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Agronomic Traits of Cassava and Their Genetic Bases: A Focus on Yield and Quality Improvements

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Abstract Cassava (*Manihot esculenta* Crantz) is a key food and industrial crop in the global tropics, valued for its high adaptability to marginal soil conditions and the starch-rich nature of its roots. As the global population continues to grow and climate change becomes more severe, the scientific community is seeking to address the challenges of food security and agricultural sustainability by improving cassava production and processing quality. This paper reviews the research progress of cassava agronomic traits and genetic basis in recent years, with special attention paid to the mining of genetic diversity, improvement of agronomic traits and application of modern biotechnology in cassava breeding. Studies have shown that the combination of traditional selective breeding, molecular marker-assisted selection (MAS), gene editing and other technologies has greatly improved the cassava root yield and starch quality. In addition, the implementation of precision agronomic technology and smart agriculture provides new possibilities for optimizing cassava production management and improving its environmental adaptability. The paper also discusses the direction of future cassava research, including further development of genetic resources, improving cassava's resilience to environmental changes and its role in the global food system.

Keywords Cassava; Agronomic traits; Genetic basis; Biotechnology; Yield and quality improvement

1 Introduction

Cassava, as one of the most important starchy root crops in the tropical regions of the world, has become the main source of carbohydrates for about 750 million people due to its unique ecological adaptability and high yield characteristics, especially in those marginal environments with hot climates and poor land, cassava plays an irreplaceable role. Cassava is grown in tropical regions around the world, from the grasslands of Africa to the rainforests of Latin America to certain tropical regions of Asia, where it is closely linked to food security and livelihoods. In these areas, cassava is not only a major food crop, but also an important cash crop, providing a steady source of income for the local population.

On a global scale, cassava planting area and production have maintained a steady growth trend. Although its planting area and yield are not yet comparable to food crops such as rice, wheat and maize, cassava still ranks fourth in global food crop production due to its unique advantages in tropical regions (Hyman et al., 2012). This status is a testament to the importance of cassava in global agricultural production and food supply. Although the yield and importance of cassava cannot be ignored, research on its breeding and agronomic traits faces many challenges. As a crop with long growth cycle and heterogeneous genetic background, it is often difficult to achieve its breeding goals. For example, breeding goals such as increasing cassava yield, improving the quality of its roots and developing resistance to disease require a long period of research and experimentation (Fregene et al., 2001). At the same time, due to the large differences in soil and climate conditions in cassava planting areas, it also brings great challenges to the research of cassava breeding and agronomic traits.

In addition, the current cassava breeding is also facing the problem of slow genetic improvement process. Due to the lack of in-depth understanding and effective utilization of cassava genetic characteristics, as well as the lack of sufficient scientific research investment and technical support, the process of cassava genetic improvement is relatively lagging behind. This not only limits further increases in cassava production, but also limits its larger role in the global food supply (Hyman et al., 2012). Therefore, the future research on cassava breeding and agronomic traits needs to pay more attention to scientific strategies and technological innovation, strengthen the research on cassava genetic characteristics, deeply understand its genome structure and function, and provide theoretical support for genetic improvement. In addition, soil and climate adaptation research for cassava cultivation needs to be strengthened to cope with the differences in planting conditions in different regions. The purpose of this study is to introduce the global status and importance of cassava, analyze the current challenges in the study of cassava agronomic traits, and look forward to future scientific strategies and techniques for cassava breeding and agronomic improvement to explore the global importance of cassava, challenges faced and current and future scientific research progress in improving its agronomic traits.

2 Basic Characteristics of Cassava

2.1 Biological description of cassava

Cassava (*Manihot esculenta* Crantz) is a perennial shrub whose roots form fleshy tubers that are used primarily for starch storage. The stem of cassava is upright and strongly branched, and can be as high as 1 to 3 m. The leaves are palmate compound leaves, usually each leaf is composed of 5 to 7 lobules, lobules are long oval, the edge is slightly wavy. At the beginning of growth, the Cotyledons of cassava unfold and photosynthesize, which is one of the growth characteristics of the seed after germination. As the plant matures, the roots gradually expand to form tubers, which are the main edible part of cassava (Pujol et al., 2005).

