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Advancements in Cultivation and Post-Harvest Handling of *Eleocharis dulcis*

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Abstract *Eleocharis dulcis* is an important aquatic vegetable. It is popular among consumers because of its crisp, sweet and delicious bulbs and has broad market prospects at home and abroad. In recent years, a large number of research has been carried out on improving the yield and quality of water chestnuts, including variety selection, breeding and seedling technology improvement, efficient cultivation management, green pest control, harvesting and processing mechanization, and storage and preservation. This study systematically reviews the botanical characteristics of water chestnuts and the current status of main plant varieties, and summarizes new technologies for rapid tissue breeding and healthy seedling cultivation. The cultivation strategies such as soil environment regulation, fertilizer and water management, dense planting and photoperiod regulation were discussed, and the impact of photoperiod on premature ripening of water chestnuts was analyzed using high-altitude areas in Yunnan as an example. Further, the main pests and diseases of water chestnuts and their occurrence patterns were explained, and green prevention and control strategies such as biopesticides, plant extracts, and rice rotation were introduced. Finally, we summarized and looked forward to the future development challenges such as regional planting, brand building, mechanization and intelligence, and organic planting certification in the water chestnut industry. Research believes that through the integrated application of good breeding and advanced cultivation and harvesting technologies, the yield and quality of water chestnuts can be significantly improved; but bottlenecks such as mechanization and disease prevention and control are still needed to be solved to achieve sustainable and high-quality development of the water chestnut industry.

Keywords Water chestnut; Aquatic vegetables; Variety selection; Rapid organizational breeding; Green prevention and control; Storage and preservation

1 Introduction

Water chestnuts (also known as horseshoe) belong to the perennial herb of the Cypress family. They are made of fat, tender, crisp and sweet underground bulbs. They are one of the important vegetable crops for traditional Chinese exports to earn foreign exchange. Water chestnuts are rich in nutrients and are rich in starch, dietary fiber, protein, polyphenols and other substances. They have medicinal value of clearing heat and detoxifying, moistening the lungs and relieving cough. In recent years, with the increase in people's demand for healthy diets and specialty vegetables, the quality of fresh water chestnut foods and deep-processed products have attracted widespread attention, and the market demand is strong.

Currently, the water chestnut planting area in my country is about 50 000 hectares, and a regional planting pattern has been formed in Guangxi, Guangdong, Jiangxi and other places. Although the cultivation scale continues to expand, the development of the water chestnut industry also faces many problems and challenges: traditional local varieties have problems such as low reproduction coefficient and poor disease resistance, and it is urgently necessary to improve the yield and quality through variety improvement. The breeding method is backward; the cultivation management is extensive; the pest control pressure is high; the harvesting and processing efficiency are low; post-harvest cleaning and peeling are mostly manual operations, and the product is not commercialized. The above problems restrict the quality improvement and efficiency improvement of the water chestnut industry (Xue et al., 2010).

In response to the above background and problems, this study focuses on the core goal of "improving the yield and quality of water chestnuts", and systematically reviews the research progress of water chestnuts in cultivation and harvesting technology in recent years. The full text is based on the key links of the water chestnut industry chain: introducing the botanical characteristics and variety selection and breeding progress of water chestnuts, discussing the technological innovation of breeding and seedling cultivation and management strategies, and elaborating on green prevention and control of diseases and diseases, harvesting and primary processing technology optimization, as well as new progress in post-harvest storage and storage transportation. Based on the current industry situation, discuss the key directions and challenges of the future development of water chestnuts. Summary of the key points of the full text and put forward suggestions for future scientific research and industrial work. Through this study, we hope to provide theoretical reference and technical reference for high-yield and high-quality cultivation of water chestnuts and sustainable industrial development.

2 Botanical Characteristics and Variety Development Status of Water Chestnuts

2.1 Biological characteristics and ecological adaptability

Water chestnuts are perennial shallow water-type herbs. The plants have stolons and clumpy leaf-like stems, and the height is generally 50 cm to 80 cm. Its underground bulb is nearly spherical, with purple-brown skin, white, crisp and tender flesh, and is the main edible part. Water chestnuts like warm and humid climatic conditions, with a suitable growth temperature of 22 ℃~30 ℃. They are often cultivated in autumn under the double-season rice fields in the southern region. It is a short-day plant, and the photoperiod has a significant impact on the formation of bulbs: Generally, when the sunlight is less than 12 to 13 hours, it is conducive to the expansion of tubers, and when the sunlight is gradually shortened in high-latitude areas, it is conducive to the formation of larger bulbs by water chestnuts, while low-latitude areas or too long light may delay the formation of tubers. Water chestnuts are resistant to shallow water and damp soil, and their roots are mainly distributed in 10 cm~15 cm soil layers, which have high requirements for soil aerability (Santosa et al., 2021). Its ecological adaptability is wide, and paddy fields and wetlands in subtropical areas can grow normally, but it is not resistant to frost and drought. Water chestnuts have certain ecological functions of purifying water quality and improving soil. They can be planted in rotation with rice to achieve both ecological and economic benefits.

