RESEARCH ARTICLE
AGROBIOLOGICAL RECORDS
ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

GLOBAL RESEARCH TRENDS IN ENHANCING MAIZE PRODUCTIVITY UNDER WATER SCARCITY: A BIBLIOMETRIC ANALYSIS OF MOLECULAR AND PHYSICAL INTERVENTIONS (1984-2026)

Muhammad Khizar Hayat [1,2], Huzaifa Ijaz [2], Sana Jamali [3], Saad Zafar [4], Zia Ullah Ashraf [5], Sadid Shahriyar [6], Rahime Cengiz [1]*, Mehmet Öten [1*], Akhi Akter [7] and Md. Nahid Mahmud [8]

[1]Sakarya University of Applied Sciences, Faculty of Agriculture, Department of Field Crops, 54580, Sakarya, Türkiye
[2]Department of Agronomy, Faculty of Agriculture, University of Agriculture, 38040, Faisalabad, Pakistan
[3]Department of Environmental Engineering, Institute of Sciences, Sakarya University, 54050, Sakarya, Türkiye
[4]Department of Agricultural Biotechnology, Faculty of Agriculture, Atatürk University, Erzurum 25240, Türkiye
[5]Department of Plant Protection, College of Agriculture, Tarim University, Alar, Xinjiang, 843300, P. R. China
[6]Faculty of Agriculture, Sher-e-Bangla Agricultural University, 1207, Dhaka, Bangladesh
[7]Department of Agricultural Botany, Faculty of Agriculture, Sher-e-Bangla Agricultural University, 1207, Dhaka, Bangladesh
[8]College of Agricultural Sciences, IUBAT- International University of Business Agriculture and Technology, Dhaka 1230, Bangladesh

**Corresponding author*: rahimecengiz@subu.edu.tr (RC); mehmetoten@subu.edu.tr (MÖ)

ABSTRACT

Maize (*Zea mays* L.) plays a critical role in global food, feed, and biofuel security; however, its productivity is increasingly threatened by drought stress, climate change, and freshwater scarcity. This study aimed to provide a comprehensive bibliometric and scientific assessment of global research trends on drought stress in maize from 1984 to 2026 and to identify major physiological, molecular, and technological strategies to improve drought resilience. Bibliometric data were collected from the Web of Science Core Collection using drought- and maize-related keywords. A total of 2860 publications were identified, from which 853 highly relevant papers for maize were selected for detailed analysis. The datasets were analyzed using VOSviewer to evaluate publication trends, keyword co-occurrence, institutional collaboration, country networks, journals, and publisher contributions. The results revealed a substantial increase in research output after 2019, with the highest annual number of publications recorded in 2024. China, the United States, and Germany emerged as the leading contributors in both publication productivity and citation impact. The Chinese Academy of Sciences, CGIAR System Organization, China Agricultural University, and CIMMYT were identified as major research institutions driving innovation in maize drought studies. Among journals, Agronomy Basel, Frontiers in Plant Science, Plants Basel, and Environmental Research Letters were the most productive publication sources, while publishers such as MDPI, Springer Nature, Wiley, Frontiers Media, and Elsevier dominated scientific dissemination in this field. The keyword analysis revealed a strong research focus on drought tolerance, root system architecture, photosynthetic stability, abscisic acid signaling, transcription factor engineering, and climate-smart agriculture. The emerging transformative tools identified for future maize improvement included CRISPR/Cas9 genome editing, speed breeding, GeoAI-driven precision agriculture, and microbiome engineering. In summary, this study highlights the transition of maize drought research toward multidisciplinary, technology-driven, and globally collaborative efforts to sustain maize productivity and food security amid increasing climatic uncertainties.

Keywords: Drought resilience, Climate-smart agriculture, Root system architecture, Precision breeding, Water-use efficiency and VOSviewer.

