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Review

Current Flaxseed Dehulling Technology in China

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Abstract: With the improvement in living standards and growing appreciation for flaxseed's nutritional value, global demand for flaxseed and its economic significance are continuously increasing. As a major flaxseed producer and exporter, China plays a crucial role in the development of its agricultural economy. Flaxseed, one of China's five key oil crops, is renowned for its rich nutritional content. This study employed a literature review to systematically examine the research status of key flaxseed dehulling technologies in China. It explored the characteristics, efficiencies, and quality differences among various dehulling methods, while also drawing on advanced techniques, such as chemical and ultrasonic dehulling, to provide new perspectives and theoretical support for flaxseed dehulling. Comprehensive analysis revealed that mechanical dehulling (the impact method and rolling and rubbing method) is the primary method used in China. The study also identified the issues in current flaxseed dehulling research in China and offers suggestions to guide future improvements and innovations in flaxseed processing, aiming to enhance the quality and nutritional value of flaxseed to meet diverse market demands.

Keywords: *Linum usitatissimum* L.; dehulling; research progress; development trends

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1. Introduction

Flax is a category within the Linaceae family, taxonomically divided into five genera: Linum, Dasylinum, Syllinum, Linastrum, and Cathartolinum. Flaxseed is the seed of the flax plant (*Linum usitatissimum* L.) belonging to the Linaceae family. Flax is mainly divided into oil flax, fiber flax, and dual-use flax (oil and fiber) categories, with resistance to barrenness, cold, and drought, high value, and other characteristics [1]. It is mainly produced in the United States, Canada, India, and China [2,3]. In recent years, China's flax sowing area has expanded, with an average annual sowing area of about 3.23×10^9 m^2, and an average annual total output of about 3.6×10^5 t, second only to that of Canada and India. Gansu Province is one of the main areas producing of flax in China, where the sowing area ranks first among the seven major flax-producing areas [4]. Its average annual sowing area is about 9.7×10^8 hm^2 and average annual total output is about 1.51×10^5 t, accounting for 30.5% of the national sowing area and for 38.67% of the country's total output, respectively; the province's sowing area and production rank first in the country [5–7].

Flaxseed is one of the important oil crops in Northwest China and North China, and the residual meal after oil extraction can be used as a protein source in animal and poultry feed [8–11]. Flaxseed is also utilized in food processing and can be used as medicine [12]. In recent years, the industrial applications of flaxseed gum and flax fiber have also been increasing [13–18]. To achieve better processing and utilization of flaxseed, expand its applications in food processing, and improve the quality and nutritional value of flaxseed [19] to meet diverse market needs, dehulling treatment of flaxseed has gradually become a research hotspot.

Currently, flaxseed dehulling in China is primarily via mechanical methods, such as the impact method and rolling and rubbing methods. While these approaches have yielded certain outcomes, numerous deficiencies persist. Most notably, the single-pass dehulling rate remains relatively low, necessitating multiple cycles. Moreover, there is limited incorporation of efficient and environmentally friendly emerging dehulling technologies, such as chemical and ultrasonic dehulling methods. Consequently, this study conducted an in-depth analysis of the prevailing key dehulling technologies and the current state of the flaxseed dehulling process in China. The aim was to provide novel insights and innovative perspectives for advancing flaxseed dehulling techniques in China, thereby offering valuable theoretical support and a reference for future research and development endeavors in this field.

2. Intrinsic Properties of Flaxseed and Significance of Dehulling

Flaxseed, known as the "golden seed", is generally flat and oval, with a hard, thick, and smooth outer skin, and a relatively large proportion of kernel to husk [20]. It is widely used in food processing and plays a crucial role in medicine, health products, and feed additives [21]. Studies show the primary nutrients of flaxseed are concentrated in the kernel, which is abundant in unsaturated fatty acids, high-quality plant proteins, and other essential nutrients [22–25]. Notably, the kernel contains α-linolenic acid, an essential fatty acid with cardiovascular, brain, and retinal health benefits [26–28], as well as phosphorus, potassium, vitamin B, and other trace elements [29–31]. Additionally, the kernel has anti-cancer, anti-aging, and gastrointestinal health properties. The seed coat contains insoluble fiber as well as anti-nutritional factors [32].

Flaxseed dehulling is of significant importance in expanding applications in food processing. It not only enhances the quality and grade of flaxseed but also increases nutritional value and reduces anti-nutritional factors, making it more suitable for subsequent processing. Additionally, while flaxseed cake is utilized as livestock feed, its utilization rate is often low, leading to resource wastage [33,34]. Therefore, flaxseed dehulling offers positive benefits for both food processing and consumption. Through in-depth research and application of flaxseed dehulling processes, exploring optimal processing and utilization methods for flaxseed can further uncover potential applications in various fields.

3. Research Status of Prevailing Dehulling Technologies

Presently, the relatively mature dehulling methods in China include chemical dehulling, enzymatic dehulling, microwave/roasting dehulling, steam explosion dehulling, and mechanical dehulling. In recent years, dehulling methods such as infrared dehulling and ultrasonic dehulling have also appeared.

3.1. Chemical Dehulling

Chemical dehulling utilizes alkaline (or acidic) solutions, ethanol, or other chemical solvents to soften or degrade the seed coat tissue. It is commonly employed to remove the outer layers of grains, legumes, oil crops, certain fruits, and tubers, thereby improving the edibility and processing utilization rate. The mechanism of chemical dehulling is illustrated in Figure 1.

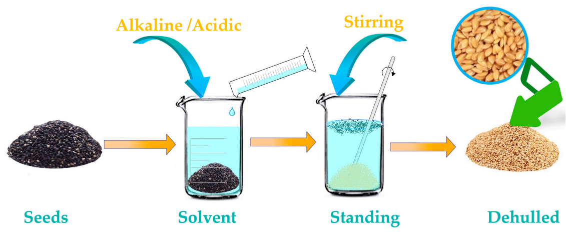

Figure 1. Chemical dehulling principle.

Researchers continuously optimize the process parameters of chemical dehulling methods to enhance the efficiency of dehulling and reduce the impact on internal components.

