Theoretical Advances and Emerging Trends in Apple Tree Stress Tolerance: A CiteSpace-Based Knowledge Graph Analysis

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Abstract. As a staple fruit tree in China, apple is often subjected to abiotic stresses such as drought, low temperature, salinity and replant disease in cultivation, which seriously affects the growth of the tree and the yield and quality of the fruits, so it is of great theoretical and practical significance to explore the mechanism of apple stress tolerance and to cultivate stress-resistant varieties for the enhancement of the quality and efficiency of the apple industry as well as for the sustainable development of the apple industry. Currently, the systematic application of bibliometric and knowledge mapping methods in the field of apple stress tolerance is limited, making it difficult to reveal the research lineage, hotspots, and frontiers in the field. To make up for this gap, this paper adopts CiteSpace software to analyze the number of articles, institutions, keyword co-occurrence, and citation burst detection of apple tree stress tolerance-related literature included in the Web of Science (WoS) database, to systematically sort out the research evolution, core themes, and frontier trends in the field. It can be seen that in recent years, the research on apple stress tolerance is in a rising trend, and in the past year, it has shown a rapid development trend, and has received more and more attention; at the same time, the analysis of high-frequency words in the relevant literature shows that the research in this field mainly focuses on drought stress, disease resistance, ABA, genes, apple rootstocks, etc., which is an obvious characteristic of the categorization hierarchy; finally, according to the distribution of time in the literature, the research on apple stress tolerance can be summarized into the following list. Finally, according to the time distribution of the literature, the research on apple stress tolerance can be roughly divided into the following periods: the research hotspots range from single factor to multifactorial, and from macroscopic phenotypic changes to changes at the microscopic gene expression level; the earliest appearing in the emergent words are abscisic acid, disease resistance, and defense response, followed by drought, low temperature, and tolerance, which continue to be the most dominant research directions until the end. In this study, we systematically present the comprehensive picture of apple stress tolerance research from the perspective of knowledge mapping, clarify the future direction of the frontier, and provide theoretical references and data support for in-depth analysis of the stress tolerance mechanism and breeding tolerance in apples.

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1 Introduction

In recent years, with climate change, frequent extreme low temperatures, drought, salinity, high temperatures, and other abiotic stresses have become increasingly important environmental factors limiting the quality, efficient production, and sustainable development of the apple industry. Apple is one of the deciduous fruit trees with the largest planted area and the highest economic value in China, which affects the tree growth, yield, and fruit quality, and other indicators. In-depth research on the physiological mechanism of apple tree stress tolerance and the discovery of varietal resources and stress tolerance genes of apple tree stress tolerance are of great practical significance to ensure the safety of apple production in China. In this context, the research on apple stress tolerance physiology, molecular regulation, and resistance breeding continues to increase, and the number of related literature is growing rapidly. Therefore, a systematic review and quantitative analysis of the research lineage, hot topics, and frontier trends in the field of apple tree stress tolerance can provide a scientific basis and reference for the subsequent selection of research topics, technological research, and breeding direction.

From the current research, a lot of studies have been carried out on the physiological responses of apple to drought, low temperature, and high temperature, and the mechanisms of some important genes and their signaling pathways have been investigated. For example, Ma F. et al., 2026 found that MdWRKY75 and MdHB7 transcription factors and signaling protein MdCNGC1C were involved in the regulation of apple stress tolerance in the process of drought, low temperature, and high temperature. MdCNGC1C was found to be involved in the regulation of apple stress tolerance, and the roles of ABA signaling, calcium signaling, and ROS scavenging pathways were elucidated in the process of response to adversity, providing important genetic resources for molecular breeding of apple stress tolerance [1] [2] [3] [4]. Liu Y. et al., 2021 analyzed the research hotspots of apple response to climate change based on bibliometric methods and proposed that abiotic stresses such as drought and temperature are the hotspots of non-climatic stress factors, but most of the research focused on the physiological and molecular mechanisms of apple under single-factor stress [5]. Zheng, X., & Bai, T, 2026 focused on the drought-resistant regulatory network of apple and found that MhSHINE2-like and MhGRF3 jointly regulate stomatal movement and ABA accumulation in drought-resistant pathways, which supplemented the molecular theory of drought-resistant apples [6]. Summarizing the views and research contents of the above scholars, the current research mainly focuses on the identification of specific functions of individual genes or a certain pathway, and there is no overall knowledge mapping of the whole apple stress tolerance research, including the overall development of the research, the linkage between the various units, and the evolution and development of the research themes, hotspots, and the prediction of the development trend, and so on; in addition, in the area of multi-stress cross-talk, the research on the regulation of stomatal