2.2 Main planting varieties and their comparisons

After long-term breeding, some water chestnut cultivation varieties with regional characteristics have been formed in various places. The "Guilin Horseshoe" in Guangxi is famous for its large balls, thin skin and crisp flesh. It is a traditional export fresh food species, but its disease resistance is average. The skin of "black taro" in Panyu, Guangdong has a purple-black skin and high sugar content, but the yield per mu is relatively low. The "red bud water chestnut" bud sheath in Qianshan, Jiangxi is red and has good cold resistance, and is suitable for cultivation in the northern margin area. The new varieties that have been bred in recent years include the "Guizushi Series" and "Guizushi Powder Hoof Series". "Guiti No. 2" and "Guiti No. 3" are fresh food species selected from tissue culture variation based on local germplasm. They are of high quality and have good commercial properties. It is reported that the average birth period of "Guiti No. 3" is 150 days, and the yield per mu can reach more than 3,000 kilograms. "Gui Fen Hoo No. 1" is a special type of starch processing, with a particularly high starch content (up to more than 30%). It is the first special type of water chestnut powder processing approved in China. Compared with traditional varieties, the new varieties have significantly improved disease resistance and adaptability (Ghazanfar, 2001).

2.3 Progress in variety improvement and molecular breeding

2.3.1 Research and exploration of using marker-assisted selection by ISSR, RAPD and other markers

Early research used molecular marker technology to reveal the genetic background of water chestnut germplasm resources. Jiang Wen and others from Jiangxi Agricultural University used RAPD and ISSR marks to analyze the genetic diversity of 24 water chestnut varieties resources across the country, and divided the water chestnut materials for trial into 5 groups. Such studies found that the genetic similarity coefficients of water chestnuts from different origins are between 0.5 and 0.8, revealing that the overall genetic basis of cultivars is relatively narrow (Chen et al., 2024), and it is urgently needed to broaden them. Another ISSR analysis of 35 water chestnut germplasms constructed a water chestnut fingerprint map, and divided the test materials into two major groups, one type from Fuzhou, Jiangxi Province was independent groups, and the other varieties were from another major category. These works provide reference for the identification of water chestnut germplasm resources and inference of kinship.

2.3.2 Case: results of the project of conservation and innovation of water chest germplasm resources of Chinese academy of agricultural sciences

The scientific research team represented by the Vegetable and Flower Research Institute of the Chinese Academy of Agricultural Sciences systematically collected and preserved domestic water chestnut germplasm with the support of the national germplasm resource protection project. They organized detoxification and rejuvenation of the core germplasm, established a water chestnut germplasm resource garden, and preserved more than 50 pieces of materials including Guangxi's "Guilin Horseshoe" and Guangdong's "Black Taro". Virus removal through stem tip tissue culture improves the vitality and consistency of the germplasm. On this basis, researchers used molecular markers to analyze the kinship relationship of the main germplasm, screened out hybrid parent combinations with strong complementarity, and carried out artificial hybrid breeding exploration (He et al., 2023). For example, a large-grained variety in Guangxi was hybridized with early-mature varieties in Guangdong, and a batch of F1-generation hybrid seedlings were successfully obtained. Although the flowering and fruiting rate of water chestnuts is low, a small number of new varieties with hybrid advantages have been cultivated through measures such as hormone treatment and distant hybridization in other places. The project also used modern molecular technologies, such as simplified genome sequencing (RAD-seq), to develop large-scale polymorphic SSR markers, and conducted preliminary analysis of genomic mutations in main varieties such as "Guizushi" and "Guizushi".

3 Innovation in Breeding and Seedling Cultivation Technology

3.1 Traditional tuber breeding methods and bottlenecks

Water chestnuts are traditionally reproduced by nutrition, that is, they are used as seeds for breeding with small bulbs harvested in the last season, commonly known as "seed shepherd" or "female shepherd". This method is simple in technology, but there are obvious bottlenecks: the reproduction coefficient is low, and 200 to 300 kilograms of seed balls need to be left per mu of water chestnut, accounting for more than 10% of the total output, and the reproduction rate is limited, making it difficult to rapidly expand and reproduce new varieties (Lü et al., 2011; Gao et al., 2015). Seed potatoes are degenerated and diseased, and their asexual reproduction for many years can easily lead to species degradation, resulting in a decrease in yield and quality. In addition, pathogenic bacteria often lurk in the epidermis and inside the seedlings, such as *Tilletia* spp. (smut fungus) and *Fusarium* spp. (wilt fungus) of water chestnu, and diseases with bacterial seed potatoes are spread, which makes the incidence rate in the seedling stage high. The storage loss is large. The water chestnut seed balls must be stored in low temperature and wet sand until the spring of the following year. During storage, it is prone to germination, weight loss or mold, rotten and deterioration, and the loss can reach about 20%. Planting and land preparation is complicated, and planting tubers requires fine field preparation and digging and point-planting. The degree of mechanization is low and the workload of people is large. These problems have to a certain extent limited the expansion of water chestnut planting scale and the promotion speed of new varieties.

3.2 Tissue culture and tibs rapid generation system

Tissue culture technology provides water chestnuts with new ways to detoxify and reproduce quickly. As early as the late 1990s, Guangxi scientific research institutions began to explore the stem tip tissue culture detoxification technology of water chestnuts, and used virus-carried germplasm to obtain virus-free test tube seedlings through ex vivo culture, and then used for purification and revitalization. In recent years, the introduction of intermittent immersion bioreactors (TIBS) has greatly improved the rapid breeding efficiency of water chestnut tissue culture. TIBS uses liquid culture medium to regularly soak the cultures to achieve automatic feeding and ventilation. Studies have shown that under the TIBS system, the average proliferation multiple of water chestnut test tube seedlings per generation can exceed 40 times, which is far higher than 8 to 10 times that of traditional semi-solid culture. The seedlings in TIBS have many tillers, thick leaf-like stems, fast rooting, and the transplant survival rate can reach more than 95%. In addition, the medium formula of water chestnut tissue culture was optimized. For example, the addition of 6-BA 1.0 mg/L+NAA 0.5 mg/L on MS was beneficial to bud plexus induction, and IBA 1.0 mg/L promoted rooting (Gao et al., 2015). Using organizational rapid breeding technology, a detoxified seedling breeding system for some new varieties has been established. For example, "Guiti No. 3" is an excellent variant strain obtained by ex vivo culture and mutagenesis of stem tip culture. At present, various places are building a "two-stage seedling cultivation" procedure for water chestnut tissue culture seedlings, that is, test-tube seedlings are first refined in a greenhouse, and then moved to the field to fake planting and cultivate strong seedlings to supply production seedlings.