Cassava usually has a growth cycle of 12~18 months, depending on the variety and cultivation conditions. At the early stage of growth (the first 2~3 months), the biomass accumulation of cassava is relatively slow. Since then, with the improvement of climate conditions and the accumulation of nutrients, the growth rate of cassava will be significantly accelerated, especially in the growth of the roots and the accumulation of starch. By the end of the growth period, even if the growth of the above-ground part begins to slow down, the accumulation of starch in the roots continues until harvest. Throughout the growing cycle, cassava's nutrients are concentrated in its tubers, which is why it is an important energy source

2.2 Main planting area and environmental adaptability

Native to South America, the potato has found its new home in tropical and subtropical regions around the globe. From the vastness of Africa to the prosperity of Asia to the rich diversity of Latin America, cassava is grown across the globe. Cassava was chosen as an important crop in these regions not only because of its high yield potential, but also because of its adaptability to the environment.

In Africa, particularly sub-Saharan Africa, cassava is considered an important food crop. Here, cassava is not only the main source of People's Daily diet, but also the key to food security in the region. With many parts of Africa facing environmental challenges such as drought and poor soil, cassava's remarkable adaptability makes it an ideal crop. Even under harsh environmental conditions, cassava remains resilient and provides a stable source of food for local populations (Nassar and Ortiz, 2006).

Cassava's adaptability is also reflected in its excellent drought resistance. During the dry season, many crops struggle to survive due to lack of water, but cassava thrives in such an environment. This is thanks to the depth and breadth of the cassava root system, which allows it to seek out and absorb scarce water underground. In addition, cassava leaves also have properties that reduce water evaporation, further enhancing its ability to survive in arid environments (El-Sharkawy, 2003).

2.3 Main uses of cassava

Cassava is an important part of the diet in many countries, especially in Africa and Latin America. It can be processed into many forms, such as starch, flour and various local specialties, such as Gari in Africa and Tapioca in Brazil. Tapioca starch is widely used in the food industry due to its unique thickening and structural properties (Parmar et al., 2017).

Another important use of cassava is the production of biofuels, especially bioethanol. Cassava contains a high amount of starch, which can be converted into ethanol through the fermentation process and used as fuel. This is particularly important in the context of growing global energy demand, and cassava offers a sustainable energy solution (Li et al., 2017).

3 Agronomic Traits of Cassava

3.1 Yield-related traits

3.1.1 Root weight and number

The root weight and number of cassava are the main indexes to evaluate its yield. Studies have shown that root tuber development and yield are related to a variety of genetic and environmental factors. Okogbenin and Fregene (2002) mentioned that the early expansion of root tuber was closely related to root diameter, dry weight, harvest index and other traits, and the selection of these traits could significantly improve the early yield. In addition, the number and weight of root tubers were positively correlated with the overall growth performance of plants, indicating that the root yield could be effectively increased by improving the overall growth status of plants (Okpara et al., 2014).

3.1.2 Growth rate and growth cycle

The growth rate and growth cycle of cassava also have an important impact on its overall yield. Studies have shown that different varieties of cassava have significant differences in growth rate and final yield under different nitrogen fertilizer levels, and these differences reflect the different effects of different genetic backgrounds on environmental resource use efficiency (Phuntupan and Banterng, 2017). In addition, cassava varieties with short growth cycles can reach harvest time faster and are suitable for use in multi-crop rotation systems, thus improving the overall utilization rate of land (Suja et al., 2010).

3.2 Quality-related traits

The starch content and quality of cassava are key factors in evaluating its commercial value. Starch yield generally accounts for 20%-35% of cassava dry matter, and there are significant differences among different varieties. The Amylose content of starch affects its gelatinization properties and the quality of the final product. In the study of Ceballos et al. (2007), a cassava natural mutant was found to show abnormally low amylose content, which has higher peak viscosity and lower solubility, showing different potential for industrial applications.

The fiber content of cassava root directly affects the taste and digestion of food. The variation of fiber content in cassava root has a direct effect on the grain size distribution and whiteness of processed products, such as flour. Studies have shown that different varieties of cassava have a negative correlation between fiber content and whiteness of treated flour (Chisenga et al., 2019).

The size and shape of the root is another important factor in determining the value of cassava as a commodity, especially in agricultural markets and processing industries. The size and shape of root tuber are influenced by both genetic and environmental factors, and are closely related to yield and harvest index. For example, it has been found that under certain environmental conditions, the root size of some varieties is larger than that of others, which is extremely important for selecting varieties suitable for specific market needs (Oliveira et al., 2014).