movement and ABA accumulation in drought tolerance has been conducted. In addition, there is a lack of systematic quantitative sorting in the frontiers of multi-stress cross-resistance, diversity of stress-resistant germplasm resources, and genome-wide mining, resulting in a lack of broad vision and unclear trend judgment. Therefore, this study takes apple tree stress tolerance as the research object, systematically combining the domestic and international research progress, mining the research hot spots, evolutionary paths, and future trends, so as to make up for the deficiencies of the existing research at the macro-measurement analysis level.

In recent years, the number of studies combining CiteSpace bibliometric analysis methods has been increasing, and its perspective based on knowledge mapping can clearly and systematically present the development of related fields, research hotspots, and trends. Therefore, this paper takes the apple stress tolerance related literature included in Web of Science database as the data source, based on the perspective of knowledge mapping, through the use of CiteSpace bibliometric tools to carry out a systematic knowledge mapping exploration centered on the theoretical progress, research hotspots and cutting-edge trends of apple tree stress tolerance, to understand the current apple stress tolerance physiology, molecular mechanisms, resistance breeding and other research areas. The knowledge mapping tool is used to systematically explore the knowledge map centered on the progress of apple stress tolerance theory and frontier trends, to understand the current research progress in apple stress tolerance physiology, molecular mechanism, tolerance breeding and other research fields, and to identify the research hotspots and cutting-edge theories from the perspective of knowledge mapping, to reveal the development law of apple stress tolerance field, optimize the layout of the research, and to provide the theoretical support and data references for the in-depth analysis of future apple stress tolerance mechanism, the selection of stress-tolerant varieties, and the innovation of cultivation technology.

2 Data and Methods

Based on CiteSpace metrology, we studied the relevant literature from 1992 to 2026, sorted out the key discussions in the field of biology, explored the gaps and potential research directions, understood the current exploration progress in the fields of apple stress tolerance physiology, molecular mechanism, and stress tolerance breeding, and utilized the perspective of knowledge mapping to identify the research hotspots and cutting-edge theories, with a view to revealing the development law of the field of apple stress tolerance, Optimize the research layout, and provide theoretical support and data reference for the in-depth analysis of apple tree stress tolerance mechanism, selection and breeding of stress-resistant varieties and cultivation technology innovation in the future.

Literature data were obtained from the Web of Science database. The literature for specific analysis was selected from the Web of Science core collection of science citation databases (SCI) in the field of horticulture, biology, botany and other research areas, the selected publications were primarily drawn from six authoritative journals in the field(Table 1), the search terms were stress tolerance, apple trees and other related

terms, the publication period was from 1992 to 2026, and a total of 103 articles were retrieved. A total of 103 articles were searched from 1992 to 2026.

Table 1. Sources of major journals in the literature.

The name of the journal	Number of articles in the literature
SCIENTIA HORTICULTURAE	11
FRONTIERS IN PLANT SCIENCE	6
INTERNATIONAL JOURNAL OF MOLECULAR SCIENCES	6
HORTICULTURAE	4
HORTICULTURE RESEARCH	3
PHYTOPATHOLOGY	3