3.3 Construction of healthy seedling system

Healthy seedlings are the basis for high and stable crop yields. In response to the problem of pathogen accumulation during water chestnut breeding, in recent years, major production areas have explored and established a water chestnut healthy seedling breeding system (Lü et al., 2011; Xu, 2011). First, breeding of detoxified seedlings: Detoxified test tube seedlings without viruses and fungal pathogens are prepared by stem tip culture combined with heat treatment and other means. Then cultivate the detoxified seedlings indoors in the isolation net to allow them to grow into intrinsic bulbs. Experiments show that after the cultivation of detoxified water chestnut seedlings, the bulb yield increased by 15%~20%, and the incidence rate was significantly reduced. The second is to classify breeding: adopt the third-level breeding system of "original seed garden-good seed breeding garden-production field". The original seeds are planted with detoxified original seeds and strictly isolate diseases and insects (Zhang et al., 2019); the good seeds are expanded to breed original seeds and promoted to various production bases to achieve the synchronous implementation of good seeds and methods. The third is to improve seed potato treatment: Based on traditional sand storage, seed potato warm soup seed soaking and agent seed soaking technology. Soak the water chestnut seed balls in warm water at 55 °C for 10 minutes to kill surface bacteria, and then soak the seeds with broad-spectrum fungicides such as pyrophyllin and Fumeishuang, which can reduce the disease rate of seeds by more than 60%. Some regions have also promoted seed potato germination technology to germinate in warm and humid environments in advance to shorten the growth period in the field and achieve premature maturity.

4 Efficient Cultivation Management and Agronomic Regulation Strategies

4.1 Soil and cultivation environment regulation

Water chestnuts are suitable for growing in loam or light clay with deep soil layers and sticky texture to ensure that the bulbs have sufficient expansion space and water supply. In cultivation practice, the following main regulatory measures are used for soil and environment: Deeply plough the fields (25 cm~30 cm) after harvesting each quarter and expose the soil to the sun, break the bottom layer of the plow, improve the soil ventilation and permeability, and eliminate some overwintering pests. Jiang Wen et al. pointed out that loose mud beds are conducive to bulb expansion and stolon elongation, and can increase yield by more than 10%. Crop rotation and fallow: Water chestnuts should not be continuously planted, otherwise the soil-borne diseases will be severe. Practice has proved that 2~3 year rotation with rice and other crops can significantly reduce soil bacteria, and the incidence of water chestnut blight has decreased by about 40% (Santosa et al., 2021). Shallow water irrigation: Water chestnuts like shallow water environments. Generally, they maintain a 3 cm~5 cm water layer after transplanting and raising their roots and growing leaves. Dry the fields appropriately 1~2 times during the middle growth period to control ineffective tillering and promote the formation of tubers. During the bulb enlargement period, the rice fields should be kept moist but not deep irrigated to prevent soil from being deficient in oxygen and causing shepherd's rot. Intermediate-cultivation: Perform intermediate-cultivation and artificial weeding 1~2 times during the tillering period of water chestnuts to loosen the soil, increase soil temperature, and reduce weed nutrient competition. During weeding, centralized treatment can be combined with the removal of diseased plants to reduce the base of disease sources in the field (Zhang et al., 2021). Environmental optimization: Water chestnut bases should choose relatively isolated paddy fields that are conducive to drainage and irrigation, and avoid industrial and mining pollution around them to facilitate the acquisition of green pollution-free products.

4.2 Fertilizer and water management and green fertilization model

Water chestnuts have a relatively concentrated demand for nutrients. According to research, each 1,000 kilograms of fresh water chestnuts produce approximately 2.5 kg~3 kg of nitrogen (N), 1.2 kg~1.5 kg of phosphorus pentoxide, and 3 kg~4 kg of potassium oxide. Reasonable fertilizer planning is crucial to improving the yield and quality of water chestnuts: base fertilizer is the main and top dressing is the auxiliary, and balanced fertilization and potassium fertilizer application is added. Field experiments show that compared with nitrogen alone, the combined application of nitrogen, phosphorus and potassium can significantly reduce the incidence of water chestnut plague and blight by about 30%~40%. Therefore, it is recommended to apply compound fertilizers (N:P:K≈1:1:1) in base fertilizer, and to increase potassium sources such as potassium sulfate or wood ash in the middle and late stages to improve bulb starch accumulation and epidermal toughness (Arisandy et al., 2018). In the rice water flow rotation system, the use of green manure (such as cymbidium) to plant green manure in winter can increase the source of soil organic matter and nitrogen and reduce the amount of fertilizer. In addition, promote commercial organic fertilizers and biological organic fertilizers to replace some chemical fertilizers, and improve soil microecology while ensuring yields (Zhang et al., 2021). Areas with conditions have begun to try micro-irrigation fertilization technology, and transport soluble fertilizers to the fields regularly and in batches with irrigation water. This technology has begun to show results in water chestnut seedling fields, which can save 30% fertilizer and 20% water, and reduce the humidity in the field, which is conducive to disease control (A'Ashri et al., 2022).