3.3 Stress resistance traits

Cassava is considered to be a highly drought-adaptable crop, with its unique physiological and biochemical mechanisms enabling it to survive and grow under extreme drought conditions. Studies have shown that cassava can reduce water loss in the face of drought stress by adjusting the opening and closing of leaf stomata, while increasing the ability of roots to absorb water from deep soil. In addition, cassava enhances its drought adaptability by regulating photosynthesis and protective enzyme activity, thereby maintaining plant growth and development (Shan et al., 2018).

Cassava also shows some resistance to a variety of pests and diseases. Cassava, for example, has been found to have some resistance to red spider mites, mainly through a combination of its growing conditions and the plant's own defense mechanisms. Studies have shown that cassava exhibits high resistance to red spider mites under drought conditions, which may be related to its physiological and biochemical reactions, such as the accumulation of secondary metabolites in the plant (Pratiwi et al., 2022). In addition, cassava improves resistance to pests and diseases by increasing the activity of certain defense enzymes and altering hormone levels in the plant, which provides a possible biomarker for cassava's resistance breeding (Zhao et al., 2015).

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4 Genetic Basis of Cassava

4.1 Genetic diversity and genetic resources

Cassava germplasm resources are very rich, including various local varieties and improved varieties. These germplasm resources play a key role in multiple research and breeding programs around the world, especially in Africa, Latin America and tropical Asia. Cassava germplasm resources not only preserve the genetic diversity of crops, but also provide a basis for the improvement of disease resistance, resistance to retrograde and yield traits. For example, a large number of cassava indigenous varieties and cultivars have been collected and preserved in national breeding programmes in Tanzania, Uganda and Kenya, and these resources show moderate genetic variation and some degree of genetic bottleneck, which has important implications for the development of regional cassava genetic resource conservation strategies (Kawuki et al., 2013).

The genetic variation of cassava is very broad, including diversity of morphological characteristics, molecular markers and genetic background. Asare et al. (2011) study in Ghana used morphological descriptors and simple sequence repeat (SSR) markers to analyze the genetic diversity of 43 cassava varieties, which showed significant genetic differences at morphological and molecular levels, providing important information for cassava breeding and germplasm resource management (Figure 1).

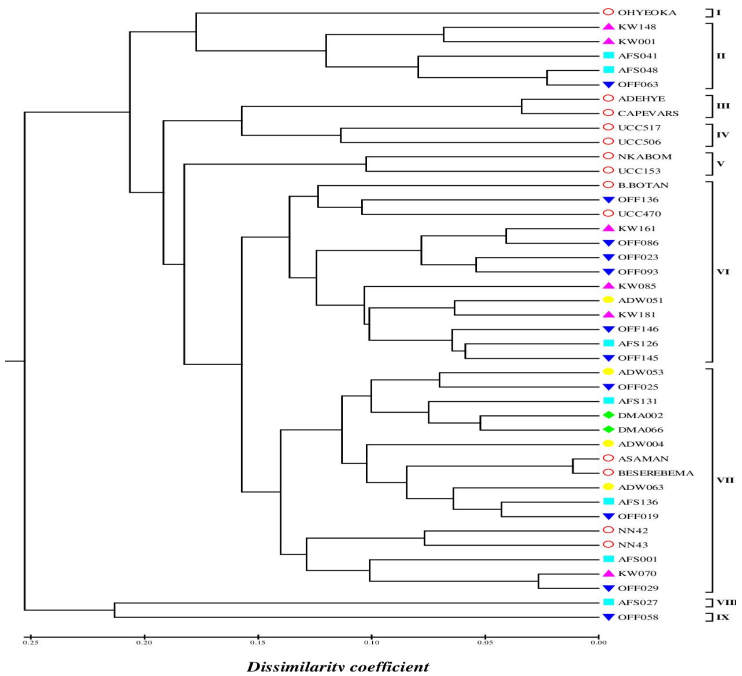

Figure 1 Dendrogram showing genetic dissimilarity among the cassava accessions based on SSR data (Adopted from Asare et al., 2011)

4.2 Key genetic factors affecting agronomic traits

In cassava, multiple quantitative trait loci (QTLs) have been identified, related to productivity, plant structure, and other agronomic traits. For example, one study successfully mapped multiple QTLS that affect cassava production performance and plant building traits, including plant height, branch height, and root yield. These QTLS showed significant genotypic and environmental interactions under different environmental conditions, emphasizing the importance of environmental factors in cassava trait expression (Okogbenin and Fregene, 2003).