3 Analysis of Progress in Resistance Research on Apple Trees

3.1 Analysis of Overall Progress and Trends in Research

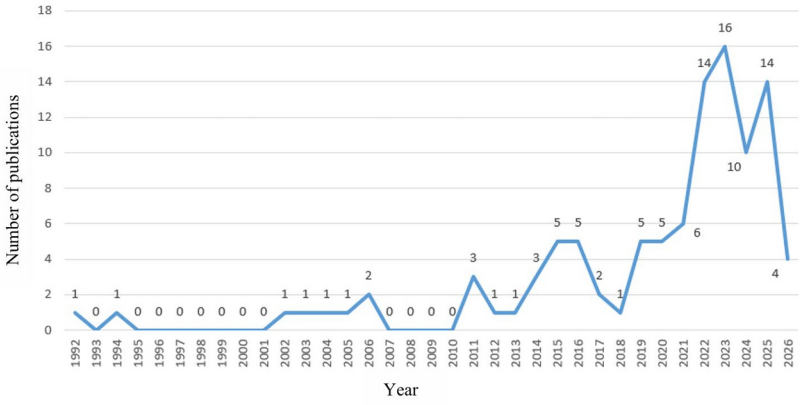

Fig. 1. Statistical table on the number of publications.

The total number of publications in the field of apple tree stress tolerance showed an increasing trend from 1992 to 2026 (Figure 1). Among them, the period of 1992-2010 is the budding period, and the number of publications is at a very low level; the period of 2011-2020 belongs to the steady development stage, and the number of publications shows a fluctuating trend of increase; and the period of 2021-2026 is a period of rapid growth. The number of articles will increase sharply, and because 2026 is just the beginning, some articles may not have been published yet, so the number of articles may

be seriously low. This shows that the value and heat of research in this field are increasing, and there is still much room for development in future research.

3.2 Keyword Clustering and Research Hotspot Analysis in the Field of Apple Tree Stress Tolerance Research

Keyword Co-occurrence Analysis. A total of 356 keywords were extracted using the CiteSpace bibliometric tool. The keywords with higher frequency were: resistance (26 times), expression (16 times), growth (15 times), Arabidopsis (14 times), plants (12 times), apple (10 times), biosynthesis (10 times), etc. The keywords with higher centrality (centrality > 0.1) were: resistance (0.28), expression (0.28), and biosynthesis (0.1). Meanwhile, the keywords with higher centrality (centrality > 0.1) are resistance (0.28), expression (0.21), growth (0.35), Arabidopsis (0.29), apple (0.32), biosynthesis (0.14), accumulation (0.25), and gene expression (0.10). It can be found that, firstly, the core theme of the study was clear, and the high frequency of the keywords " resistance ", " expression ", " growth ", and " apple " was high. The high frequency of the keywords " resistance " " expression " " growth " " indicates that the research on apple resistance has always centered on the analysis of resistance mechanism, gene expression regulation, plant growth response, which is the core research direction in the field; second, the research hotspots are more focused, and the high frequency of the keywords " Arabidopsis " and gene expression (0.10) are related to the high frequency of the keywords " Arabidopsis ". The high frequency and high centrality of "Arabidopsis" reflect the important reference role of the model plant Arabidopsis in apple tree stress toleranceh research, reflecting the research paradigm of cross-species mechanism borrowing; finally, the research path is clear: "biosynthesis" "accumulation" "gene expression" and so on. accumulation " " gene expression " and other high-centered keywords, revealing that the research in the field of metabolism synthesis, material accumulation, gene expression regulation from the level of analysis of the mechanism of resistance to adversity, for the follow-up research to provide a clear direction to guide. On the whole, the current research on apple stress tolerance has formed a stable research system, centered on gene expression and physiological regulation with stress response as the core, and the application of model plants has also provided important support for the research.

Keyword Clustering Timeline Analysis. On the basis of keyword co-occurrence analysis, keyword clustering analysis was carried out using the log-likelihood ratio (LLR) algorithm to form a keyword clustering analysis map (Figure 2). The keyword clustering analysis maps (Figure 2) were formed to further categorize and summarize the similar hotspots and highlight the research direction. Compared with the time-zone mapping of keyword clustering, the time-sequence mapping can better reflect the evolution and correlation of keywords among the clusters, and effectively depict the hotspot changes, development, and evolution trends in the research field. Using the CiteSpace software keyword clustering timeline function, the year of the first appearance of the keywords is the X-axis, and the keyword clustering label is the Y-axis (Figure 3).