Shi et al. [35] investigated the heat-alkali dehulling process of peony seeds and determined the optimal process conditions for peony seed dehulling based on single-factor experiments. They found that the best conditions were achieved with a NaOH concentration of 9%, a heating time of 5 min, and a heating temperature of 80 °C. Liu et al. [36] studied the wet dehulling and hot air drying processing of sesame seeds. Using the dehulling rate, brightness, and yellowness score as indicators, they determined the optimal process conditions for wet dehulling of sesame seeds through single-factor and orthogonal experiments. The optimal conditions were found to be an alkali solution mass concentration of 0.9 g/mL, soaking temperature of 60 °C, soaking time of 5 min, and a material–liquid ratio of 1:6. Under the optimal dehulling conditions, the comprehensive score of sesame seed quality was 154.51. This dehulling process combined with hot air drying can produce high-quality sesame seeds. Zhu et al. [37] studied the effects of various factors on the dehulling efficiency of hazelnuts in the alkali dehulling process through single-factor and orthogonal experiments using European hazelnuts as the test material. They optimized the process conditions of alkali dehulling and obtained the optimal process parameters, providing references for subsequent research. Liang et al. [38] disclosed an invention of a method for separating sesame husks and kernels based on ethanol wet filtration (Figure 2). Using anhydrous ethanol or 95% ethanol for defatting crushed sesame seeds, they effectively separated sesame husks and kernels through wet filtration. This method is characterized by its simplicity, high separation efficiency, low energy consumption, low pollution, and high comprehensive recovery rate.

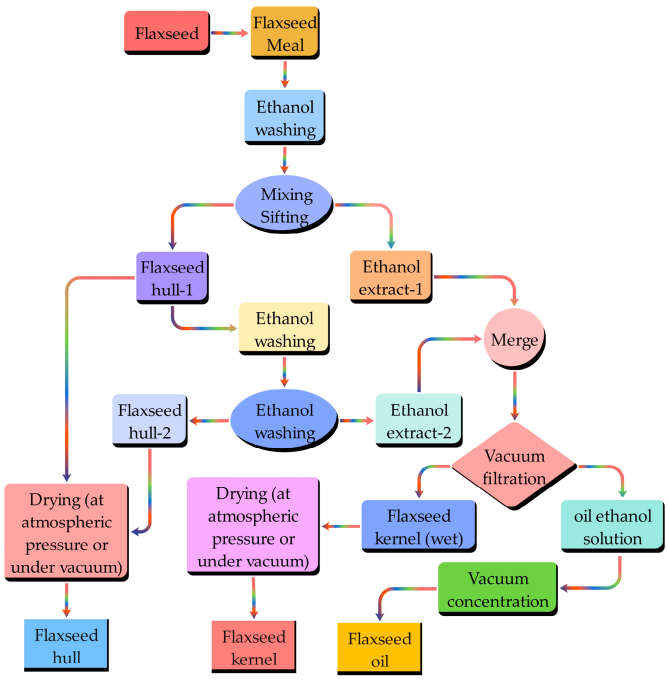

Figure 2. Ethanol dehulling process of flaxseed.

Comprehensive analysis shows that the chemical dehulling method is simple to operate, has relatively high efficiency, achieves uniform dehulling, and is not affected by the external shape of the material, making it widely adaptable. However, it can easily lead to issues such as chemical solvent residues, nutritional losses, and environmental pollution.

3.2. Biological Dehulling

Biological dehulling mainly relies on the catalytic action of biological enzymes to degrade the seed coat tissue and achieve dehulling. Ma et al. [39] summarized the role of enzymes in the dehulling process of buckwheat, aiming to provide an important theoretical basis for the key technology of buckwheat seed dehulling. Song et al. [40] used cellulase and xylanase for enzymatic dehulling of sesame seeds (Figure 3), achieving a dehulling rate of up to 98.3%. This process can replace the traditional alkaline wet dehulling process and meets the requirements of green and environmentally friendly production. Wang Jianhui et al. [41] utilized a biological composite enzyme to remove the seed coat of lotus seeds, not only preserving the original color and flavor of the lotus seeds but also reducing production costs. Wu et al. [42] studied an enzymatic method for removing the seed coat of oil-tea camellia seeds, which avoids nutritional losses in the kernels and features low consumption, environmental friendliness, and mild conditions.

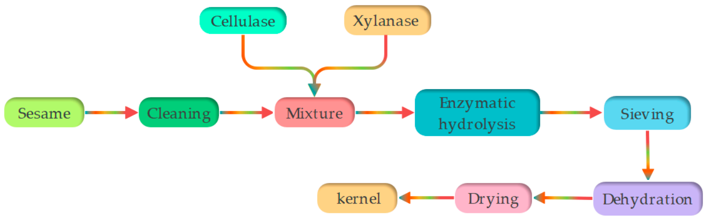

Figure 3. Enzymatic dehulling process of sesame.

Overall, biological dehulling technology has the characteristics of high efficiency, mildness, and environmental friendliness. Compared to chemical dehulling, enzymatic dehulling is more costly, time-consuming, and requires stringent reaction conditions. Therefore, it is necessary to weigh the pros and cons to decide whether to adopt enzymatic dehulling.

3.3. Mechanical Dehulling

Mechanical dehulling removes the skin through physical force and mechanical action, with various methods such as rolling and rubbing, shearing, impact, extrusion, etc. [43–46]. It has wide applicability, featuring simple operation, diverse methods, and ensures food quality and safety. The working principle is shown in Table 1.

Table 1. Mechanical dehulling principle.

Dehulling Method [47–51]	Dehulling Principle	Characteristics
Rolling and rubbing method	Utilizes crushing and frictional forces between high-speed rotating abrasive rollers or grinding wheels and conical rolls.	Suitable for seeds with weak shell-kernel adhesion like peanuts and rapeseed. High efficiency but prone to material damage, unsuitable for soft surfaces.
Shear method	Under the shearing action between the knife disk and rotating plate, seeds experience shear forces that cut through the seed coat, achieving dehulling.	Minimal kernel breakage, and low mass loss, but susceptible to seed leakage and requires high equipment precision, resulting in lower dehulling efficiency.
Impact method	By utilizing centrifugal forces, seeds undergo high-speed motion, colliding with the drum wall, causing the seed coat to rupture and detach, achieving dehulling.	Suitable for seeds with weak adhesion and brittle coats. Simple and low-cost, but challenging to control impact forces, leading to higher damage rates.
Extrusion method	The dehulling process is achieved by compressing the seed coat, separating it from the kernel, and thus accomplishing dehulling.	Suitable for dehulling hard-shelled materials, it offers high efficiency but faces challenges with varying raw materials, leading to increased seed breakage rates. Oily seeds are especially problematic due to oil seepage during squeezing, causing adhesion and hindering kernel separation.