In the genetic study of cassava, the relationship between phenotype and genotype is the key to understanding the genetic mechanism. Through genome-wide association studies (GWAS), the scientists identified more than 40 QTLS associated with biodefense, quality, and agricultural morphological traits in cassava. Rabbi et al. (2020) not only revealed new genetic loci, but also provided a catalog of favorable SNP markers and candidate genes that could be used in cassava breeding programs, which could help improve cassava agronomic traits and stress resistance (Table 1).

Table 1 Broad-sense heritability calculated on a plot-mean basis and SNP heritability estimates, variance components and coefficients of variation of 14 traits in cassava GWAS panel (Adopted from Rabbi et al., 2020)

Trait	SNP-h^2	H^2	σ_g	$\sigma_{g\times e}$	σ_e	CV
CMD severity	0.434	0.766	0.783	0.086	0.140	63
CGM severity	0.165	0.149	0.074	0.177	0.244	19
Apical pubescence	0.502	0.531	0.175	0.083	0.071	113
Leaf shape	0.499	0.510	0.679	0.475	0.178	22
Apical leaf colour	0.496	0.567	1.160	0.629	0.601	23
Mature leaf greenness	0.586	0.531	0.427	0.186	0.191	18
Petiole colour	0.716	0.754	3.322	0.602	0.485	33
Harvest index	0.308	0.538	0.010	0.002	0.007	28
Plant type	0.384	0.369	0.376	0.180	0.465	38
Quter stem colour	0.516	0.388	0.907	0.191	1.241	22
Total carotenoids content (colour chart)	0.675	0.726	0.401	0.066	0.085	49
Dry matter content	0.565	0521	14.776	3.385	10.184	15
Root periderm colour	0.548	0.610	0.190	0.035	0.086	19
Root cortex colour	0.518	0.415	0.070	0.036	0.062	20

Note: H^2 is the broad-sense heritablity, σ_g is the clonal genotypic variance, $\sigma_{g\times e}$ is the variance due to genotype by environment (G×E), and σ_e is the being the residual variance

4.3 Application of molecular markers and genomics in cassava improvement

Molecular marker-assisted selection (MAS) plays a key role in cassava improvement, especially in accelerating the selection process for genetic traits. By utilizing specific molecular markers, such as single nucleotide polymorphisms (SNPS) and simple sequence repeats (SSRS), breeders are able to more precisely select plants with desired traits. A study by Mba et al. (2001) using SSR markers provided a preliminary molecular genetic map of the cassava genome, which helped to locate quantitative trait loci (QTL) and genetic analysis, thereby improving the efficiency and accuracy of breeding. In addition, genotyping based on high-throughput sequencing (NGS) techniques, such as Genotyping by sequencing (GBS), has emerged as a highly effective MAS tool suitable for a wide range of plant breeding programs (He et al., 2014).

Gene editing technologies, particularly the CRISPR/Cas9 system, offer revolutionary improvements in cassava breeding. By precisely modifying the DNA sequence of specific genes, these techniques allow scientists to introduce or correct genetic variants directly into the cassava genome, thereby improving the performance of specific agronomic traits. Dheer et al. (2020) mentioned that gene editing technology has been used to develop cassava varieties with improved disease resistance and enhanced nutritional quality. In addition, transgenic techniques, such as the use of Agrobacterium mediated transformation systems, have also been used to introduce foreign genes into cassava to produce new traits, such as improved starch quality and insect resistance.

5 Current Cassava Improvement Strategies and Progress

5.1 Combination of traditional breeding and modern biotechnology

In the current cassava improvement strategy, the combination of traditional breeding methods and modern biotechnology is particularly important. By integrating traditional selection with molecular marker-assisted selection (MAS), gene editing, and other biotechnologies, breeders are able to produce new varieties with high yields, high quality, and good stress resistance. For example, the International Centre for Tropical Agriculture (CIAT) has significantly increased cassava yields and dry matter content over the past few decades by working with international and national projects, supported by biological and social factors. This integrated breeding strategy has enabled many countries to develop improved varieties adapted to local conditions.