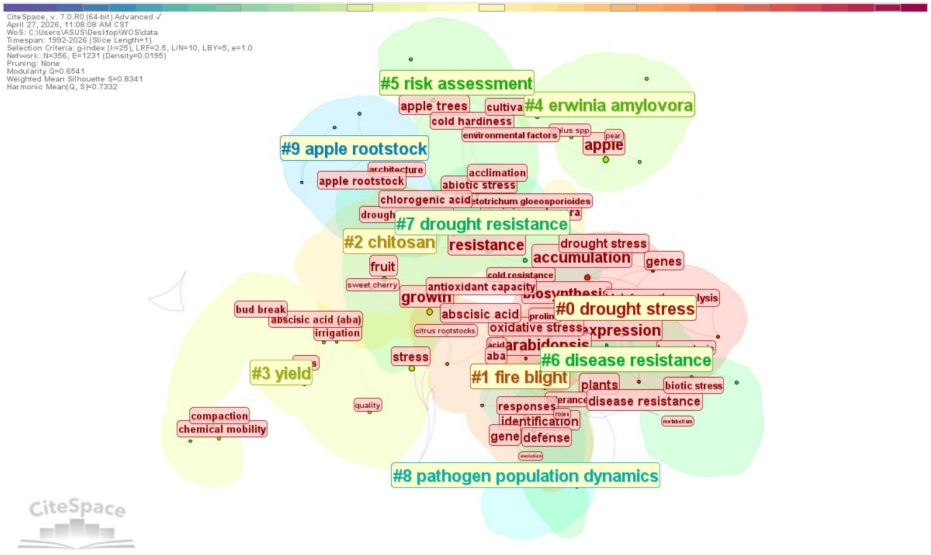

Fig. 2. Keyword cluster analysis mapping.

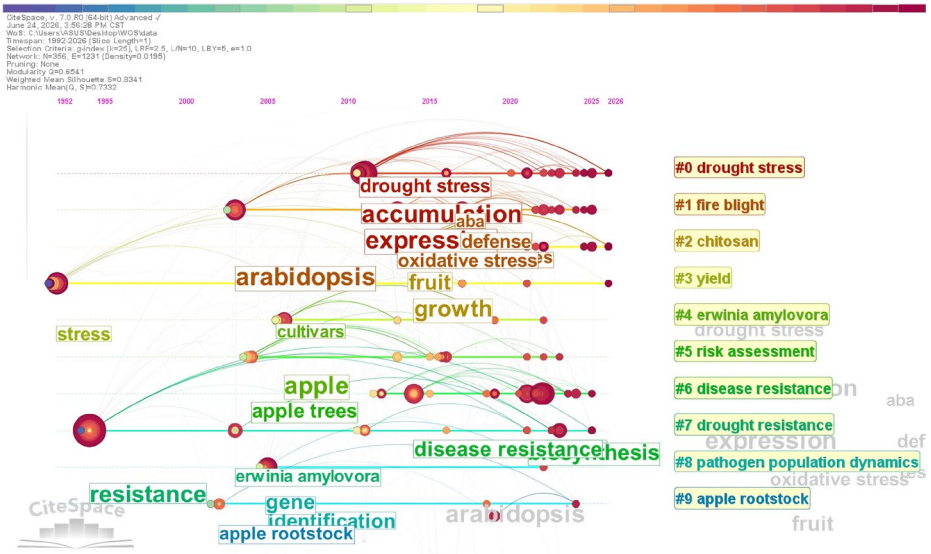

Fig. 3. Plot of keyword clustering timeline analysis.

(1) In the budding stage (1992-2000), the research mainly focused on the basic growth of fruit trees, yield formation, and basic response to abiotic stresses, centering on drought stress, oxidative stress, irrigation management, tree growth and yield enhancement, and focusing on exploring the basic physiological response of fruit trees under adversity and cultivation control mechanisms.

(2) In the stage of slow development (2000-2015), the research hotspots were shifted to biotic stress prevention and control, signal transduction in adversity and disease resistance related mechanisms, focusing on fire blight and Owen's bacillus as breakthroughs, and exploring the defense pathways regulated by ABA, the regulation of disease resistance and drought resistance, as well as the molecular mechanisms of resistance to adversity revealed through bioinformatics analysis.

