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Advancements in Cultivation Techniques and Post-Harvest Handling of Lotus Rhizome (*Nelumbo nucifera*)

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Abstract This study provides an overview of the latest techniques in lotus rhizome cultivation, including water quality management, soil improvement, the development of high-yield and disease-resistant varieties, and integrated pest and disease management strategies. It thoroughly explores advancements in mechanized harvesting, storage and preservation, and value-added processing technologies, with a particular focus on measures such as temperature and humidity control, coating preservation, and controlled atmosphere storage to extend shelf life. The study indicates that integrating smart agriculture and automated equipment can further enhance lotus rhizome production efficiency, while data-driven decision-making supports precision cultivation and disease prevention. This research highlights the critical role of technological innovation in improving the sustainability and market competitiveness of the lotus rhizome industry and calls for strengthened international collaboration and knowledge exchange to drive continuous progress in lotus cultivation and processing.

Keywords Lotus rhizome cultivation; Integrated pest and disease management; Mechanized harvesting; Storage and preservation; Smart agriculture

1 Introduction

Lotus root (*Nelumbo nucifera*) is a very useful crop, especially in Asia, where many people use it to cook or use it as medicine. Now, people's demand for ready-to-eat food is getting higher and higher, which has led to the continuous increase in consumption and planting of lotus roots (Worarad et al., 2021). In order to ensure the quality of lotus roots and extend the shelf life, better methods are needed to plant and process lotus roots. Establishing an efficient method for lotus root callus culture can help us better study its rhizome development and the nutrients inside. This also contributes to the advancement of agricultural technology (Zhao et al., 2016; Deng et al., 2020).

Lotus, which we often call "lotus", has a deep cultural and historical background in many Asian countries. People like it not only because it looks good, but also because it represents purity, strength, and revelation in religion and traditional culture. In the past, lotus was planted mainly to harvest its rhizomes, which is the lotus root we eat. This part is not only the ingredient of many traditional dishes, but is also used as a medicinal ingredient (Huang et al., 2021; Jiang et al., 2023). Lotus grows well in water and is also regarded as a highly adaptable and symbolic plant.

This study will introduce some new advances in lotus root planting and post-harvest treatment. We will see how you grow lotus roots now, how effective these methods are in improving yield and quality; we will also study new technologies for harvesting, storage and transportation. In addition, some more environmentally friendly cultivation practices will be analyzed, and how these practices will help environmental protection. Our goal is to promote the cultivation and management of lotus roots, make agriculture more sustainable, and promote economic development.

2 Current Status of Lotus Rhizome Cultivation

2.1 Major producing regions and global cultivation trends

Lotus root (*Nelumbo nucifera*) is now mainly grown in Asia and is an important ingredient in the diet and culture

of many Asian countries. It is rich in nutrients, has many methods and is loved by people. As people's demand for healthy foods and convenient ingredients increases, global interest in lotus roots is also rising. This growth trend has led more people to focus on how to improve planting technology so that yields can keep up with market demand (Karthika et al., 2023).

2.2 Traditional cultivation practices and their limitations

In the past, planting lotus roots was basically manual operation, and it took a lot of effort from planting to harvesting. This method relies on the experience of farmers and is particularly sensitive to the weather and environment, so the yield and quality are not very stable. Another big problem is that disease prevention and control is not very good. For example, the rhizome rot caused by "Fusarium" can easily cause a large piece of lotus root to reduce production or even rot, and in severe cases it will lose a lot of money (Min et al., 2021; Zhu et al., 2022).

2.3 Recent innovations and technological adoption

Now, scientists and farmers have begun to try new ways to improve the efficiency of lotus root planting. A technology called "cause induction" can help lotus roots grow better and increase the yield of nutrients in their body. People have found that it is more suitable to use cotyledons or embryos when lotus seeds are not yet mature, especially embryos 9 to 18 days after fertilization, which has the best effect. These materials are easily grown after being placed in a culture medium containing a growth regulator (Figure 1) (Deng et al., 2020). In addition, there is a molecular detection technology called LAMP, which is now used to quickly discover bacteria at the roots of lotus roots, such as *Fusarium apicus*. This detection method can detect problems early, facilitate timely handling, and reduce losses caused by diseases (Deng et al., 2021). There are also many new methods for post-harvest treatment. For example, using a liquid that is anti-browning can prevent lotus root from discoloring during storage and transportation, thereby maintaining its freshness and appearance. This approach also helps to extend shelf life and improve market value (Worarad et al., 2021).