5.2 International cooperation and resource sharing

Across the globe, several research institutions and projects are dedicated to the improvement and development of cassava. The International Centre for Tropical Agriculture (CIAT) and the International Institute for Agricultural Biotechnology (IITA) are leaders in cassava research and breeding. These institutions have not only made significant progress in genetic improvement, but also conducted extensive research in agronomic management, pest control, and aftercare. In addition, the Global Cassava Partnership 21st Century (GCP21) conference focused on various aspects of cassava research, including addressing the challenge of climate change (Hyman et al., 2012). One successful example of cassava improvement is the promotion in Nigeria of improved varieties with high yields and disease resistance, combined with efficient processing techniques. This strategy has significantly increased farmers' productivity and income, further boosting local and national economies. The National Research and Extension Project, in collaboration with IITA, has widely disseminated these varieties and technologies, increasing the processing capacity of farmers and improving market acceptance and competitiveness of cassava products (Abdoulaye et al., 2014).

Table 2 Average reported cassava yields among farmers (Adopted from Abdoulaye et al., 2014)

Variable	Adopter	Non-adopter	Difference	Participating villages	Non-participating villages	Difference
Yield (ton/ha)	16.1±4	11±5	4.9**(114)	15.0±4	13.0±8	2**(5.2)

Note: Figures in the bracket are t-values; **means significant at 1 and 5%, respectively; Source: Survey data (2012)

6 Future Research Direction

6.1 Further exploitation and utilization of genetic resources

Cassava is an important crop, and its abundant genetic resources provide a broad space for scientific research. In the future research, further mining and utilization of cassava genetic resources will become one of the important directions. The study of cassava genetic diversity is the basis of exploiting and utilizing genetic resources. By collecting and sorting out cassava germplasm resources in different regions and under different ecological conditions, a comprehensive germplasm resource bank can be established, which can provide rich materials for subsequent research. At the same time, the use of molecular biology technology, in-depth study of cassava genome, reveal the rules and mechanisms of genetic variation, will help to find more favorable genes.

Through the combination of traditional breeding and modern biotechnology, the effective utilization of cassava genetic resources can be realized. Traditional breeding methods, such as cross breeding and selective breeding, can further improve cassava yield, quality and resistance on the basis of maintaining excellent characteristics. Modern biotechnology, such as gene editing and gene transfer, can achieve accurate transformation and optimization of cassava genes, thereby creating cassava varieties that are more adaptable to different environments and needs.

For the utilization of cassava genetic resources, it is also necessary to pay attention to its practical application value. For example, the efficient use of cassava genetic resources on small-scale farms using ECobiology can not only improve cassava yield and quality, but also bring economic benefits to local farmers. At the same time, through the excavation and utilization of cassava genetic resources, it can also provide strong support for the improvement and development of cassava industry chain and promote the sustainable development of cassava industry.

6.2 Application of precision agronomy and intelligent agricultural technology in cassava production

In the development process of modern agriculture, the application of precision agronomy and smart agricultural technology is gradually becoming a key driver for improving the efficiency and sustainability of crop production. For cassava, an important tropical crop, the introduction of these advanced technologies is also important. Through the application of precision agronomy and smart agriculture technologies, cassava producers can better manage land and resources and optimize planting schemes, thereby improving cassava yield and quality. The core of precision agronomy is to develop personalized management strategies based on the specific environment and conditions in which crops are grown. In cassava production, this means the need to precisely adjust the planting time, fertilizer application, irrigation frequency and other production links according to soil properties, climatic conditions, variety characteristics and other factors. Through the application of precision agronomy, cassava producers can maximize the potential of the land and resources, increasing the growth rate and yield of cassava.

Smart agriculture technology provides strong support for the implementation of precision agriculture. The application of advanced technologies such as remote sensing technology, big data analysis, and the Internet of Things allows cassava producers to monitor crop growth conditions, soil nutrient content, climate change and other information in real time, and adjust management measures in a timely manner based on these information. For example, through remote sensing technology, producers can detect the occurrence and spread of pests and diseases in time, and take effective measures to prevent and control them; Through big data analysis, producers can predict future weather changes and market demand based on historical data and current conditions, so as to make reasonable planting and sales plans.

However, the application of precision agronomy and smart agriculture technology also faces some challenges and limitations. The introduction of these technologies requires a large amount of capital and human resources, which may be unbearable for some regions and farmers with poor economic conditions. The application of these technologies requires certain professional knowledge and skills, and requires systematic training and learning by producers. Due to the complexity and diversity of cassava production, how to effectively apply these technologies to actual production still needs further research and exploration.