Article History (ABR-26-184) || Received: 18-May-2026 || Revised: 15-Jun-2026 || Accepted: 20-Jun-2026 || Published Online: 27-Jun-2026

1. INTRODUCTION

Maize (*Zea mays* L.) is among the most significant cereal crops in the world and a cornerstone crop for global food, feed, industrial and biofuel production systems (Wang & Zhang, 2024). Maize, along with wheat and rice, supplies a large share of the calories consumed worldwide and is an important part of agricultural economies in

Citation: Hayat MK, Ijaz H, Jamali S, Zafar S, Ashraf ZU, Shahriyar S, Cengiz R, Öten M, Akter A and Mahmud MN, 2026. Global research trends in enhancing maize productivity under water scarcity: A bibliometric analysis of molecular and physical interventions (1984-2026). Agrobiological Records 24: 252-276. https://doi.org/10.47278/journal.abr/2026.042

both developed and developing countries (Erenstein et al., 2022; Akram et al., 2023; Raza et al., 2024; Hayat et al., 2025). According to the Food and Agriculture Organization (FAO), maize is now produced globally in excess of 1.2 billion tons each year from over 200 million hectares of land worldwide. Maize is not only a staple food for millions of people, but it is also a major ingredient of livestock feed and the primary feedstock for the production of bioethanol, accounting for some 60-70% of global use of maize. The world's maize needs will increase by more than 50% by 2050 because of rapid population growth, urbanization, changes in dietary habits and the emergence of renewable energy sources (Erenstein et al., 2022).

Maize is a crop of strategic importance but faces unprecedented challenges, particularly climate change and freshwater scarcity. Today, nearly 70% of the world's available freshwater resources are used for agriculture, and growing competition among the agricultural, industrial and domestic sectors is putting strain on water supplies (Li et al., 2026a). Four billion people currently face acute water shortages for at least a month each year, a figure expected to rise dramatically in future climate scenarios. The Intergovernmental Panel on Climate Change (IPCC) also forecasts an increase in global temperatures of 1.5-4.5°C by the end of the century, along with more climatic variability, changes in precipitation patterns and more extreme weather events, such as prolonged droughts and flash droughts. Such changes pose serious threats to maize-producing regions of Asia, Africa, Europe and the Americas (Du & Xiong, 2024).

Drought is considered the most damaging environmental constraint limiting maize productivity worldwide among all abiotic stresses (Kim & Lee, 2023). Under moderate drought conditions, yield losses from drought stress are typically in the range of 15% to 30% and can be greater than 70% during severe drought episodes, especially when the stress occurs at the flowering and grain-filling stages (Khan et al., 2025). Drought influences almost every stage of corn growth and development, from seed germination to root growth, nutrient absorption, photosynthesis, reproductive timing, and kernel formation (Ortez et al., 2023). Water deficits in the reproductive stage are particularly damaging because they increase the anthesis-silking interval (ASI), reduce pollination success, reduce kernel set, and ultimately reduce grain yield (Silva et al., 2022). Recent global assessments indicate that the effects of drought on maize yield losses have increased over the past 30 years, as a result of higher temperatures and the increased frequency of extreme climate events (Ojara et al., 2022). The Anthropocene has further accelerated the complexity of drought-related challenges (Ravinandrasana & Franzke, 2025). Anthropogenic activities such as greenhouse gas emissions, land-use change, deforestation and unsustainable water extraction have altered hydrological cycles and increased the occurrence of agricultural droughts (Pandit & Sharma, 2024). Recent studies have shown that flash droughts, which are rapidly developing drought events characterized by rapid soil moisture depletion, have become increasingly prevalent in major maize growing regions (Christian et al., 2024). Unlike regular droughts, flash droughts can form in days or weeks, so there is little time for farmers to take mitigation measures. Consequently, the knowledge and improvement of the drought resilience of maize has been made a global scientific priority for sustainable agricultural production and food security (Azrai et al., 2024).

Maize plants have developed many physical, physiological, biochemical and molecular adaptations to survive in environments with limited water (Peer et al., 2024). Physical adaptations include alterations in root system architecture (RSA), root cortical aerenchyma formation, leaf rolling, canopy structure optimization, and hydraulic regulation. Lynch's "Steep, Cheap, and Deep" root ideotype has become a cornerstone concept of improving drought tolerance through enhanced subsoil water acquisition (Maqbool et al., 2022). Deep-rooted maize genotypes can access water stores that are unavailable to shallow-rooted genotypes, and metabolically efficient root systems reduce the carbon cost of soil exploration (Dai et al., 2024). Such traits have been linked to large improvements in water use efficiency and stability of grain yield under drought stress.