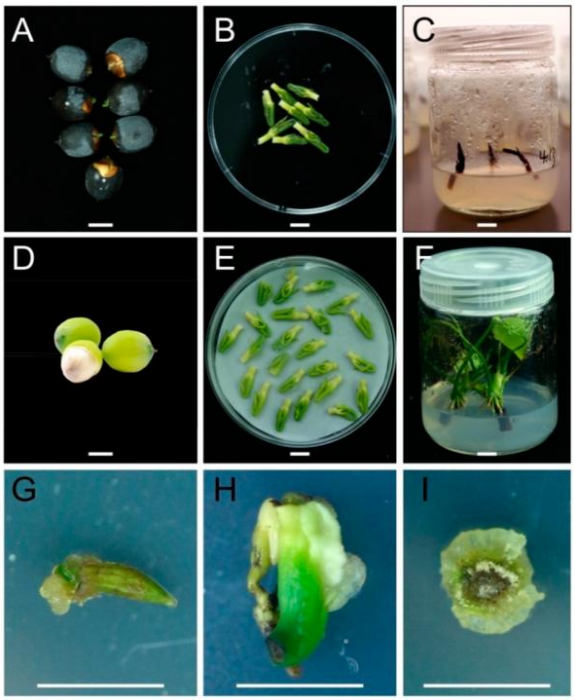

Figure 1 Regeneration of aseptic lotus seedlings for callus induction in lotus genotype “WBG_S1” (Adopted from Deng et al., 2020)
Image caption: (A) Stored mature lotus seeds with part of episperm removed. (B) Embryos taken from mature lotus seeds. (C) An example of mature embryos that died during culture. (D) Immature seeds at 15 days after pollination. (E) Immature embryos taken from lotus seeds 15 days after pollination. (F) Aseptic seedlings developed from immature embryo cultures. (G-I) Callus induced from leaf sections, epicotyl-petile complex sections and epicotyl sections of aseptic seedlings respectively. Bars indicate the length of 1 cm (Adopted from Deng et al., 2020)

3 Advances in Cultivation Techniques

3.1 Soil and water management

If you want to plant lotus roots well, the management of soil and water is particularly important. Lotus is aquatic plant and likes to grow vigorously in a watery environment. The water level must be controlled well, not too high or too low. Too much water may cause damage to the roots, and too little water is not conducive to growth. Keep the water level stable and allow enough oxygen to the roots so that lotus roots can grow well and not easily get sick (the soil must also be nutritious) (Sun and Qian, 2024).

3.2 Planting methods and density optimization

When planting, pay attention to the method and density. If planted too densely, the lotus root will not grow; if it is too thin, it will be a waste of land. Adjusting the planting density can help farmers increase their yields. Research has found that the growth of lotus roots is related to many factors, such as which variety is used, lighting conditions, growth stage of the material, etc. (Huang, 2011; Minh et al., 2019). These factors can also be used to guide field planting. Choosing the right variety and adjusting the planting distance according to the situation can make the yield higher and the management more convenient.

3.3 Pest and disease management

Lotus roots are prone to illness during planting, especially the rotten rhizomes, which is a common problem. This disease is mostly caused by Fusarium, such as Fusarium asteroids and other Fusariums, which are common pathogens. Now, new technologies can help us discover these bacteria faster. For example, a molecular detection method called LAMP can quickly determine whether there are bacteria on the ground (Lan and Liao, 2008; Karthika et al., 2023). If you find it early, you can start dealing with it earlier. You can use medicine accurately to avoid the spread of diseases and reduce the loss of lotus roots. Using this detection method can also help farmers better manage pests and diseases, protect crop health, and improve harvests.

4 Post-Harvest Handling and Processing

4.1 Harvesting techniques

When harvesting lotus roots, the method is very important. If the method is used well, it can ensure that the harvested lotus roots are of good quality and are not easy to break. Some diseases, such as decay caused by Fusarium, can affect the harvest. There is now a new technology called LAMP detection, which can quickly check whether lotus roots are sick in the field (Deng et al., 2021). If discovered early, you can deal with it early to prevent the spread of diseases, reduce losses, and ensure healthy harvest.