(3) In the fast-rising period (2015-2026), keywords such as apple rootstock improvement, risk assessment, chemical mobility, and tree structure were proposed, and triggered discussions among scholars on varietal resistance, pathogen population dynamics, and identification of functional genes; application of bioactives such as chitosan and chlorogenic acid, AP2/ERF transcription factor regulation, biotic and The application of biologically active substances such as chitosan, chlorogenic acid, AP2/ERF transcription factor regulation, biotic and abiotic stress cross-tolerance, and the evaluation of adversity adaptation and cold tolerance are the hot words. The research system involved in the present study has changed from a single type of stress response to multiple types of adversity improvement, and combined with the knowledge mapping software CiteSpace, the synergistic research on the physiology of stress tolerance in apple trees, cultivation and management, and molecular selection was promoted, to lay the theoretical foundation for the high-yield, stress tolerance and high-quality production of the apple industry.

Analysis of Citation Bursts. As an important tool for literature content mining, citation burst refers to keywords that have been used with a sudden increase in frequency during a certain period of time, indicating that the keyword has been highly valued by researchers in that time period. Citation Burst is used to detect the emergence of dynamic concepts and potential research problems in a certain field, which is suitable for examining the emerging trends and sudden changes in the development of a discipline, and reflecting the active or cutting-edge research nodes. By analyzing the CiteSpace data and calculating the literature, the detection of a keyword burst was obtained (Figure 4).

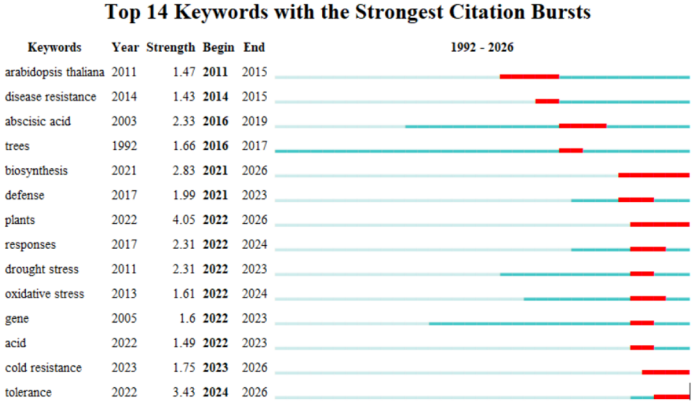

Fig. 4. Plot of emergent analysis of keywords (γ=0.4).

It can be seen that abscisic acid keyword appeared for the first time in 1992, and lasted for 27 years, indicating that abscisic acid as a major phytohormone plays a very important role in the regulation of plant response to adversity, and it has played a fundamental role in the study of plant stress tolerance for a long period of time, and it is the main substance involved in the signaling of adversity, defense response and stress tolerance, and has been widely concerned by scholars. Disease resistance appeared in 2003, and oxidative stress appeared in 2005, and it has been widely discussed. Disease resistance appeared in 2003, and oxidative stress appeared in 2005, indicating that the research has been gradually expanded from basic physiology to the mechanism of biotic and abiotic stresses, which provides a theoretical basis for the research on stress tolerance in the later stage.

From 2011 to 2015, Arabidopsis thaliana became the keyword of emergence, and the molecular mechanism research with model plants as the carrier emerged rapidly, promoting the plant stress tolerance from physiological phenotype to the level of genes and signaling pathways. From 2016 to 2019, abscisic acid emerged strongly again, with a strength of 2.33, and biosynthesis emerged simultaneously, indicating that the abscisic acid synthesis pathway and metabolic regulation became the focus of research, and deepened the study of stress tolerance mechanisms to the level of molecular metabolism. In 2016~2019, abscisic acid again appeared strongly, with a strength of 2.33, and biosynthesis appeared synchronously, indicating that abscisic acid synthesis and metabolism regulation have become the focus of the research, and the research on the mechanism of stress tolerance has been deepened to the molecular metabolic level.