4.3 Plant distance density and photoperiod regulation

The planting density of water chestnuts has a significant impact on the population structure and yield, and it needs to be reasonably determined based on the variety characteristics and cultivation season. Traditional experience believes that "sparse planting balls are large", but too sparse will reduce the total population output. Studies have shown that medium density (13 000 to 15 000 plants per mu) often produces the highest yield, taking into account both the size and total yield of single shepherds. In practice, early planting and high fertility fields can be appropriately increased in density (Gao et al., 2015), while late planting or thin soil can be reduced in density. Generally, the distance between the plants is about 40 cm × 30 cm, with 1~2 seeds of shepherd's species per acre. This way, about 12 000 seeds per mu, which is considered to be a more reasonable density configuration.

Water chestnuts are short sunshine crops, and the sunshine length affects the induction of tubers' differentiation. It is reported that the critical day length of water chestnuts is about 12 hours. If sunlight is below this, it is conducive to bulb formation, and lengthening delays tuber development (Li et al., 2000). At the same time, under the facilities, research has been conducted using a light-shading network to manually shorten the sunlight to induce bulb differentiation. When the water chestnut seedlings are 30 cm tall, the treatment is started for 4 hours a day. As a result, the tuber formed about 10 days earlier than the natural light group.

4.3.1 Case: premature maturity caused by shortening of photoperiod in low latitude and high altitude areas in Yunnan

In some water chestnut planting areas in Yunnan (such as Qujing, Honghe and other places, at an altitude of about 1 600 m), farmers found that water chestnuts often wither and mature early in early and mid-October, earlier than the expected harvest period. Survey of this phenomenon shows that the sunshine in these areas has dropped to about 11.5 hours in late August, and the night temperature has also dropped below 18 °C. Water chestnut plants are stimulated by the "double signals" of shorter sunshine and low temperature, and enter reproductive growth early, causing the tubers to stop swelling prematurely. As a result, although water chestnuts were launched early, the single bulb was small and the yield was damaged. To this end, the local agricultural department has taken some countermeasures: improve varieties, cover cultivation, and change the sowing period. Practice has proved that after these measures are combined with the application, the maturation period of water chestnuts in high-altitude areas in Yunnan can be postponed by about 10 days, and the yield per unit increase by more than 15% (Huo and Sun, 2024). This case illustrates the importance of adjusting cultivation measures to regulate water chestnut breeding according to regional ecological characteristics, and also reminds breeders to pay attention to the differences in photoperiod responses in different ecological regions and cultivate water chestnut varieties suitable for different latitudes to avoid adverse phenomena such as premature ripening or late ripening without shepherd's formation, and ensure stable and high yield.

5 New Strategies for Green Prevention and Control of Diseases

5.1 Main types of diseases and pests and epidemic rules

There are relatively few types of pests and diseases in water chestnuts, but once they occur, they are often serious harm, which is an important factor in limiting continuous cropping and increasing yield. The main diseases include: water chestnut plague (also known as stalk blight), blight, and powdery powder. In addition, underground pests such as grubs can also chew on bulbs to cause wounds (Zhu et al., 2014). Generally speaking, water chestnut pests have the characteristics of "the main transmission of soil is the first, the second transmission of qi is the second, and the underground pests are hidden and the occurrence is concealed." Among them, blight bacteria can survive in the soil for many years, which is the biggest obstacle to continuous cropping; while water chestnut plague is mostly caused by bacteria in long-distance airflow zones, and may have a cross-infection relationship with crop pathogens such as rice. In terms of climate, diseases occur more severely in years with high temperature and high humidity. Traditional prevention and control relies on chemical pesticides, but long-term single use of drugs can easily lead to bacterial resistance and pesticide residue problems. In recent years, with people paying attention to food safety and ecological environment, water chestnut pest control is developing towards green prevention and control (Zhu et al., 2016).

5.2 Application of biopesticides and plant extracts

In order to reduce the use of chemical pesticides, various places have gradually introduced efficient and low-toxic biopesticides and plant-source preparations in the prevention and control of water chestnut diseases and pests: mycotoxins and bio-drug agents, plant-source pesticides, natural antioxidants, and natural insect use. It should be pointed out that the effect of biological pesticides is relatively slow and usually needs to be combined with agricultural prevention and control and physical prevention and control to maximize their effectiveness. However, with the development of plant-source preparation purification technology and biofermentation preparations, its prevention and treatment effect and stability are constantly improving. For example, organic planting bases have successfully used mixed spraying of matrine and Bt (*Bacillus thuringiensis*) to replace chemical pesticides to control borers, with an effective prevention of more than 70%. The application of biopesticides and plant extracts (Li et al., 2022) not only reduces the risk of pesticide residues, but also helps to delay pest resistance and protect the agricultural ecological environment. It is an important direction for green prevention and control of water chestnut pests.

5.3 Rice rotation and ecological regulation technology

In response to the problems of continuous cropping of water chestnuts and disease and insect circulation, crop rotation and ecological regulation have proven to be simple and effective strategies: Rice-water chestnut crop rotation: Promote the "early rice+water chestnut" or "one-season rice+water chestnut" crop rotation model in the southern double-season rice areas. Rice and water chestnuts are mutually stubborn, which not only makes full use of the solar and thermal resources of paddy fields, but also breaks the disease and insect cycle. The promotion data of Shaodong County Agriculture Bureau in 2015 showed that in the high-incidence zone of Jiangxi, the prevention effect of water chestnut wilt can reach 34%~41%, while water chestnut plague has interspecies hosts due to bacteria, which can be weakened by crop rotation but is difficult to completely control.