4.2 Storage and preservation

After the lotus root is dug out, the storage process is also very important. If the method is wrong, lotus roots may easily change color, such as browning, which will affect their appearance and price. The study found that wrapping it with anti-browning solution can greatly reduce discoloration during storage and transportation. There is also scientific basis behind this technology. Researchers have found key points to control browning by analyzing the genetic changes of lotus roots (Worarad et al., 2021).

4.3 Value-added processing

4.3.1 Processing into food products and nutritional supplements

Lotus root is rich in nutrition and good for the body, so many people now process it into food or nutritional supplements. Callus induction techniques used in the study can enrich the nutrients in lotus roots, which is very helpful in developing high-quality nutritional products (Li et al., 2022).

4.3.2 Industrial applications of lotus rhizome extracts

Lotus root can not only be eaten, but also extract useful compounds. These extracts can be used in the industry, especially in the production of natural ingredients that have active effects. By using efficient tissue culture methods, these useful ingredients, such as substances such as benzylisoquinoline alkaloids, can be better studied and extracted in pharmaceuticals or health products (Li et al., 2016; Zhang et al., 2023).

4.3.3 Packaging innovations and market expansion

In order to prevent lotus root from breaking easily before being sold, some new packaging technologies have been developed. For example, adding anti-browning ingredients to the packaging materials can make the lotus root look fresher and more stable during transportation and storage. These methods not only extend the shelf life, but also help lotus roots better enter further markets and increase sales (Fan et al., 2015).

5 Economic and Environmental Impacts of Lotus Rhizome Cultivation

5.1 Contribution to local and global markets

Nowadays, more and more people like to eat convenience and ready-to-eat foods. This makes the demand for lotus roots very high. Not only is it needed by the local market, many lotus roots are also exported abroad. This has driven the development of the global market. In order to make lotus roots sell better, people have developed new treatment methods, such as adding anti-browning solutions. In this way, lotus roots are not easily discolored during storage and transportation, can maintain good quality, and are more suitable for long-distance sales (Deng et al., 2021).

5.2 Socio-economic benefits for rural communities

Planting lotus roots is a good source of income for rural areas. If scientific planting and harvesting methods are used, not only can the yield be increased, but the losses caused by diseases can also be reduced. For example, one of the diseases that lotus roots fear the most is rotten rhizomes, which are often caused by Fusarium. Now using LAMP rapid detection technology, the disease can be detected early, deal with it early, and reduce farmers' losses (Deng et al., 2021). In addition, by optimizing the tissue culture method of lotus root, the variety can be improved, making lotus roots easier to plant and yield higher. These new methods can help farmers make more money and are of great help to the rural economy (Zhang et al., 2022).

5.3 Environmental sustainability and ecosystem benefits

Lotus roots are not only economical, but also beneficial to the environment. It is an aquatic plant that purifies water quality and provides a "home" for fish and other organisms in the water. If managed properly, lotus root cultivation can be more environmentally friendly. For example, using molecular detection technology to prevent diseases can reduce the use of pesticides and reduce the damage to the environment (Zhang et al., 2014). In addition, improving storage technology and reducing waste after harvest can also make resources more efficient and protect the environment.

6 Case Studies of Successful Cultivation and Post-Harvest Practices

6.1 High-yield farms and technological integration

Now many high-yield farms have begun to use new technologies to improve lotus root yield and processing efficiency. For example, someone has developed a LAMP detection method that can quickly distinguish whether lotus roots are infected with *Fusarium apicus* or Fusarium. These two bacteria are the main cause of lotus root rot, and lotus root rot disease is also the most serious disease at present. The study found that 91% of the diseased lotus roots are caused by Fusarium and only 9% are caused by *Fusarium nisarium*. This new method finds three distinct locations by aligning the mitochondrial DNA of the two bacteria, and then designs specific primers. These primers can be used in conjunction with different detection methods, such as ordinary PCR, qPCR, and LAMP rapid detection (Figure 2) (Deng et al., 2021). With this technology, farmers can detect diseases as soon as possible and spray them in time to avoid the spread of the disease and ensure that more lotus roots can grow up healthily. In addition, transcriptome analysis has been used to study why lotus roots turn brown when stored. Through this method, researchers have found key factors that cause discoloration, which is very helpful in maintaining the quality and appearance of lotus roots (Gong et al., 2024).

