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Genetic and Environmental Factors Controlling Tuber Shape in Commercial Varieties

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Abstract Tuber shape is an important agronomic trait in many commercial crops, with a significant impact on the market value and economic benefits. In this study, the genetic and environmental factors controlling tuber shape were systematically analyzed, and the localization and functional annotation of major genes and loci in quantitative traits (QTL) were revealed. We further explored the mechanism of genetic and environmental interaction, and found that gene expression is significantly responsive to environmental signals, and that genetic and environmental factors jointly influence the formation and stability of tuber shape. In polyploid genomic crops, genetic regulation exhibits complexity and requires further resolution of its contribution to phenotypic variation. The results deepen the understanding of the mechanism of tuber shape formation, and provide the theoretical basis and practical guidance for the accurate breeding of tuber shape in commercial crops. The analysis also points out the technical bottlenecks in the current research, and explores the application prospects of high-throughput omics technology and multi-environment data integration in future research, emphasizing the need for international collaboration and data sharing. This study is important to improve the market competitiveness and breeding efficiency of tuber crops.
Keywords Tuber shape; Genetic factors; Environmental factors; QTL, Marker-assisted selection (MAS); Gene editing techniques

1 Introduction

The shape of potato tubers is an important quality trait that directly affects their market value. The different shapes of potatoes determine their positioning in processing markets such as French fries and potato chips, where certain shapes are most suitable for enhancing efficiency and product quality. If the shape of the tubers is irregular or not good, the processing cost will rise and the consumer acceptance will also decline. Therefore, making the shape of tubers more uniform has become the main goal of potato breeding projects (Fan et al., 2022). The shape of the tuber also affects processing and storage, as well as the appeal of potatoes to buyers, which increases their economic significance (Si et al., 2018).

The shape of potatoes is influenced by both genes and the environment. Studies have shown that several loci in DNA (referred to as quantitative trait loci (QTLS)) are associated with shape changes. The most important ones among them are located on chromosomes 2, 4, 6 and 10. A specific locus on chromosome 10, namely the Ro locus, is regarded as the main controller of the round tuber.

The growth environment is also of vital importance. Soil type, available nutrients and weather all affect the formation of tubers. For instance, different levels of nitrogen and potassium can alter the depth of the bud eyes and affect the uniformity of the shape. These results suggest that good field management is the key to achieving an ideal tuber appearance (Yusuf et al., 2024). New measurement methods are now very common. Technologies such as 3D imaging and digital analysis make shape measurement more accurate. They can also help scientists better study how genes and the environment work together.

This study will explore how genes and the environment jointly shape the tuber shape of commercial potato varieties, and utilize advanced tuber shape measurement and genetic testing methods to identify the main loci and conditions related to tuber morphology. Researchers selected a large number of diploid and tetraploid varieties to cover a wide range of genetic variations. This study focuses on mapping the genetic regions related to tuber shape, testing how different environments affect tuber traits, and constructing predictive models using genetic and phenotypic data. These findings can assist potato breeding projects in designing new varieties with ideal tuber shapes to meet the diverse market demands.

2 Case Background and Research Methods

2.1 Selection criteria and characteristics of commercial varieties

In this study, the screening criteria for commercial potato varieties mainly include market value, genetic differences and tuber shape. Varieties such as Van Gogh, Yukon Gold, Bellona, Lady Rosetta, Pito and Sabina were selected due to significant differences in tuber shapes and large market demand. Some materials carry known tuber shape markers, such as the Ro locus located on chromosome 10 (Hasan et al., 2021). The study also supplemented several varieties that demonstrated high yields and stability in different environments, such as Twister, Alouette, Kokra, Levante and Gardena.

2.2 Description of the study area and environmental conditions

Experiments were conducted in multiple regions to capture different environmental conditions. Organic farms in Poland have demonstrated a strong genotype-environmental interaction (GEI) in terms of yield and quality traits. Soil, climate and farming methods and other conditions vary, all of which can affect the shape of the tubers (Goldman et al., 2023). Other research sites include research farms in Woxhall, Alberta, Canada and Umuddik, Umuahia County, Abia State, Nigeria, where there are a wide variety of soil and climate factors.