3.3.1. Rolling and Rubbing Method

Huang et al. [52,53] developed an extrusion milling camellia seed dehulling machine (Figure 4), employing a roller and cylindrical sieve mechanism. The device is characterized by operational simplicity, stable performance, and low raw material moisture requirements. Under specific conditions, it achieves a minimum dehulling rate of 98.5%, with less than 4% hull content in kernels and less than 1% kernel content in hulls. Zhu et al. [54], through comparative dehulling experiments with different pretreatments, found that dehulling ginkgo nuts pre-treated by boiling, microwave, and drying processes, using a grinding wheel with a 10 mm gap and a 15° incline, resulted in nearly 100% shell breaking rates, with whole kernel rates of 98%, 94%, and 97% respectively. These results provide a basis for the optimized design of ginkgo nut dehulling devices. Hou et al. [55], based on the physical and mechanical properties of castor capsules, designed a double-conical castor dehulling and cleaning device, achieving a clean dehulling rate of 92.03% and a breakage rate of 3.1%. This device offers high dehulling efficiency and broad adaptability, meeting the industrial processing needs for castor. Fan et al. [56,57] invented a grinding-type sunflower seed hulling device, conducting two hulling operations on sunflower seeds. Employing the principle of aerodynamics with a suction fan for sorting the dehulled materials, this device achieves complete dehulling and impurity removal while maintaining the integrity and cleanliness of the seeds, thus enhancing the automation and efficiency of the dehulling and cleaning process.

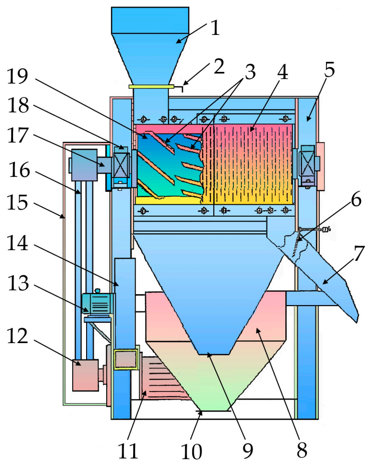

Figure 4. Oil-tea camellia seed sheller: (1) feed hopper; (2) feed regulating baffle plate; (3) spiral ribs and straight ribs; (4) cylindrical screen; (5) frame; (6) automatic dosing gate; (7) discharge port; (8) settling chamber; (9) fine shell outlet; (10) coarse shell outlet; (11) main motor; (12) belt pulley; (13) motor; (14) blower; (15) belt guard; (16) belt; (17) main shaft; (18) bearing block; (19) drum.

3.3.2. Shear Method

Shearing dehulling is generally not used alone, but rather combined with impact, extrusion, and rolling and rubbing in a multi-mode approach. Li et al. [58] designed a toothed roll-type dehulling mechanism for mechanically dehulling knife beans. The mechanism utilizes the principle of combined extrusion and shear to generate a tearing effect on the shell, which meets the performance requirements of the mechanized dehulling processing of the knife bean. Hao et al. [59] designed a cone-plate peanut shelling device, which accomplishes dehulling through the shearing and grinding of the upper and lower cone plates, achieving a 97.84% dehulling rate and 3.27% damage rate, providing a reference for the research and improvement of peanut shelling machines. Wan [60] designed a clamping-type freshwater chestnut dehulling machine, as shown in Figure 5. In this machine, the freshwater chestnuts are first longitudinally cut open by the rotating transversal cutting blade, which is fixed on the baseplate. Subsequently, the shearing and extrusion between two pairs of rubber rollers rotating at different speeds are utilized to dehull the pre-cut freshwater chestnuts. Through theoretical analysis, simulation, and prototype testing, the optimal working parameters for the horizontal cutting and dehulling units were studied, providing a theoretical basis for the design and application of dehulling equipment.

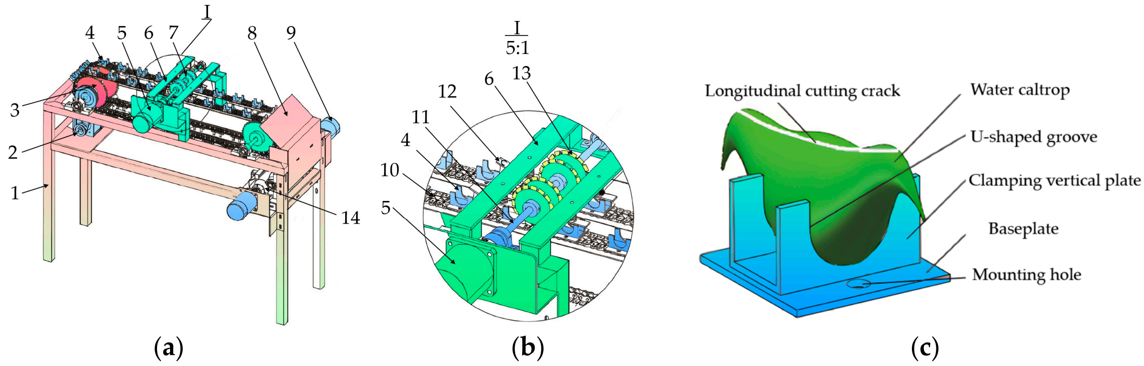

Figure 5. Clamping-type fresh water chestnut dehulling machine: (**a**) horizontal cutting and dehulling device; (**b**) local enlargement; (**c**) clamping-type device; (1) frame; (2) pulley I; (3) chain wheel; (4) baseplate; (5) transversal cutting motor; (6) beam; (7) transversal cutting blade; (8) retaining plate; (9) rubber roller motor; (10) chain; (11) blade shaft; (12) elastic strip; (13) transversal cutting blade; (14) rubber roller.