6.2 Community-led cultivation initiatives and cooperative models

Some places do not rely on one person or a company, but are promoted by the community to promote lotus root cultivation. This cooperation model is also very successful. Farmers and researchers work together, they share experience and try methods together, such as establishing a better callus induction system. This system can

improve the reproduction capacity of lotus roots and can also increase yield by selecting appropriate varieties and adjusting environmental conditions (Yang et al., 2015; Li et al., 2023; Wang, 2024). This cooperation makes production efficiency higher and encourages the use of new technologies, which is of great help to promote sustainable planting methods.

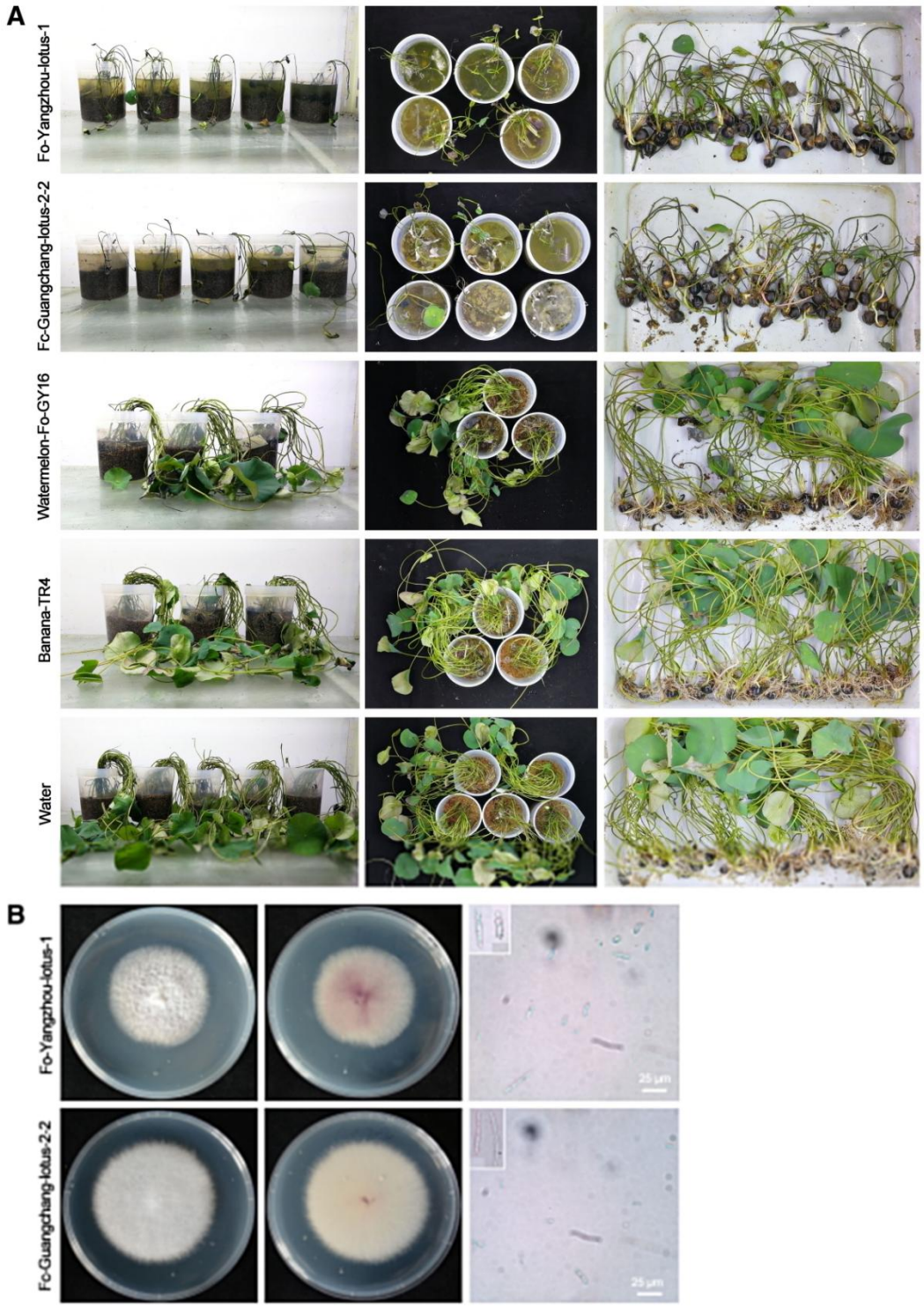

Figure 2 Pathogenicity assays and the comparison in morphology of *Fusarium oxysporum* Yangzhou-lotus-1 (Fo-Yangzhou-lotus-1) and *F. commune* Guangchang-lotus-2-2 (Fc-Guangchang-lotus-2-2) (Adopted from Deng et al., 2021)