2.3 Data collection methods: genetic data, environmental data, and tuber shape evaluation

Genetic data are derived from high-density linkage maps and QTL-seq. The Ro locus on chromosome 10 was located in a diploid isolated population, in which the main QTL controlling the shape of the tuber was identified. DNA methylation and transcriptome analysis are helpful for locating candidate genes related to shape differences. Researchers collected environmental data from all locations over the years, covering soil, climate and farming methods. The GEI was analyzed and studied using AMMI and GGE bilayer maps to examine how the environment affects yield and tuber shape.

The recording of tuber shapes was carried out by combining manual measurement with imaging tools. The aspect ratio (L/W) is the main measurement index, supplemented by 3D modeling and RGB imaging techniques to display detailed surface properties and growth defects (Neilson et al., 2021). In addition, feedback from agronomists and potato growers is also used to assess the shape of tubers to meet the demands of the processing market.

2.4 Research design: experimental setup and analytical framework

The experiment used a random block design. It took place at several sites over multiple years. Similar methods were used in yam tuber studies. These tests mixed different varieties and shapes. The study used three types of data: genetic, environmental, and physical traits. This helped find the main factors that shape tuber form. Researchers used linkage mapping and QTL-seq to precisely locate related genes (Tatarowska et al., 2024). Gene activity data and chemical tags on DNA showed how these affect tuber growth. Later, imaging tools and two statistical methods (AMMI and GGE biplots) helped see how environments changed tuber shape.

3 Role of Genetic Factors in Tuber Shape

3.1 Major genes controlling tuber shape and QTL analysis

The shape of potato tubers is an important trait, controlled by multiple major genes and quantitative trait loci (QTL). The Ro locus located on chromosome 10 is one of the key genetic loci. The round allele (Ro) is dominant relative to the long allele (ro) (Zhao et al., 2023). QTL studies have also reported other loci, such as TScha6 on chromosome 6 of diploid potatoes and QTL on chromosomes 2, 4 and 10 of tetraploid potatoes. These loci together explain most of the variations in the shape of the tubers. The Ro locus alone can account for up to 75% of genetic differences.

3.2 Distribution of genetic variation and functional annotation of candidate genes

The genetic variation of tuber shape is distributed on multiple chromosomes, mainly on chromosomes 2, 4, 5, 6 and 10. The candidate genes in these regions have been studied through annotation. For example, the Ro locus contains 18 genes, among which 5 genes are candidate genes discovered after tissue studies and transcriptome sequencing (Tiwari et al., 2021). Other genes related to hormones, sugar utilization, transcriptional regulation and cell wall changes are also associated with tuber shape.

3.3 Correlation analysis between genotypes and tuber shape phenotypes

Links between genotypes and tuber shapes have shown clear results. The CAPS marker C6-58.27_665, tied to the TScha6 QTL on chromosome 6, is strongly linked with the tuber length/width ratio (r = 0.55, $p < 0.01$). QTLs on chromosome 10 also show consistent ties with tuber shape, both in visual ratings and in ratio measures. These findings support the use of marker-assisted selection in potato breeding to improve shape traits.

3.4 Influence of polyploid genome characteristics on genetic regulation

The potato is polyploid, which makes genetic control more complex. Each locus of tetraploid has multiple alleles, which makes genetic and QTL mapping more difficult (Park et al., 2024). Even so, new molecular markers and advanced polyploid tools make the discovery of key QTLS and genomic breeding worth estimating. These methods help breeders select better clones earlier and choose tuber shapes more effectively.

4 Impact of Environmental Factors on Tuber Shape

4.1 Regulation of tuber development by temperature and water availability

Temperature and water are key factors for tuber growth and shape. High temperature often changes important growth pathways and slows tuber development. For example, the FT homolog StSP6A is blocked under high heat, which affects both the early and late stages of tuber growth (Park et al., 2020). In the swelling stage, even a small rise in temperature can lower yield and quality. A steady water supply can ease part of this effect. But even with enough irrigation, yield still falls when the heat is high. This shows that water is very important for keeping tuber size and shape (Huntenburg et al., 2021). When water is lacking, more tubers grow in a deformed way. Stable water supply is therefore essential.