The peak of emergence occurred from 2021 to 2026, and the intensity of defense reached the maximum value of 4.05, and the high clustering of "drought stress", "oxidative stress", "plants" and "responses" appeared in this stage, indicating the high clustering of emergence in this stage, and the high clustering of emergence in this stage, indicating the high clustering of emergence in this stage. There was a high degree of clustering of "drought stress", "oxidative stress", "plants", and "responses" at this stage, indicating that the focus of research at this stage was on the defense and response mechanisms of plants in the face of compound adversities. The emergence of cold resistance in 2023 and tolerance in 2024, with a strength of 3.43, both of which extended to 2026, reflected the rapid emergence of research on the synergistic tolerance of multiple stresses, such as low temperature, drought, and oxidation.

Combined with the time sequence and intensity of emergence in the figure, we can see that molecular defense mechanisms, drought stress response, cold tolerance regulation, stress tolerance enhancement, and functional gene mining are expected to become the hotspots in the future. On the whole, the research in this field has evolved from basic physiology to molecular regulation, from single stress to compound adversity, and from model plants to fruit crops, and the evolution of the emergent keywords clearly presents the cutting-edge research on plant stress tolerance, which provides an important direction for the stress tolerance breeding and cultivation improvement of apples and other economic forest trees.

4 Discussion

4.1 Synthesis of Major Findings

To summarize, this part of the paper mainly combines the issues raised in the previous paper to make a comprehensive analysis, and gives a comprehensive overview of the related work on apple stress tolerance, and statistically summarizes the related literature on WoS from 1992 to 2026, to have a more comprehensive understanding of its overall development trend, and to obtain the results that the development of the research on apple stress tolerance has gone through the germination period, the developmental period, and the period of rapid development. The rapid increase in the number of literature in the past two years indicates that the related research has been paid more and more attention to, which is of great practical significance, and has an important reference role in summarizing the overall research on apple resistance from a large perspective. In this paper, we used the visualization method to dig out the hidden information in a large amount of literature, and obtained the current research hotspots and trends, mainly focusing on drought, disease resistance, abscisic acid pathway, transcription factors, and the apple root system. The high centrality of the keywords further confirmed that the analysis of stress tolerance mechanism, molecular regulatory mechanism, and plant growth response are the main research lines throughout the field, which solved the problem of the overall inadequacy of the current research that only focuses on a certain point but fails to summarize and organize the hotspots. At the same time, the analysis of emergent words realized the scientific prediction of the frontier trend of the field, and made it clear that ABA signaling, defense response, drought stress, cold tolerance and stress tolerance are the core frontiers of the field in the long term, so that the focus of the research has gradually shifted from the single stress research to the exploration of the compound adversity, and from the observation of the phenotypes to the molecular regulation, which accurately captures the key shift in the field research. This paper adopts CiteSpace-based bibliometric visualization and analysis technology, which can show the trend, hotspot, and evolution pattern of the related fields in an all-around way, and overcomes the problem of subjective evaluation in the previous reviews to a certain extent, and lays an important empirical foundation for further revealing the response mechanism of apple tree stress tolerance and guiding the selection and breeding of stress-resistant varieties. This study was conducted to explore the current development of this field and to predict the future development trend to serve the purpose of production.

4.2 Research Implications and Limitations

Through the systematic analysis of the knowledge map in the field of apple stress tolerance, this study provides a multidimensional direction for subsequent research. On the one hand, the research angle is to increase the study of multiple adversities, such as drought + low temperature or saline and alkaline conditions, to explore the related mechanisms of apple resistance to multiple adversities, to enrich the breadth and depth of single-factor research; on the other hand, in the direction of application, to expand

the degree of utilization of the key resistance genes, and to cultivate varieties with comprehensive traits by means of grafting technology. The basic research results will be applied in breeding practice; in cooperative research, we strongly advocate joint research, strengthen cooperation and exchange between different units and disciplines, and unite the advantages of horticulture, molecular biology, bioinformatics, etc. to form a synergy and improve the utilization rate of scientific research results; in germplasm resources, we will continue to expand the excavation and screening of wild apple germplasm resources for resilience to enrich the resilience gene pool, which will provide the basis for long-term resistance breeding of apples. In terms of germplasm resources, we will continue to expand the excavation and screening of wild apple resistance germplasm resources, enrich the resistance gene pool, and provide solid material support for long-term resistance breeding of apple.

