed of the first and third brush roller is 40 r/min, the speed of the second and fourth brush roller is 56 r/min, the moving speed of immersion mechanism conveying net chain is 0.04 m/s, the speed of the brush roller in the high pressure spray and brush roller combination mechanism is 40 r/min, the ultrasonic power of 1200 W, the ultrasonic frequency of 33 kHz, the bubble intensity of 300 L/min, and the moving speed of the conveying net chain in the ultrasonic and bubble combination mechanism is 0.05 m/s. The results of cleaning test under the optimal parameter combination showed that the average impurity removal rate is 99.05% and the average damage rate is 2.48%, which can meet the relevant needs of potato cleaning.

Author Contributions: Conceptualization, H.Y. and J.Y.; methodology, H.Y., J.Y. and H.W. (Hai Wei); software, H.W. (Huichang Wu) and L.J.; validation, H.X., S.W. and X.X.; formal analysis, H.Y. and J.Y.; investigation, H.Y., J.Y., S.W. and H.W. (Hai Wei); resources, H.Y. and J.Y.; data curation, H.Y. and J.Y.; writing—original draft preparation, H.Y., J.Y. and S.W.; writing—review and editing, H.Y., J.Y. and S.W.; visualization, H.Y., L.J. and J.Y.; supervision, H.W. (Huichang Wu) and H.X.; project administration, H.Y.; funding acquisition, H.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Key Research and Development Program of China, grant number 2018YFD0700102; Key Laboratory of on Site Processing Equipment for Agricultural Products, Ministry of Agriculture and Rural Affairs, P.R. China, grant number 2011NYZD2001; Central Public-interest Scientific Institution Basal Research Fund, grant number S202110-02; China Postdoctoral Science Foundation, grant number 2020M681690.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on-demand from the first author at (yanghongguang@caas.cn).

Acknowledgments: The authors would like to acknowledge Jiangsu Ligong fruit and vegetable Machinery Co., Ltd. for providing the test site for this study and the help in the test process.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Xu, N.; Zhang, H.L.; Zhang, R.H.; Xu, Y.K. Current situation and prospect of potato planting in China. *Chin. Potato J.* **2021**, *35*, 81–96.
2. He, J.Y. Status quo and suggestions of China's potato industry development. *Agric. Outlook* **2020**, *16*, 34–39.
3. Li, Z.H.; Wen, X.Y.; Lv, J.Q.; Li, J.C.; Yi, S.J.; Qiao, D. Analysis and prospect of research progress on key technologies and equipments of mechanization of potato planting. *Trans. CSAM* **2019**, *50*, 1–16.
4. Yang, H.G.; Hu, Z.C.; Wang, B.; Peng, B.L.; Wang, G.P. Research progress of harvesting mechanization technology of potato. *J. Chin. Agric. Mech.* **2019**, *40*, 27–34. [CrossRef]
5. Wang, X.Y.; Sun, J.B.; Xu, Y.C.; Li, X.Q.; Cheng, P.F. Design and experiment of potato cleaning and sorting machine. *Trans. CSAM* **2017**, *48*, 316–322.
6. Lv, J.Q.; Yu, J.Y.; Feng, X.; Li, Z.H.; Li, J.C.; Liu, Z.Y. Design and experiment of roller potato grading machine. *Trans. CSAM* **2019**, *50*, 323–332.
7. Yang, H.G.; Xie, H.X.; Yan, J.C.; Wei, H.; Wang, H.O.; Zhang, H.J. Overview of mechanized cleaning technology of post-harvest potato. *J. Chin. Agric. Mech.* **2020**, *41*, 115–120.
8. Bai, L.; Chen, X.; Sun, J.; Zhang, X.Y. Development of potato processing industry in China from perspective of industrial integration. *Trans. CSAE* **2019**, *35*, 316–322.