4.2 Correlation between soil structure, nutrient levels, and tuber shape

Soil type and nutrients can also significantly affect the shape of tubers. Dry and hard soil can slow down root growth, limit water supply, thereby altering the growth of buds and causing uneven tuber morphology. Soil compaction and water shortage can reduce the final yield and change the size distribution of tubers, usually resulting in an increase in the number of tubers but smaller ones (Musse et al., 2024). The position of the tuber in the soil is also very important, as the water flow between the mother plant and the tuber during the leaf drying process will change the growth pattern of the tuber (Gonzales et al., 2020) (Figure 1). Planting density and watering methods can also change the traits of tubers. In the early stage of tuber growth, a colder and wetter environment will make the tubers longer, heavier, and produce more buds and buds.

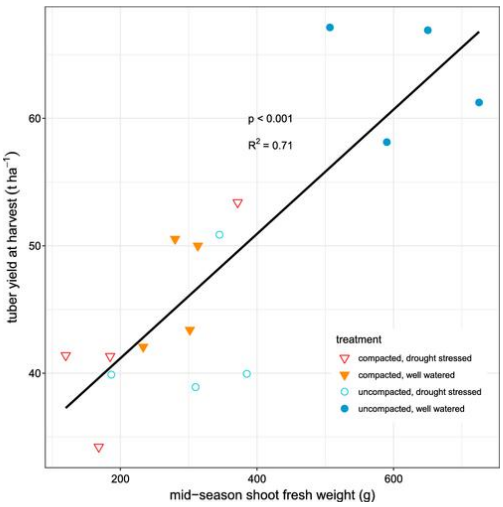

Figure 1 Association of reduced biomass under complete ground cover and tuber yield per hectare (Adopted from Huntenburg et al., 2021)

4.3 Modulation of tuber shape stability by environmental factors

Tuber shape is influenced by temperature, moisture, and soil quality. These factors control when tubers sleep and when they start growing. Temperature and humidity decide when tubers wake from dormancy and begin growth. High temperatures usually disrupt the transportation of sugar within plants. This will reduce the yield and make the tuber shapes inconsistent. Drought conditions or high-temperature stress can also slow down the swelling of tubers, reducing yield and quality (Kondhare et al., 2021). These factors seldom act alone; they are usually combined with genetic control. For instance, the StCDF1-StFLORE region helps manage water use and participates in tuber formation. This indicates how genes and the environment interact when conditions change (Li, 2024).

5 Mechanisms of Gene-Environment Interaction

5.1 Relationship between gene expression and environmental signals

The genes of potatoes respond to external signals. The length of sunlight and the chemical tags on DNA are particularly important. When the level of microRNA156 is relatively high, tubers can form from above-ground stems under short-day conditions. This indicates how the environment directly affects gene behavior and growth patterns (Thomson et al., 2022). Another example is the DXS gene, which contributes to the synthesis of isoprene. The change of this gene will affect the morphology and germination characteristics of the tubers. This once again demonstrates the close relationship between growth conditions and gene function (Nahirnak et al., 2022).

5.2 Comprehensive effects of gene-environment interactions on tuber shape formation

The shape of the tuber is the result of the combined effect of genetic background and environmental signals. The Ro site on chromosome 10 is the main regulatory factor and can explain most of the shape differences. Meanwhile, the length of light exposure and epigenetic modifications also play a role in shaping the form. Studies have found that there are significant differences in DNA methylation patterns and transcriptional activities between round tubers and long tubers, indicating that environmental signals change the appearance of tubers by regulating gene expression (Kolchanov et al., 2017).