However, there are some limitations in this study; these boundaries are not insufficient, but are based on the reasonable setting of the research objectives and scope, and also reserve space for the subsequent expansion of the study. In this paper, only the literature of some authoritative journals in the WoS core collection is chosen as the data source, and the literature of Chinese core journals is not covered because of the analysis of the international English literature, the comprehensiveness of the data dimensions can be improved in the future research; this paper mainly analyzes the keywords co-occurrence, clustering, emergence and the number of articles issued by the several major dimensions. Because the research object of this paper is the domain theme and trend mining, not the author's cooperation, cooperation between countries and regions and other aspects of in-depth mining, so it can be used as a separate aspect of further research; this paper's time scale until 2026, but the articles of 2026 are not included completely, to a certain extent, it will affect the outbreak of the trend of the period of judgment, to be further tracking research after the future update of the data. We will do further follow-up research after the data are updated. This paper is based on the bibliometric research method, not combined with specific experimental data, so it does not give a more detailed description of the specific gene pathways, metabolic mechanisms, etc., and the mechanism can be further explored based on the combination of experimental and metrological methods.

5 Conclusions and Research Outlook

5.1 Conclusions

In this study, we used CiteSpace software to visualize and analyze the literature related to apple stress tolerance, and summarized the research results on apple stress tolerance from 1992 to 2026, which mainly include the following aspects: the development of apple stress tolerance is on the rise, and there is a rapid growth after 2021, which indicates that the research on apple stress tolerance is increasingly being emphasized by the scientific and production communities; the research mainly focuses on drought stress, pest resistance, the mechanism of ABA hormone, gene regulation and the use of rootstocks to improve fruit tree stress tolerance. The research on apple stress tolerance has

been increasingly emphasized by the scientific and production communities; the research hotspots are mainly centered on drought stress, resistance to pests and diseases, the mechanism of ABA hormone, gene regulation and the use of rootstocks to improve the stress tolerance of fruit trees in five aspects; the research direction is gradually transitioned from pure physiological phenotypic observation to the study of molecular regulation. Thirdly, the research progress in this field has continuity and stages, which can be roughly divided into three parts: analysis of basic plant physiological response and stress response, analysis of stress biology and its mechanism, and comprehensive research of adversity improvement, and in the process of research, from the impact of a single stress factor to gradually change into a comprehensive research of adversity. Fourthly, the development trend of this field is relatively clear, and ABA and its signaling pathway, stress response, drought stress, low-temperature adaptability, and stress tolerance have been the focus of research in this field in different research periods. The intensity and duration of the emergent words can prove their long-term research value. This study bridges the gap of macro-econometric analysis in the field of apple stress tolerance, and presents the research lineage, core hotspots and development trend of the field in a panoramic view with a knowledge map, which provides important theoretical references and data support for the analysis of stress tolerance mechanism, selection and breeding of tolerant varieties, and optimization of cultivation techniques in the field of apple stress tolerance.

5.2 Research Outlook

In conclusion, future research on apple stress tolerance can be further refined to enrich the research results in this field and provide more guidance for production practice. The research on apple can be strengthened in the aspect of integrated adversity, in-depth investigation of some important pathways in apple under the joint action of multiple adversities, exploring some important TF and signaling pathways, to establish a regulatory system of apple stress tolerance; at the same time, with the help of genomics and genome editing and other related technologies to accurately explore the excellent stress tolerance germplasm resources, and to create new stress tolerance germplasm materials with independent intellectual property rights. Taking the improvement of rootstock resistance as a breakthrough, promote the joint improvement of rootstocks and varieties, and select and breed high-quality apple rootstock combinations that integrate dwarfing, resistance, and yield. Research and development of chitosan, chlorogenic acid, and other biologically active substances, and the development of green stress-alleviating agents for apples. Actively introduce artificial intelligence, phenomics, metabolomics and other related advanced technologies to combine with apple resistance research, to provide technical support for accurate prediction of resistance traits and rapid breeding; always production-oriented, pay attention to the combination of basic theories and production, and explore simple, easy-to-operate, easy to promote the application of cultivation and management measures, to comprehensively serve China's apple industry to enhance the quality and efficiency of the sustainable and healthy development.

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