9. Ji, L.L.; Xie, H.X.; Yan, J.C.; Wei, H.; Yang, H.G. Research status and prospect of potato cleaning equipment. *J. Chin. Agric. Mech.* **2020**, *41*, 98–104.
10. Cai, W.; Zhang, Y.; Liang, D. Mechanical design and test based water jet potato cleaning. *J. Agric. Mech. Res.* **2013**, *35*, 169–172.
11. Feng, Z.R. Design and Experimental Study of Cleaning Machine of the Squirrel Cage Potato. Master's Thesis, Gansu Agricultural University, Lanzhou, China, 2018.
12. Ji, L.L. Experiment and Optimization of Potato Dry-Type Brush Roller Cleaning Device. Master's Thesis, Chinese Academy of Agricultural Sciences, Beijing, China, 2021.
13. Ji, L.L.; Xie, H.X.; Yang, H.G.; Wei, H.; Yan, J.C.; Shen, H.Y. Simulation analysis of potato dry soil cleaning device based on EDEM-Recurdyn coupling. *J. Chin. Agric. Mech.* **2021**, *42*, 109–115.
14. Wang, L.; Chen, Q.C. Experimental study on cleaning cherry tomatoes with submerged jets mechanism. *Trans. CSAE* **2007**, *23*, 86–90.
15. Mulugeta, E.; Geyer, M. Characterising the washing processes of vegetables and potatoes. *Biosyst. Eng.* **2005**, *91*, 441–453. [CrossRef]
16. Wang, H.O.; Hu, Z.C.; Wu, F.; Cao, S.F.; Xie, H.X.; Zhong, T. Design and test of ultrasonic ozone combined fruit and vegetable cleaner. *Trans. CSAM* **2011**, *42*, 165–169.
17. Sam, L.H.; Son, T.A. A study on application of ultrasonic wave and ozone micro-bubbles in leafy vegetables washing. *Key Eng. Mater.* **2020**, *963*, 79–84. [CrossRef]
18. Ma, H.L.; Sun, B.S.; He, R.H.; Luo, L.; Zhen, B.W. Process optimization of dimethoate pesticide degradation by ultrasound in aqueous solution. *Trans. CSAM* **2012**, *43*, 169–173.
19. Ma, S.H.; Zhang, X.J. Working parameters optimization of ultrasonic cleaning machine for jujube. *Trans. CSAE* **2012**, *28*, 215–220.
20. Roknul Azam, S.M.; Ma, H.L.; Xu, B.G.; Devi, S.; Bakar Siddique, M.A.; Stanley, S.L.; Bhandari, B.; Zhu, J.S. Efficacy of ultrasound treatment in the removal of pesticide residues from fresh vegetables: A review. *Trends Food Sci. Technol.* **2020**, *97*, 417–432. [CrossRef]
21. Wang, X.H.; Mao, H.L.; Huang, Z.F. Measurement of cavitating intensity in a washing trough under the effect of ultrasonic wave. *Appl. Acoust.* **2005**, *24*, 188–191.
22. Wang, H.O.; Hu, Z.C.; Wang, J.N.; Wu, F.; Xie, H.X.; Lv, X.L. Effects of connection mode between transducer and tank on ultrasonic field distribution. *Trans. CSAE* **2011**, *27*, 26–31.
23. Ding, X.M.; Wang, L. Study on washing vegetables with air bubble flow washer. *J. Agric. Mech. Res.* **2007**, *12*, 119–123.
24. Yang, H.B.; Ding, W.M.; Chen, K.J.; Li, Y.N.; Wang, H.P. Research and development of a new-style washer of vegetable. *Trans. CSAE* **2005**, *21*, 92–96.
25. Standardization Administration of China. *Code of Practice for Grading and Inspecting of Commercial Potatoes: GB/T 31784-2015*; Standards Press of China: Beijing, China, 2015.
26. Ministry of Agriculture and Rural Affairs of the People's Republic of China. *Vegetable Cleaning Machine: DG/T 125-2019*; Standards Press of China: Beijing, China, 2019.