5.3 Analysis of multi-environment experimental results in the case study

Experiments in different regions have shown that gene-environment interaction (GEI) significantly affects the yield and quality of potatoes. A study on organic farms in Poland found that the yield differences mainly stem from the environment. However, plant genes and GEI also play significant roles (Ma et al., 2024). Some varieties can maintain high and stable yields under different conditions. This indicates that combining excellent genes with environmental adaptability is of vital importance. This discovery indicates that in order to achieve better results, breeding programs should take into account both genetic effects and environmental factors.

5.4 Genetic and environmental regulation of phenotypic adaptability and stability

The adaptability and stability of tuber traits depend on both genes and the environment. For instance, the StGA2ox1 gene responds to external signals. It can alter the level of growth hormone, helping the tubers start growing earlier (Merrick et al., 2022). Transcription factors within cells and chemical tags on DNA also play a crucial role in shaping the development of tubers and their final morphology (Deng and Chen, 2024). These studies show that genetic programs and external pressures work together to shape the way potato tubers form and their final form.

6 Strategies for Improving Tuber Shape in Commercial Varieties

6.1 Application of marker-assisted selection (MAS) using genetic information

Marker-assisted selection (MAS) is a commonly used breeding method, which is particularly effective for single-gene traits or major QTL-related traits. In the study of potato tuber shape, the use of molecular markers closely related to superior traits can significantly improve breeding efficiency (Figure 2). For instance, the QTL TScha6 found on chromosome 6 of diploid potatoes is closely related to the shape of the tubers. The CAPS tag C6-58.27_665 has also been confirmed to be related to the aspect ratio height. These markers can be directly used in MAS to help quickly screen plants with more ideal shapes and accelerate the breeding process of superior commercial varieties (Hickey et al., 2019).

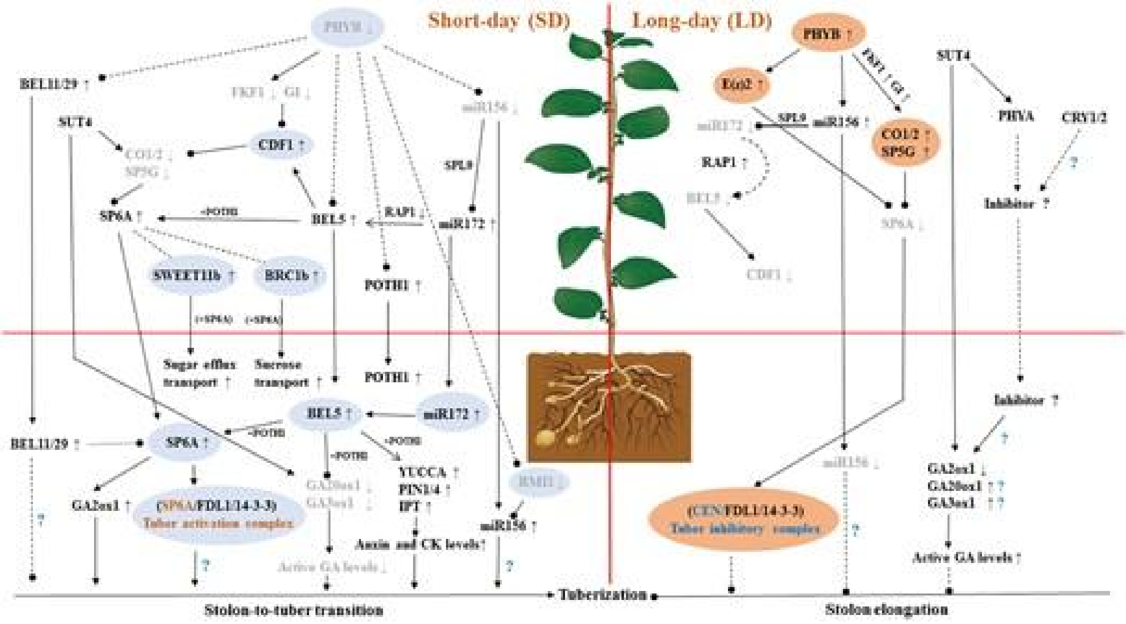

Figure 2 Model of the potato tuber chemical pathway (Adopted from Kondhare et al., 2021)

6.2 Optimizing environmental management to regulate tuber shape

The shape of tubers is not only regulated by genes but also deeply influenced by external conditions. Soil texture, irrigation methods and nutrient supply will all change its growth pattern. In recent years, rapid breeding has been regarded as an effective means. Accelerating growth in a controllable environment and combining it with traditional methods can significantly shorten the selection cycle. Through reasonable environmental regulation, the genetic potential of tubers can be manifested more clearly, thereby helping commercial varieties maintain a more stable shape (Ahmad et al., 2022).