6.3 Long-term impacts of environmental changes on cassava production

In the context of global climate change, the long-term impact of environmental change on cassava production has gradually emerged, and has attracted wide attention. Cassava is a highly adaptable crop whose growth and yield are affected by a variety of environmental factors such as climate change, soil degradation and loss of biodiversity. Therefore, in-depth research on the long-term impact of environmental change on cassava production is of great significance for formulating adaptive planting strategies and ensuring sustainable development of cassava industry. The impact of climate change on cassava production cannot be ignored. As global temperatures rise and precipitation patterns change, the temperature and moisture conditions required for cassava growth will change. On the one hand, high temperature may reduce photosynthesis efficiency and enhance transpiration of cassava, thus affecting its growth rate and yield. On the other hand, changes in precipitation patterns may lead to an increase in the frequency and intensity of extreme weather events such as droughts or floods, adversely affecting cassava growth.

Soil degradation is also one of the important factors affecting cassava production. Unreasonable land use, such as excessive cultivation, fertilizer and pesticide abuse, may lead to soil organic matter content decline, structural damage and nutrient imbalance. These problems will not only reduce soil fertility and affect the normal growth and yield of cassava, but also may exacerbate environmental problems such as soil erosion and salinization. The loss of biodiversity has also had an impact on cassava production. Biodiversity provides cassava with rich genetic resources and ecological services such as pollination and pest control. However, with the interference of human activities and the destruction of ecological environment, many cassava related species and ecosystems are at risk of loss. This could lead to a reduction in cassava genetic resources, outbreaks of pests and diseases, and disruption of ecological balance, adversely affecting cassava production.

6.4 Role of socio-economic factors in cassava industry development

As one of the world's important crop industries, the sustainable development of cassava industry not only depends on technological progress and environmental protection, but also closely related to social and economic factors. Socio-economic factors have played an indispensable and key role in promoting the development of cassava industry. Market demand is the direct driving force of cassava industry development. With population growth and economic development, the demand for cassava and its processed products is increasing. This demand comes not only from the food industry, but also from feed, biofuels and other industrial applications. The expansion of market demand has provided a broader development space for cassava producers and promoted innovation and upgrading of the cassava industry.

Economic incentives are crucial for the development of the cassava industry. The government has encouraged farmers and enterprises to increase their input into cassava production through policy measures such as subsidies, tax breaks, and price support. These incentives not only improve the income of cassava producers, but also stimulate their enthusiasm to adopt new technologies and new varieties, thus promoting the rapid development of cassava industry. Policy support has also played an important role in the development of cassava industry. The government has created a good environment for the development of cassava industry through the formulation of laws and regulations, the provision of infrastructure construction and public services. These policy supports not only protect the legitimate rights and interests of cassava producers, but also promote the standardization, standardization and sustainable development of cassava industry.

International cooperation is also important for the development of the cassava industry. Through cooperation with international organizations, multinational corporations and other countries, advanced planting technology, management experience and market resources can be introduced to improve the international competitiveness of cassava industry. At the same time, international cooperation can also promote international trade in cassava industry, expand overseas markets, and bring more development opportunities for cassava producers. Abdoulaye et al. (2014) can promote the technological progress and industrial upgrading of cassava industry by strengthening education and training for cassava producers and improving their skill level and planting knowledge. Education and training can also improve the market awareness and operational capacity of cassava producers, so that producers can better adapt to market needs and changes.

7 Concluding Remarks

Cassava is one of the most important food crops in the world. Remarkable achievements have been made in the study of its agronomic traits and genetic basis. From the perspective of increasing production and efficiency, these studies not only improved cassava root yield and quality, but also enhanced its ability to adapt to environmental adversity. Research results on agronomic traits and genetic basis: Through extensive genetic resource mining and molecular breeding techniques, researchers have identified several key genes and quantitative trait loci (QTLS) that control yield and tolerance traits. By integrating traditional selection and modern biotechnology, the dry matter content and disease resistance of cassava were effectively improved, which provided a new direction for cassava breeding.

The importance of improving cassava production and quality: With a growing global population and the challenges of climate change, increasing cassava production and quality is key to ensuring food security and agricultural sustainability. The improvement of cassava needs to consider not only increasing the yield of the root and improving the quality of its starch, but also enhancing the resistance of the plant to pests and diseases and environmental adaptability.

Prospects for future research and applications: Future cassava research should continue to explore and exploit genetic diversity, using advanced gene editing and transgenic techniques to introduce or improve important agronomic traits. At the same time, the application of precision agriculture and smart technology will further improve the efficiency and environmental adaptability of cassava production. In addition, international cooperation and resource sharing will play an increasingly important role in promoting cassava research and industry development.

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Conflict of Interest Disclosure

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