Combination of ecological breeding and breeding: In fields with water source conditions, farmers try to apply comprehensive breeding experience of rice fields to water chestnut fields, such as the variant of the rice and shrimp co-cultivation model - "water chestnut-crawfish co-cultivation". Dig up the trenches in the water chestnut planting ditch to raise shrimps, and use crayfish to feed the weeds and some pests in the field. At the same time, the shrimp manure provides water chestnuts with organic fertilizer to achieve ecological circulation. For example, in some water chestnut fields in Guangdong, loaches are raised, so that the loaches loosen the soil, eat grub larvae, and reduce the harm of underground pests.

Agricultural prevention and control measures: including the selection of pest-resistant varieties, cleaning the countryside and reasonable rotation of crops and stubborns. Promoting disease-resistant varieties such as the "Babu Water Chest" that is relatively tolerant to blight, according to the experiment, its incidence rate is reduced by 25.5% compared with local varieties. After harvesting each season, remove the remaining shepherds in the fields in a timely manner, and buried in depth or burn it to eliminate the source of overwintering bacteria. At the same time, the "bacterial land" elimination system was implemented, and water chestnut planting was suspended for 1 to 2 years in severely ill fields, and the planting of dry crops or rice was changed to purify the soil (Khairullah et al., 2020).

6 Optimization of Harvesting and Primary Processing Technology

6.1 Judgment of maturity and optimal harvesting time

The harvesting period of water chestnuts varies according to the variety and planting period. Generally, the bulbs mature 120 to 150 days after sowing. From the external morphology, when the foliar stems on the ground are yellow and lofty and the stolon at the base are loose, it indicates that the underground bulbs have fully developed. Traditional experience uses the harvest signal of "seedlings with dry sounds and crisp sounds", that is, pull up the stems and listen to the crisp sounds of breaking, indicating that the water chestnut skin is thick and hard and can be harvested and dug. If harvested too early, the bulbs have not grown enough and the starch accumulation is insufficient, which will affect yield and taste (Zhang et al., 2021); if harvested too late, the bulbs will easily regenerate or rot in the mud, and the bulbs will not be easily found after the upper part of the ground is completely dead. Therefore, it is very important to choose appropriate harvesting. Studies have shown that nutrient accumulation of water chestnuts reaches its peak around one week before full maturity, and at this time, the best balance between yield and quality can be achieved by harvesting. For commercial fresh water chestnuts on the market, they should be dug appropriately in advance to ensure full appearance and bright skin color; for starch processing, they can be harvested a few days later to make the starch content higher (Figure 1) (Chen et al., 2024). In the main production areas in the south, water chestnuts sown in autumn are usually harvested from January to February of the following year, and the weather is cool at this time, which is conducive to storage and transportation. All localities should flexibly determine the harvest period based on local climate and market demand.

6.2 Comparison of artificial and mechanical harvesting methods

Traditional water chestnut harvesting is mainly artificial. Usually, the field water is drained first, and the topsoil is turned manually with a hoe or an iron rake, and the bulbs in the mud are turned off the surface, and then the shepherds are picked manually. The advantages of artificial methods are that they are highly adaptable to different soils, have a low damage rate (the damage rate of manual mining is about 5%~10%), and can be selected simultaneously in grading. But the disadvantage is that the labor intensity is extremely high. A skilled worker can only harvest 200 to 300 kilograms of water chestnuts per day, and it needs to bend over and work in the mud for a long time, which is inefficient. With the shortage of rural labor and rising costs, artificial harvesting has become a bottleneck in the development of the water chestnut industry. The demand for mechanical harvesting is becoming increasingly urgent. In recent years, various places have developed various types of water chestnut harvesting machinery: vibration screening excavator, paddy field harvester, and layered harvesting technology. Based on this, enterprises in Guangxi and other places have developed a double-layer shovel harvester: the front shovel pushes the upper layer of mud, and the rear shovel digs out the lower layer of water chestnut-containing soil for screening and separation.

6.3 Standardization of cleaning, brushing and grading processes

The main links of water chestnut processing include cleaning, peeling and grading packaging. In the past, it was mostly done by hand, but is currently improving in the direction of standardization and mechanization: the surface of water chestnuts is often covered with soil after harvest, and must be thoroughly cleaned before sale or processing. Nowadays, bubbling cleaning machines or high-pressure spray cleaning lines are mostly used, and water chestnuts are put into batches of water chestnuts into the sink with bubbles and spray devices to roll and clean. Fresh water chestnuts have a hard outer skin and a slightly bitter taste. They usually need to be peeled before consuming and storing. In recent years, water chestnut mechanical peeling machines have been developed. There are two main types: one is a roller brush peeling machine, which uses a roller lined with a bristle brush on the inner wall to brush off the skin of the water chestnut. In order to meet the market's requirements for the uniformity of water chestnut size, it must be graded according to the horizontal diameter of the bulb after harvest. Traditionally, hole screens or artificial visual measurements are divided into three levels: large, medium and small. Currently, rolling bar-type grader is promoted. The spacing between a set of parallel rollers gradually increases. During the rolling process, the small water chestnuts fall first, and then the large water chestnuts are discharged to the end. The equipment can be divided into several tons of water chestnuts per hour, with a grading accuracy of more than 90%. After classification, water chestnuts are packaged according to sales needs. For example, fresh water chestnuts are mostly sold in woven bags or plastic frames, while exports and supermarkets often use small vacuum plastic packaging, with 5 to 10 pieces per bag and filled with fresh air conditioning, which can extend the shelf life.