6.3 Potential of gene-editing technologies (e.g., CRISPR) in tuber shape breeding

Gene editing tools like CRISPR offer new methods for precisely controlling the shape of potato tubers. Unlike traditional genetic methods, this technique directly alters the target gene without the need to add DNA from other species. This approach reduces regulatory concerns and public worries about genetically modified products. Studies show that CRISPR can improve various potato traits, including tuber shape. Breeders can use this tool to rapidly change key genes, thereby greatly improving the speed and efficiency of breeding (Ćeran et al., 2024).

6.4 Integrated breeding approaches combining genetic and environmental factors

Improving the shape of commercial potato tubers usually requires a combination of multiple methods. A good strategy is to combine genetic tools such as marker-assisted selection (MAS) and gene editing with better field management. This includes improving the soil, managing water sources and adopting scientific planting methods. The combination of genetic and environmental methods can enhance the accuracy of selection and accelerate the speed of improvement. This complete method helps maintain the stability of the tuber shape and enables the variety to better adapt to different growth conditions, thereby increasing its market value (Huang et al., 2022).

7 Research Challenges and Future Perspectives

7.1 Current technical bottlenecks in tuber shape research

The research on tuber shapes is still subject to many technical limitations. Shape measurement remains a challenge. Traditional methods such as manual determination of aspect ratio are not only time-consuming and laborious, but also often ignore secondary growth or slight irregular shapes (Semenenko et al., 2023). In addition, identifying the specific genes that control shape is also quite challenging. Take the Ro gene on chromosome 10 as an example. Precise positioning requires the construction of a high-density genetic map and the long-term collection of a large amount of phenotypic data. Although the combination of genetics and transcriptomics provides important clues, achieving precise localization and gene cloning remains a challenging task.

7.2 Prospects of high-throughput omics technologies in tuber shape studies

New technologies such as genomics, transcriptomics and methylomics offer opportunities for improving the study of tuber shape. Genome-wide association studies (GWAS) have identified multiple important SNP loci related to tuber shape and bud depth, which can serve as potential breeding markers. Transcriptome and methylation studies have also screened out some candidate genes, which are closely related to hormone regulation, glucose metabolism and cell wall modification (De Jesus Colwell et al., 2021). The accuracy of predicting tuber traits can be further improved if different omics data are combined with machine learning methods (such as random forest regression) (Aliche et al., 2019).

7.3 Importance of data sharing and international collaboration

Data sharing and cross-border cooperation are conducive to promoting the development of potato shape research. When teams from different countries integrate their genetic resources and field records, the accuracy of genetic research (GWAS) and trait mapping (QTL) can be improved (Bist et al., 2023). Cooperation also helps to create common standards for measuring traits and supports shared databases. This makes it easier to compare and verify the results among different studies.

New tools such as drone imaging also support this kind of cooperation. Drones have accelerated large-scale field trials. They also help to link genetic data with the actual growth of tubers in farmers' fields and connect genes with real-world outcomes.

7.4 Application potential of predictive models and multi-omics integration

The use of predictive models containing multiple biological data offers new opportunities for tuber shape breeding. Machine learning methods (including random forest regression) can identify key genes and pathways that affect tuber traits. This provides a strong marker for selection (Acharjee et al., 2016).

By integrating genomics, transcriptomics and other data types, it is possible to have a clearer understanding of how genes control the growth and morphology of tubers. It also helps to discover important candidate genes and their networks.

These combined methods have accelerated the breeding speed and improved the stability of the shape of the tubers under different conditions. This eventually breeds potato varieties that are more adaptable and have higher market value.

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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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