Image caption: A, Disease symptoms of lotus seedlings inoculated by Fo-Yangzhou-lotus-1, Fc-Guangchang-lotus-2-2, Watermelon-Fo-GY16, Banana-TR4, and mock (water treatment). The photos were taken at 60 days postinoculation. B, The morphology of potato dextrose agar cultures, sporodochial conidia, and microconidia of indicated strains (Adopted from Deng et al., 2021)

6.3 Lessons from international collaborations and research programs

Many technologies actually come from international cooperation projects. Foreign research teams and local cooperation have introduced some very advanced tools and ideas. RNA sequencing technology can help study the mechanism of lotus root browning and find solutions. This is useful for extending the shelf life of lotus roots (Zhu et al., 2022). There are also some portable detection equipment, such as the LAMP detection tool mentioned just now, which was also developed under the cooperation of international teams. These tools help farmers quickly identify diseases without waiting for laboratory reports. These cooperation shows that in the face of common agricultural problems, it is easier to find a good way at home and abroad.

7 Technological Innovations in Lotus Rhizome Cultivation

7.1 Smart agriculture and automation

Smart agriculture and automation have begun to play an important role in the cultivation of lotus rhizomes. The development of rapid diagnostic tools such as LAMP detection can quickly identify pathogens that cause rhizome rot, such as *Fusarium alaris* and Fusarium. This technology enables farmers to make informed decisions about pesticide use and disease management, thereby increasing the efficiency of cultivation practices and reducing crop losses (Feng et al., 2016).

7.2 Genetic improvement and biotechnology

Advances in biotechnology have led to the establishment of a high-efficiency callus induction system for lotus, which is crucial for genetic improvement and rhizome development research. By optimizing factors such as explant type, growth medium and environmental conditions, the researchers achieved efficient callus production. This system not only facilitates genetic research, but also supports the production of valuable secondary metabolites such as benzylisoquinoline alkaloids, which are important for plant defense and human health applications (Li et al., 2015; 2023).

7.3 Data-driven decision making

Data-driven methods are increasingly used to improve the processing and storage of lotus roots after harvest. Transcriptome analysis has been used to understand the molecular mechanisms of browning during storage, which is the main issue affecting the marketability of lotus roots. By identifying differentially expressed genes associated with browning, researchers can develop strategies to alleviate this problem, thereby extending the shelf life of lotus roots and maintaining the quality of lotus roots during long-term storage and transportation (Deng et al., 2021).

8 Concluding Remarks

Recently, there have been a lot of new progress in the cultivation and post-harvest treatment technology of lotus roots. These progress is mainly to improve yield and quality. One important achievement is the establishment of an efficient callus induction system. This system makes the lotus root more likely to form callus by selecting the appropriate variety, adjusting the lighting conditions, and selecting the appropriate explant development stage. Combined with specific culture media and plant hormones, the efficiency of seedling cultivation can greatly improve. In terms of storage, researchers have also solved some problems, such as browning of lotus roots. Now with anti-browning solutions and RNA sequencing technology, key genes that cause browning can be found, thereby extending the shelf life of lotus roots and keeping them on the market.

Another key point is disease prevention and control. A quick diagnosis method like LAMP detection can quickly detect whether lotus root is infected with Fusarium. This bacteria is the main cause of rhizome rot and has a particularly great impact on yield. Now with new technology, farmers can detect diseases faster and deal with them in time to avoid losses. These technological advances not only improve planting and treatment effects at present, but also have great significance for future agricultural development. For example, callus system can be used in breeding to help select better lotus root varieties. Understanding the browning mechanism can also develop better preservation methods. Rapid diagnostic tools can also make pest management more effective, helping crops grow healthier and produce higher yields.

In the future, research should promote these technologies to large-scale agriculture, and we can also try to see if they can be used on other crops. To make these results really work, researchers, growers and policy makers work together. Share your experience and resources to speed up the promotion of new technologies. Cooperation projects can also help farmers in different regions adjust their practices according to local conditions. Holding some training classes and lectures can also allow more people to understand these technologies and learn how to use them. Only when everyone works together can lotus root planting become more stable and profitable.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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