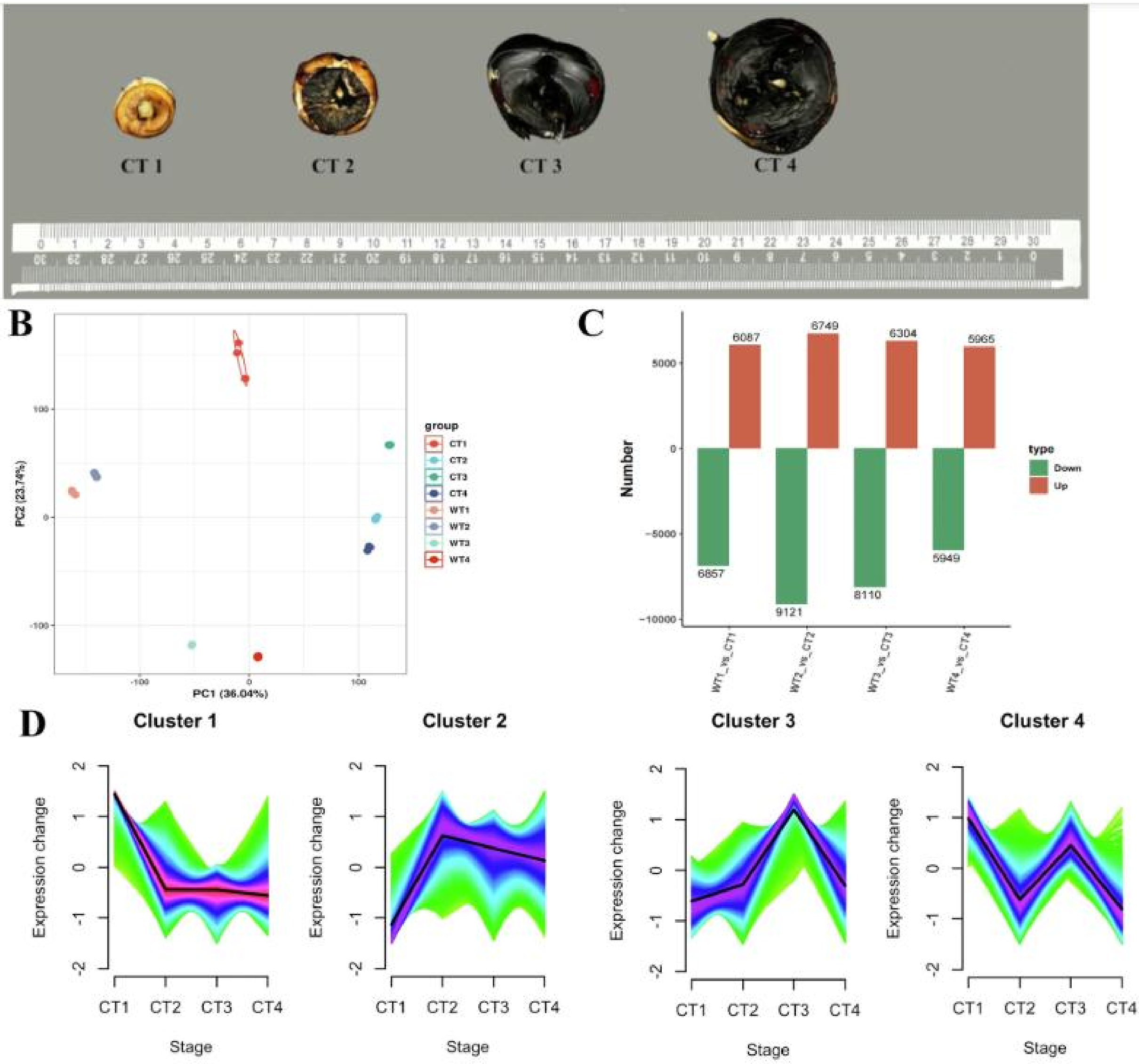

Figure 1 (A) Four developmental stages of corms of cultivated ('Xuanci')/wild accessions (S1: initial swelling stage; S2: middle swelling stage; S3: late swelling stage and S4: maturity stage) used for RNA sequencing. (B) Principal components analysis (PCA) of the transcriptomes of all samples. (C) Numbers of differentially expressed genes (DEGs) in cultivated and wild corms. (D) Changes in gene expression in terms of four reaction norms for cultivar ('Xuanci') at the four stages (S1 to S4) (Adopted from Chen et al., 2024)

7 Progress in Storage and Storage Technology after Harvest

7.1 The impact of storage environment on quality changes

The water content of fresh water chestnuts is as high as 75%, and it still maintains a high respiratory strength and metabolic activity after harvesting, and is very prone to water loss, wilting, browning and rot. The storage environment has an important impact on the quality changes of water chestnuts. Low temperature can effectively inhibit the respiration and bacterial reproduction of water chestnuts, which is the key to prolonging the shelf life. Studies have shown that under conditions of 0 ℃~4 ℃, water chestnuts can be stored for about 4~6 weeks without changing their quality; while obvious germination and rot occurred in only about 2 weeks at room temperature of 25 ℃ (Baehaki et al., 2019). Therefore, most of the cold storage refrigerated water chestnut raw materials are used. However, it is necessary to note that water chestnuts are not resistant to freezing. If they are below -1 ℃, they will become transparent and water-stained. The skin of the water chestnut is not dry enough to have a leather layer of 0.5 mm~1 mm, which has a certain ability to prevent water loss. However, long-term storage will still cause weight loss. The relative humidity should be maintained at 85%~90%. Too low humidity will accelerate the evaporation of water and cause wilting; too high humidity will easily breed mold. Generally, open water trays are placed in cold storage or humidifiers are used to maintain a high humidity environment. In addition, moderate drying of the surface before storage can reduce moisture transpiration during storage (Luengwilai et al., 2014).