3.3.3. Impact Method

The impact method is considered ideal for dehulling small-grained oil crops [61], because it avoids hull-kernel adhesion and utilizes relatively simple dehulling equipment and processes without material grading. Sharma et al. [62,63] studied the dehulling performance of a centrifugal impact-type camellia seed dehuller, achieving higher whole kernel rates and dehulling efficiency under lower moisture content and suitable rotational speeds. This machine is applicable for small or medium-sized enterprises to dehull camellia and similar seeds. Yu et al. [64] developed a rapeseed dehulling and separation device utilizing centrifugal and impact forces, attaining an 85% dehulling rate, with kernels containing 4% hull, hulls containing 1% kernel, and a 3% powder rate after industrial trials. This device has a simple structure, and advanced technical indicators, and is well-suited for industrial applications. Guo et al. [65,66] employed a two-stage impact dehulling method to optimize the performance of a dehulling machine (Figure 6). Initially, rapeseeds are accelerated and impacted against a toothed ring by a centrifugal disc for preliminary dehulling, followed by a secondary dehulling plate to further enhance the dehulling rate. Ranjeet et al. [67] developed a centrifugal melon seed dehuller based on the centrifugal collision principle, achieving a 51% dehulling rate and a 32% seed damage rate. While this device has a simple structure and low maintenance cost, its dehulling rate is relatively low, and seed damage is significant, necessitating optimization of structural parameters.

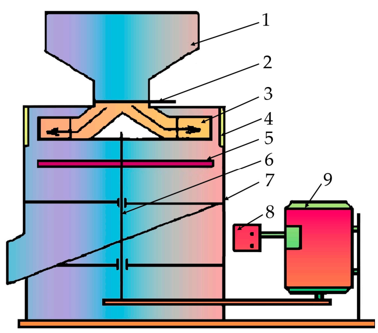

Figure 6. Rapeseed double impact husking test device: (1) hopper; (2) feed and adjustment set; (3) throwing plate; (4) dentiform circle; (5) secondary dehulling plate; (6) transmission shaft; (7) frame; (8) governor; (9) timing electrical machinery.

3.3.4. Extrusion Method

Wang et al. [68] developed an innovative pine seed sheller with two counter-rotating extrusion rollers with arched (Figure 7), indented surfaces and a guiding device for precise nut positioning and feeding, achieving a dehulling rate with more than 98% whole kernel retention. This technology, showcasing versatility, is also applicable to hazelnuts and apricot kernels. Guo et al. [69] introduced a side extrusion-type apricot kernel shelling machine, noted for its simplicity, cost-effectiveness, and superior dehulling performance, making it ideal for small-to-medium scales and a diverse variety of processing methods. Li et al. [70,71] presented a walnut cracking device using an extrusion-friction mechanism, systematically exploring the impact of walnut physical properties on cracking efficiency to establish optimal design parameters. Zhu et al. [72,73] designed a lotus seed dehulling machine (Figure 8) that integrates mechanical cutting and extrusion with an internal feed sorting system for eliminating size classification, and enhancing adaptability to seeds of various sizes. The machine incorporates a unique suspended vibratory dehulling mechanism (Figure 8b), achieving a 92% dehulling rate, 100% whole kernel retention, and less than 10% damage rate, fulfilling the high standards of fresh lotus seed processing. Its design prioritizes simplicity, robustness, and cost-effectiveness, promoting its potential for widespread use in lotus cultivation.

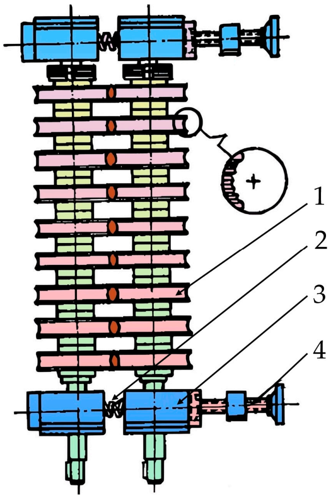

Figure 7. Roller structure: (1) extrusion rollers; (2) compression spring; (3) bearing seat; (4) adjusting screws.

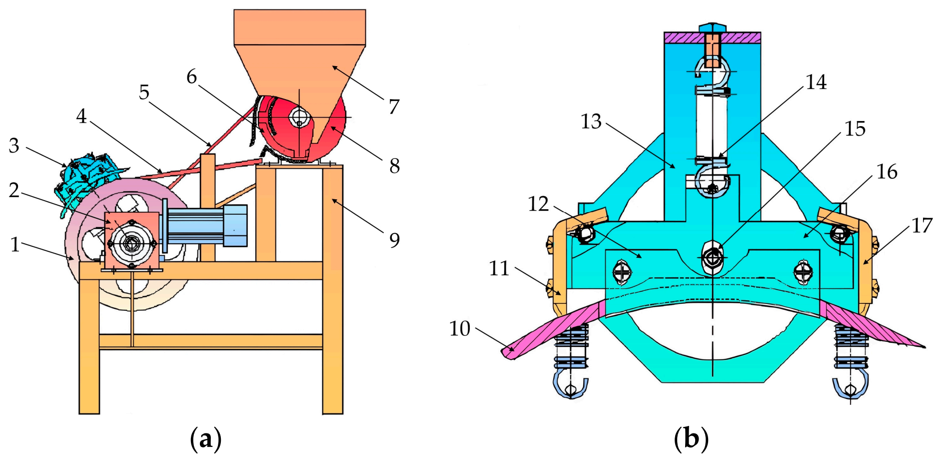

Figure 8. Schematic of lotus seed sheller: (**a**) overall structure diagram; (**b**) suspended vibratory dehulling mechanism; (1) driving wheel; (2) speed regulating motor; (3) suspended vibratory dehulling device; (4) chute; (5) V-belt; (6) hopper; (7) discharge wheel; (8) discharge wheel cover; (9) frame; (10) pressing plate; (11) left guide rail; (12) blade; (13) spring fixing plate; (14) spring; (15) eccentric pin; (16) blade holder; (17) right guide rail.