Using air conditioning (CA) storage technology can further inhibit the respiration of water chestnuts and delay browning. Some studies have tried to reduce oxygen concentration, increase carbon dioxide or add inert gases in storage environments. As Japanese scholars have found that placing water chestnuts in an environment of 5% O_2+5% CO_2+90% N_2 can significantly slow down their browning and corruption. The latest research has introduced rare gases: filling low-concentration xenon (Xe) and krypton (Kr) gases into the packaging, and it was found that these two inert gases can effectively inhibit the enzymatic browning of peeled water chestnuts and at least double the storage period.

7.2 Fresh preservation and disease prevention plan

In order to further extend the storage period of water chestnuts and prevent storage diseases, a series of preservation treatment technologies have been developed in recent years: water chestnuts are prone to browning due to phenolic oxidation after harvesting. To address this problem, chemical and physical methods can be used to inhibit PPO enzyme activity. Commonly used chemical treatments such as coating 0.1% sodium sulfite or citric acid on the surface of water chestnuts can effectively prevent browning for 2~3 weeks, but sulfite may have residual problems. In physical methods, high concentration of carbon dioxide atmosphere can significantly inhibit browning. To reduce water dispersion and bacterial infection, a edible film can be applied to its surface. Commonly used coating materials include polysaccharides such as sodium alginate and chitosan (Zhang et al., 2021).

The most common storage period is soft rot and mildew caused by fungi. For example, mold and rot during storage caused by *Penicillium* and *Rhizobium*. In this regard, water chestnuts can be subjected to preventive sterilization after harvesting. Based on food safety, the surface of water chestnuts can be cleaned and disinfected with low concentration of hypochlorous acid or peracetic acid solution. Ozone fumigation or ultraviolet irradiation can also be used to kill attached bacterial spores. The ozone concentration is 5 ppm~10 ppm and the action is 30 minutes, which can effectively reduce the occurrence of mold and rot in the later stage. Since the deterioration of the quality of water chestnuts after harvest involves many factors and the effect of a single measure is limited, it has tended to comprehensive preservation technology in recent years. For example, a study combined 2% acetic acid+low dose ozone+ice-temperature refrigeration, and found that freshly cut water chestnuts remained in good color and qualified microbial indicators after 10 days of storage under this combination. Comprehensive treatment achieves the dual purpose of extending shelf life and controlling disease through the synergistic effect of multiple targets.

7.3 Diversified processing forms and market expansion

In addition to fresh sales, processing and adding value to water chestnuts is also an important direction to improve industrial efficiency. In recent years, some new progress has been made in the processing and utilization of water chestnuts: for starch processing, the breeding variety with high starch content has been introduced, and its bulb starch rate is 5 percentage points higher than that of ordinary varieties. Water chestnut starch processing plants have been established in Guangxi and other places, and their products have been exported to Southeast Asia. Using the crispy taste of water chestnuts, a variety of convenience foods have been developed. Such as vacuum fried water chestnut slices (horsehound slices), freeze-dried water chestnut kernels, etc., the flavor and nutrition of water chestnuts are retained to the greatest extent. The skin and residue of water chestnuts are rich in polyphenols and dietary fiber. Studies have shown that water chestnut peel extract has strong antioxidant and antibacterial activities and can be used as a natural additive for food preservation. At present, phenolic compounds such as puchiin have been isolated from the skin of water chestnuts, and it was found that they have a significant inhibitory effect on Staphylococcus aureus and *E. coli* (Figure 2) (Amaliaa et al., 2023). These extracts are expected to be developed into plant-sourced preservatives or health care ingredients. At the same time, water chestnut residue can be mixed with cereal powder to prepare high-fiber brewed food, or used as feed raw materials to achieve comprehensive utilization of by-products.