3.4. Other Dehulling

3.4.1. Microwave/Roasting Dehulling Method

The microwave/roasting dehulling technique utilizes thermal energy from a microwave or roasting oven to induce moisture evaporation within the intricate tissue structures of the material. This evaporation leads to cellular dehydration and tissue shrinkage, consequently facilitating the separation of the husk from the kernel. Notably, microwave energy primarily acts on the material's surface, whereas roasting promotes internal heating. Materials with high moisture content are well-suited for microwave dehulling, while those with a higher fat content are more amenable to roasting dehulling. This method is characterized by its operational simplicity, rapid processing speed, high efficiency, exceptional dehulling efficacy, and minimal material degradation, rendering it one of the widely adopted pretreatment techniques. In a pioneering study, Zhang et al. [74] conducted a comparative evaluation of four distinct dehulling methods using peanut kernels as the test material. The findings revealed that the frozen-microwave roasting dehulling method yielded superior results, achieving a 100% dehulling rate. The detailed process flow is illustrated in Figure 9. Notably, the dehulled peanut kernels exhibited the lowest peroxide value, a visually appealing bright appearance, and a significant reduction in rancidity, thereby effectively preserving the intrinsic quality and organoleptic properties of the peanut kernels.

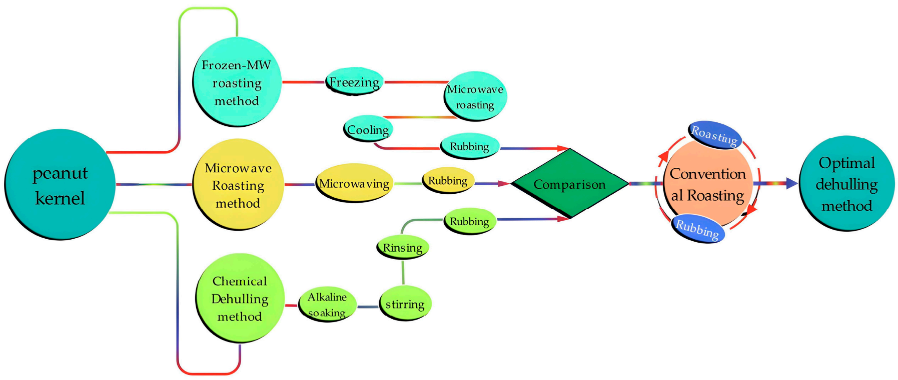

Figure 9. Process flow of removing seed coat from peanut kernels.

The limited effectiveness of employing singular techniques, such as microwave treatment [75] or roasting [76], in achieving satisfactory husk removal has been well documented, often resulting in undesirable color alterations in chestnut kernels. To address this limitation, He et al. [77] devised an innovative approach that synergistically combined microwave treatment and roasting for the husk removal of chestnuts. The method involved an initial microwave pretreatment stage to loosen the chestnut husk layer, followed by a subsequent roasting step to facilitate the complete removal of the chestnut skins. This integrated process yielded an impressive husk removal rate of up to 97.96%. Concurrently, Oomah et al. [78] conducted a comprehensive investigation into the impact of microwave treatment on the husking efficiency of sesame seeds. Their findings conclusively demonstrated that microwave pretreatment significantly enhances the husking efficiency of sesame seeds. Notably, this combined microwave and roasting technique exhibits promising potential for extension to the husking treatment of various other oilseed varieties.

3.4.2. Steam Explosion Dehulling Method

The steam explosion process involves two distinct phases: high-temperature steam cooking and instantaneous pressure release explosion [79]. The principle involves subjecting fibrous materials to high temperatures (160–260 °C) and pressures (0.69–4.83 MPa) for a predetermined duration. Under these extreme conditions, steam diffuses into the intricate microstructure of the lignocellulosic fiber cell walls, effectively weakening the adhesive forces between the kernel and its enclosing hull or husk. Upon completion of the high-pressure steam treatment, an abrupt depressurization and cooling phase is initiated, triggering the rapid release of the high-pressure gaseous species confined within the material matrix. Sudden release induces substantial expansion and rupturing of the fibrous cell walls, consequently facilitating the desired separation of the kernel from its surrounding hull or husk [80]. The principle is illustrated in Figure 10.

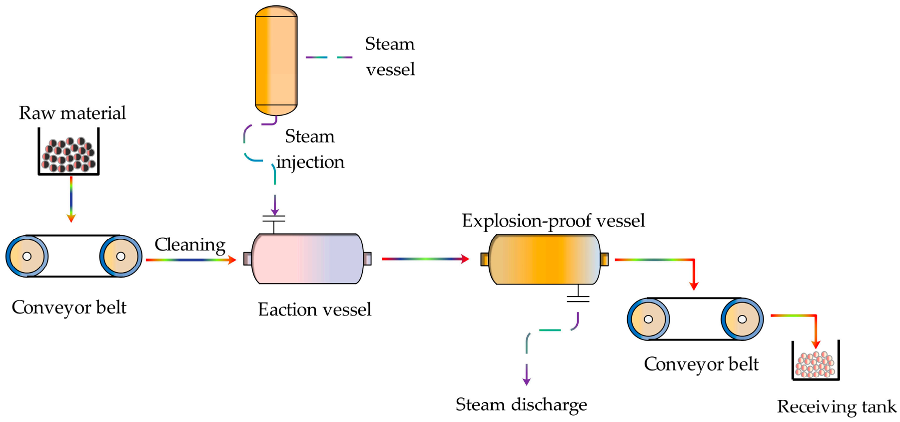

Figure 10. Steam explosion dehulling principle.