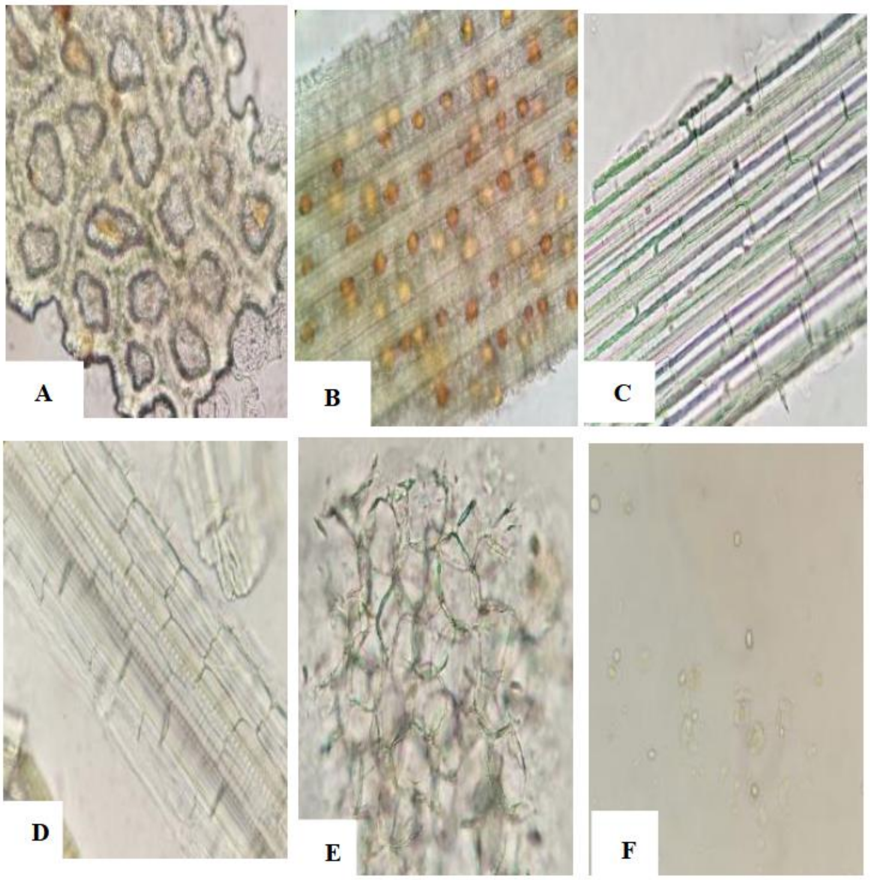

Figure 2 Microscopic result of dried powdered sample of *E. dulcis*. A: oil gland cell; B: collenchyma; C: vascular bundle; D: spongy parenchyma; E: cork tissue cell; and F: Amylum (Adopted from Amaliaa et al., 2023)

8 Industrial Development and Future Challenges

8.1 Regional planting pattern and brand building

China's water chestnut production has obvious regional concentration, with South China and Central China as the main production areas. At present, Guangxi's planting area and output rank first in the country, and Guilin Horseshoe, Yulin Beiliu Water Chest and other regional specialty agricultural products have become regional specialty agricultural products. Panyu, Guangdong, Fujian, Qianshan, Jiangxi, Shaodong, Hunan and other places have also formed well-known water chestnut production areas. However, there are differences in product quality in different regions, and the brand effect in various regions still needs to be strengthened. In the future, we should give full play to regional advantages and create a well-known brand of water chestnuts. Guangxi can continue to strengthen the "Guilin Horseshoe" brand, apply for geographical indications and organic certification, and occupy the high-end market with its crisp and sweet taste; Jiangxi Qianshan can highlight the cold-resistant and late-ripening characteristics of "red bud water chestnuts" to fill the winter off-season market. In terms of brand building, local governments and leading enterprises should increase publicity and marketing, and enhance the popularity and reputation of water chestnut products through e-commerce live broadcasts, origin traceability and other means. At the same time, strengthen cooperation and exchanges between production areas, avoid disorderly competition and low-price dumping, and jointly maintain the overall image and benefits of the water chestnut industry.

8.2 Bottlenecks of mechanization and intelligence technology

The water chestnut cultivation and harvesting process has a high degree of dependence on manpower and a low level of mechanization. Especially in the harvest stage, there is currently a lack of mature and reliable special machinery, which has limited large-scale planting. The development of full-process mechanized equipment for water chestnuts is an urgent need for industrial upgrading, but it also faces many challenges: First, water chestnuts grow in paddy fields with complex harvesting machinery design and poor equipment versatility, and specific models need to be developed for different mud soils. Second, the bulb burial depth and distribution are highly random, and mechanical excavation must take into account both the leakage yield and the damage rate, which is difficult to balance. Third, the current market capacity is limited, and professional agricultural machinery enterprises are not very enthusiastic about investing in R&D. In order to break through the bottleneck, it is necessary to strengthen the integration of industry, education and research, and strive for special support for water chestnut mechanization technology research on national and local agricultural machinery research. In terms of cultivation management, intelligent means should also be actively introduced, such as using the Internet of Things technology to achieve automatic regulation of water levels and water fertilizers, and using drones to carry out field growth and disease monitoring.

8.3 Organic planting and green certification barriers

Driven by consumption upgrades and export foreign exchange earnings, producing safe and high-quality organic water chestnuts has become the direction of industry efforts. However, organic water chestnut cultivation faces some unique obstacles: high pest pressure, soil restrictions, cost-benefit issues, etc. To overcome these obstacles in the future, innovation in technology and models is required. For example, developing a circular organic breeding model of rice+water chestnut+fish farming, using the ecological chain to suppress pests and reduce external investment; cultivating disease-resistant varieties to reduce the risk of organic cultivation diseases; the government provides financial and technical support to organic bases to help them overcome the difficulties during the transition period. At the same time, we will increase publicity and increase the market recognition and price advantages of organic water chestnuts, so that growers are willing to invest in the long term. As the concept of green agriculture is deeply rooted in the hearts of the people, the water chestnut industry should also follow this trend, gradually increase the proportion of green food, pollution-free and organic products, and promote the sustainable development of the industry and the improvement of international competitiveness. Although there are many challenges ahead, through the joint efforts of all parties, the scale of organic water chestnut cultivation is not out of reach.

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Conflict of Interest Disclosure

The authors confirm that the study was conducted without any commercial or financial relationships and could be interpreted as a potential conflict of interest.

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