Tian et al. [81] proposed a steam dehulling machine (Figure 11) that utilizes a steam boiler to generate high-temperature and high-pressure steam. The steam is conveyed through pipelines and rotary joints into a horizontally positioned, rotatable steam reaction vessel. Material is fed into the steam reaction vessel through the discharge port of the top feeder. As the steam reaction vessel rotates, the high-temperature and high-pressure steam acts on the surface of the material, causing the outer skin to separate and fall away from the inner core. The dehulled material is discharged from the bottom discharge port of the steam reaction vessel and transported to the external collection pool via a mesh belt conveyor for further processing. Through the synergistic action of mechanical rotation within the steam reaction vessel and exposure to high-temperature, high-pressure steam, this machine achieves continuous, rapid, and automated dehulling treatment of various materials. Liu et al. [82] disclosed a steam dehulling machine, as illustrated in Figure 11, which employs high-temperature and high-pressure steam treatment to rapidly transform the internal moisture of the product into pressurized water. Subsequently, relying on the substantial expansion energy released during the depressurization and evaporation process, the pressurized water effectively separates the outer skin from the pulp, ultimately achieving the desired dehulling outcome.

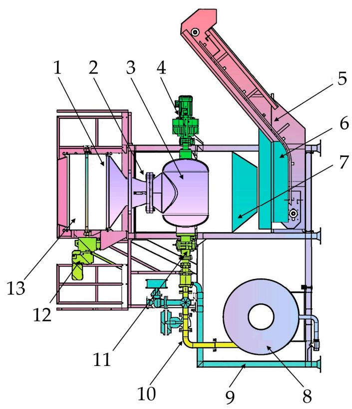

Figure 11. Structure diagram of steam sheller: (1) separator; (2) discharge port; (3) steam reaction tank; (4) motor; (5) mesh belt conveyor; (6) collection pond; (7) discharge port; (8) steam tank; (9) rack; (10) pipeline; (11) rotary joint; (12) gear motor; (13) driveshaft.

In summary, the steam explosion dehulling method has been an emerging economic physicochemical pretreatment approach in recent years. It is not limited by material shape, can better preserve flavor and nutritional value, and features high efficiency, and low-consumption environmental friendliness. However, the equipment cost is relatively high, making it unsuitable for low-budget or small-scale production demands.

3.4.3. Ultrasonic Dehulling Method

The principle of ultrasonic dehulling is based on high-frequency sound waves (20–100 kHz) [83,84]. Under the influence of ultrasonic waves, tiny bubbles in the liquid undergo cyclic expansion and collapse, resulting in the generation of extremely high localized pressure and temperature within the liquid [85,86]. This phenomenon, known as "growth-collapse" cavitation, along with the shearing effect of the liquid jet, disrupts and loosens the surface tissue of the grains, facilitating the decomposition of macromolecules such as cellulose in the cortex or cell wall components. Simultaneously, the oscillation of sound waves enhances cell membrane permeability, expediting penetration and softening of the grains. Additionally, localized high temperatures induce protein denaturation or alteration of other constituents between the cortex and endosperm, thereby reducing the bonding force within the husk and enabling effective dehulling [87–89]. The dehulling mechanism is illustrated in Figure 12.

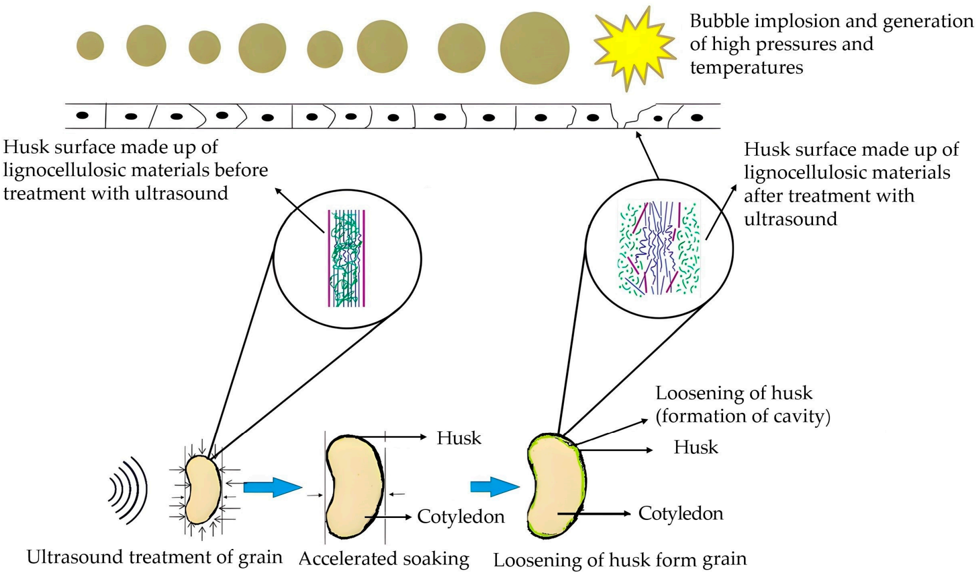

Figure 12. Ultrasonic dehulling principle.

Fang et al. [90] employed ultrasonic-assisted alkaline peeling technology to process walnut kernels. The process flow is illustrated in Figure 13. Through single-factor experiments, the researchers determined four influencing factors: NaOH concentration, alkali solution temperature, alkali solution treatment time, and ultrasonic power. They optimized the dehulling process conditions of walnut kernels using the response surface methodology. This method demonstrated easy dehulling, high whole kernel yield, and a high dehulling rate. The peeled walnut kernels exhibited a crispy texture, milky-white color, and no alkaline taste, providing valuable insights for further research into ultrasonic dehulling techniques. Sunil et al. [91] utilized the response surface methodology to investigate the impact of ultrasound on the dehulling of black beans. The results revealed that increasing ultrasound power and treatment time significantly enhanced the dehulling yield and reduced dehulling loss. The dehulling yield reached 75.71%, with a dehulling loss of 12.72%. Compared to mere soaking, ultrasound pretreatment effectively improved the dehulling efficiency of black beans.

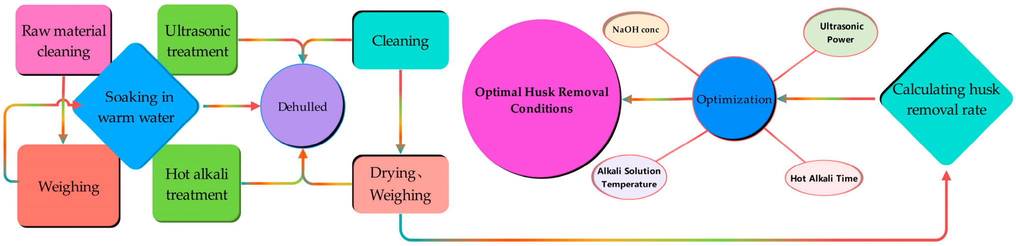

Figure 13. Ultrasonic-assisted lye peeling ultrasonic walnut kernel dehulling process flow.

Overall, ultrasonic pretreatment is an efficient, gentle, and environmentally friendly dehulling technique that significantly improves the effectiveness of the dehulling process while ensuring high product quality [92,93]. However, the efficacy of dehulling is susceptible to limitations imposed by the size and shape of the raw materials. Large or irregularly shaped raw materials hinder the propagation and action of ultrasound, thereby impacting the uniformity of the dehulling process.

3.4.4. Infrared Dehulling Method

The principle of infrared dehulling relies on the thermal effect of infrared radiation [94,95]. Surface tissues selectively absorb infrared radiation energy, leading to rapid moisture vaporization and expansion within these tissues. This process weakens the bond between the hull and the kernel, making it a current research focus in dehulling technology. Jong et al. [96,97] validated selective heating characteristics using infrared technology, enabling targeted heating of surface tissues for dehulling. Gao et al. [98] optimized infrared parameters for rice drying and dehulling, aiming to provide valuable references for infrared technology applications in grain pretreatment. Kate et al. [99] achieved a 92.77% ginger dehulling rate, 6.94% dehulling loss, and 9.6% unhulled rate through infrared dehulling experiments. Li et al. [100–103] designed an infrared tomato peeling device (Figure 14), utilizing infrared emitters to heat and soften tomato surfaces, achieving effective tomato peeling by improving heating uniformity and radiation intensity through rotation.

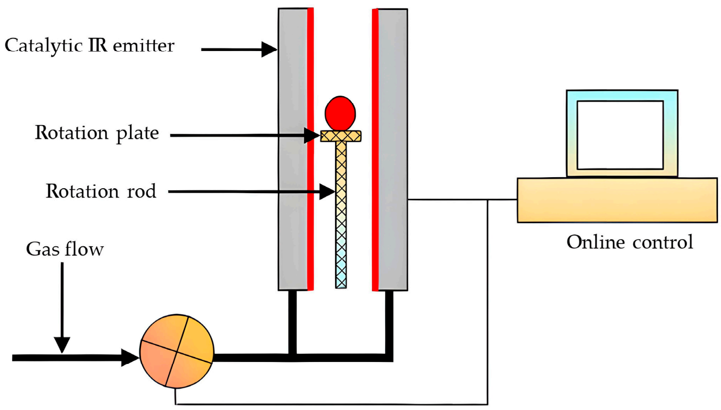

Figure 14. Principle of infrared tomato peeling.

Infrared dehulling achieves selective heating by precisely controlling the parameters of infrared radiation. It rapidly and effectively removes seed coats without damaging the kernels, offering advantages such as low losses, high efficiency, environmental friendliness, and flexible control. Additionally, infrared pretreatment disrupts cell structures, promoting oil release and significantly increasing rapeseed oil yield [104]. However, the successful application of infrared dehulling technology requires thorough research and testing tailored to specific materials and requirements to ensure high efficiency and applicability.

4. Current Status of Flaxseed Dehulling Technologies in China

In the early stages of oilseed processing in China, traditional manual methods were primarily used for dehulling. However, research on oilseed dehulling and separation equipment began to emerge gradually in the early 20th century. Developed by Huazhong Agricultural University, the rapeseed shell-kernel separation machine incorporates a pneumatic system for suction-based material transport and air separation, as well as a mechanical system comprising a centrifugal impact dehuller and dual separation units. The operating principle involves fracturing rapeseed kernels under centrifugal and impact forces, then conveying the resulting mixture of dehulled shells, kernels, seeds, and powder to a vibrating screen in the first separation unit. The screen's oscillatory motion, driven by an eccentric wheel, creates a suspended, stratified state of the mixture under suction, enabling the separation and extraction of shells and powder, which are collected via a cyclone separator. The kernel-seed mixture then undergoes further separation by airflow to remove residual shells, before proceeding to the second separation unit where purified kernels are collected using another cyclone separator, while any un-dehulled whole seeds are recycled for reprocessing. This machine achieves kernel and hull contents of less than 4% and 5%, respectively. The Oil Crops Research Institute of the Chinese Academy of Agricultural Sciences has developed a shell-kernel separation device [105] that utilizes the principle of centrifugal collision to evenly feed the mixture of dehulled shells and kernels onto a fluidized screening plate of a sorting box. An upward airflow is introduced at the lower end of the fluidized screening plate, causing the mixture to suspend and move forward under the action of the screening plate and airflow. Gradually, shells, kernels, and un-dehulled whole seeds form three distinct layers. Powder, shells, and kernels are then separately extracted through three suction ports positioned at different heights, while un-dehulled whole seeds are discharged from the end of the screening plate and returned to the dehuller for reprocessing. The extracted shells, kernels, and powder are further separated and collected using a cyclone separator. This process ultimately achieves a kernel content in shells of 2% to 4% and a shell content in kernels of less than 2%. Li et al. [106,107] developed a flaxseed dehuller based on centrifugal collision, utilizing electrostatic adsorption to separate kernels and hulls. At optimal conditions, it achieved <1% kernel content in hulls and <3% hull content in kernels, with simple operation but high power consumption, seed breakage rate, and cost, hindering large-scale production. Ding et al. [108,109] utilized rolling action from dynamic/static sand discs and flaxseeds themselves for shell-kernel separation (Figure 15). The adjustable-clearance structure suits various seed sizes, but frequent disc replacement leads to seed damage and low efficiency. Xiao proposed automated flaxseed processing equipment based on electrostatic separation [110], achieving continuous sterilization, dehulling, and separation. It utilizes opposing rollers for crushing/dehulling and an electrostatic belt for automatic hull-kernel separation, improving efficiency but with a complex structure, high power consumption, breakage rate, and waste. Wang et al. proposed a new dehulling process: pretreatment → enzymatic hydrolysis → liquid nitrogen freezing → centrifugal impact → kernel [111]. Li et al. developed a centrifugal collision dehuller [112] based on this, improving efficiency through pretreatment with low losses and good kernel integrity, but risking chemical residues and weak continuous capacity for industrial demands. Currently, the advanced TFYMZ-200 (Figure 16) employs pneumatic and electrostatic dehulling. Through a control panel, airspeed is adjusted to separate flax seeds from the hulls. After dehulling, the mixture undergoes an initial selection via a vibrating air separator. Subsequently, the principle of electrostatic adsorption is employed for the further precise separation of flax seeds from their hulls. This machine boasts a raw material processing capacity of up to 200 kg/h, with both the kernel content in seeds and the seed content in hulls being below 2%, indicating a high dehulling rate. The equipment is stable, reliable, and highly automated, capable of dehulling, hull removal, and sorting of flaxseed materials, thus meeting the demands of industrial processing.

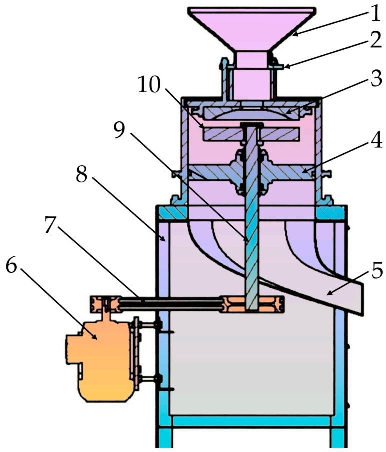

Figure 15. The structure of flaxseed dehulling equipment: (1) hopper; (2) feeding control board; (3) fixed table; (4) fixed device of transmission shaft; (5) outlet port; (6) motor; (7) belt; (8) stand; (9) transmission shaft; (10) dynamic table.

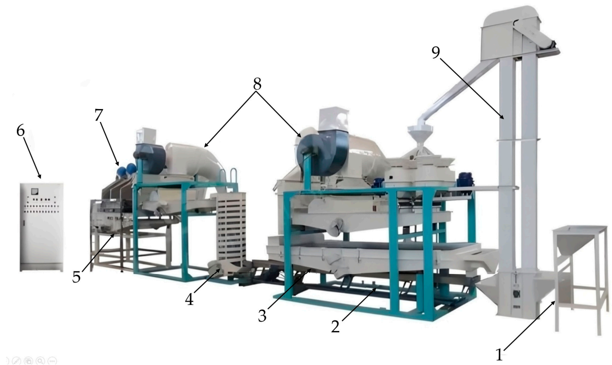

Figure 16. Flaxseed dehulling equipment TFYMZ-200: (1) input hopper; (2) main part of the equipment; (3) leaf-spring conveyor; (4) spiral elevator; (5) vibrating air-separator; (6) electric control cabinet; (7) electrostatic air separator; (8) vertical air-separating system; (9) bucket elevator.

An analysis of the current literature reveals that China has conducted extensive research on flaxseed component extraction and nutritional value. However, studies focusing on the fundamental properties and parameters of flaxseed remain scarce, leading to inadequate theoretical guidance [113]. Currently, flaxseed dehulling equipment is still in the experimental stage, with few manufacturers producing such equipment at scale. Although efforts have been made domestically to develop various types of new dehulling machinery based on traditional methods, progress has been slow. The few mature models available and limited batch production capabilities significantly lag behind the increasing demand for deep processing of agricultural products. Many technical challenges still need to be addressed, necessitating further optimization and research in this area.

5. Issues and Development Suggestions

Comprehensive analysis reveals that there are several issues with flaxseed dehulling technology in China. To address these challenges and further promote innovative development, it is recommended to implement further improvements.

1. Insufficient foundational research on flaxseed in China. The mechanical properties and dehulling kinetics of flaxseed remain inadequately studied, hindering accurate modeling and simulation of the dehulling process. This lack of theoretical guidance leads to deficiencies in process design and equipment development. Therefore, strengthening theoretical research on flaxseed dehulling is essential to provide a scientific basis for process and equipment design and parameter optimization.

2. Innovative and efficient flaxseed dehulling technologies are essential to address the inefficiencies and substantial losses of current mechanical methods in China, which achieve dehulling rates of $\leq$80% with losses $\geq$10% [114]. Exploring eco-friendly, advanced techniques such as ultrasonic, enzymatic, and microwave-assisted dehulling [78,91,115], and developing chemical reagents for selective seed coat dissolution, hold promise for improving dehulling quality and yield. Moreover, the advancement of rapid, real-time monitoring technology for dehulling quality is crucial for process optimization and represents a significant avenue for innovation in flaxseed processing.
3. The industrial production system for flaxseed dehulling equipment needs improvement. Existing equipment is predominantly in the external design and small-scale testing phase. It is imperative to encourage enterprises to increase technological investment and drive the development of automated, intelligent, and large-scale flaxseed dehulling equipment.

6. Conclusions

This study performed a comprehensive analysis of key and advanced dehulling technologies, summarizing methods and process flows across different techniques, and examined their characteristics and the variance in dehulling outcomes. The goal is to foster innovative development in China's flaxseed dehulling technology by providing new theoretical insights and support. It finds that mechanical dehulling, the predominant method in China, achieves less than 80% efficiency with a damage rate of more than 10%, lagging significantly behind international standards. This shortfall is attributed to a lack of in-depth theoretical research on flaxseed, insufficient equipment innovation, and delayed process improvements, with many dehulling machines still at the experimental stage.

The future development of flaxseed dehulling technology in China should focus on: (1) intensifying research on flaxseed's physical and chemical properties and dehulling mechanisms to underpin process and equipment innovation; (2) continuous optimization of mechanical dehulling technology, including key component design and process parameters, while advancing automation and intelligence; (3) exploring more environmentally friendly dehulling methods, coupled with the development of detection technologies for real-time quality monitoring to adjust processes and improve flaxseed quality and nutrition; and (4) encouraging enterprise investment in standardization and large-scale production to meet diverse market demands. This approach aims to provide valuable insights and guidance for the advancement of flaxseed dehulling technology in China.

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