Drought tolerance involves complex physiological mechanisms such as stomatal conductance, osmotic adjustment, antioxidant defense systems and photosynthetic maintenance (Haghpanah et al., 2024). The phytohormone abscisic acid (ABA) is an important regulator of drought perception and signaling by controlling stomatal closure and activating stress-responsive pathways (Kumar et al., 2024). Simultaneously, drought-tolerant maize genotypes accumulate osmoprotectants such as proline, glycine betaine, soluble sugars and polyamines to maintain cell hydration and protect membranes against oxidative damage (Burlakoti et al., 2024). Maintenance of photosynthetic efficiency is especially important in maize because drought-induced disruptions of C4 photosynthesis directly impair biomass accumulation and grain yield (Khamis et al., 2025).

Over the last two decades, tremendous advances in molecular biology and biotechnology have revolutionized drought-resilience research. High-throughput genomics, transcriptomics, proteomics, metabolomics and epigenomics have facilitated the identification of key drought-responsive genes, signaling pathways and regulatory networks (Seraj & Vafaee, 2026). Special attention has been paid to the ABA-mediated signaling cascades, regulation of aquaporins and transcription factor families such as DREB, NAC, WRKY and MYB (Kaya, 2025; Xiong et al., 2025). At the same time, CRISPR/Cas9 genome editing has emerged as a powerful technology to precisely engineer drought-related genes, enabling the rapid development of climate-resilient maize genotypes

(Abdullah et al., 2025).

Simultaneously, digital agriculture and precision farming are changing drought management at the field level (Aarif et al., 2025). Innovations like artificial intelligence (AI), Geographic Artificial Intelligence (GeoAI), remote sensing, unmanned aerial vehicles (UAVs), Internet of Things (IoT)-based sensors, and machine learning models enable real-time monitoring of crop health, soil moisture, and environmental conditions (Akram et al., 2025; Hayat et al., 2026). These technologies contribute to optimize irrigation scheduling, to detect drought in early stages and to improve resource-use efficiency (Rabie et al., 2025). In addition, microbiome engineering and plant growth-promoting rhizobacteria (PGPR) have been recognized as promising biological tools to improve maize drought tolerance through enhanced nutrient acquisition, root development, and stress signaling (Biswas et al., 2025).

The scientific literature in this field is growing fast, and a comprehensive bibliometric evaluation is crucial to identify research trends, influential contributors, emerging technologies, and future knowledge gaps. Therefore, the present study provides a bibliometric analysis of global maize drought research from 1984 to 2026 based on the Web of Science Core Collection database and VOSviewer analytical tools. The study aims to (i) examine the publication growth and citation dynamics, (ii) identify the leading countries, institutions, authors, journals and collaborative networks, (iii) explore emerging research themes using keyword co-occurrence analysis, and (iv) highlight the future directions in molecular breeding, genome editing, precision agriculture, GeoAI, and microbiome engineering. This paper contributes to the development of sustainable strategies for safeguarding future maize productivity under increasing global water scarcity by including bibliometric insights and scientific advances in drought resilience.

1.1. Physical Blueprints for Drought Resilience

Drought resilience in maize is strongly governed by physical and morphological adaptations that improve water acquisition, conservation and transport under water-limited environments (Hayat et al., 2025; Zahedi et al., 2025). Among these, root system architecture (RSA) is considered one of the most critical determinants of drought tolerance because roots directly regulate access to deep soil moisture (Lynch, 2013; Guo et al., 2024). The "Steep, Cheap and Deep" root ideotype proposed by Jonathan P. Lynch emphasizes the development of deeper and metabolically efficient root systems to enhance drought adaptation (Lynch, 2013). Steep root angles facilitate deeper soil penetration, in Fig. 1, enabling maize plants to access subsoil water reserves during prolonged drought periods, while "cheap" roots reduce metabolic expenditure through fewer cortical cell files and enhanced aerenchyma formation (Chimungu et al., 2014; Shoaib et al., 2022). Studies indicate that deeper nodal roots can improve water uptake efficiency by nearly 20-40% under water-deficit conditions, thereby stabilizing grain yield (Uga et al., 2013; Gao & Lynch, 2016).

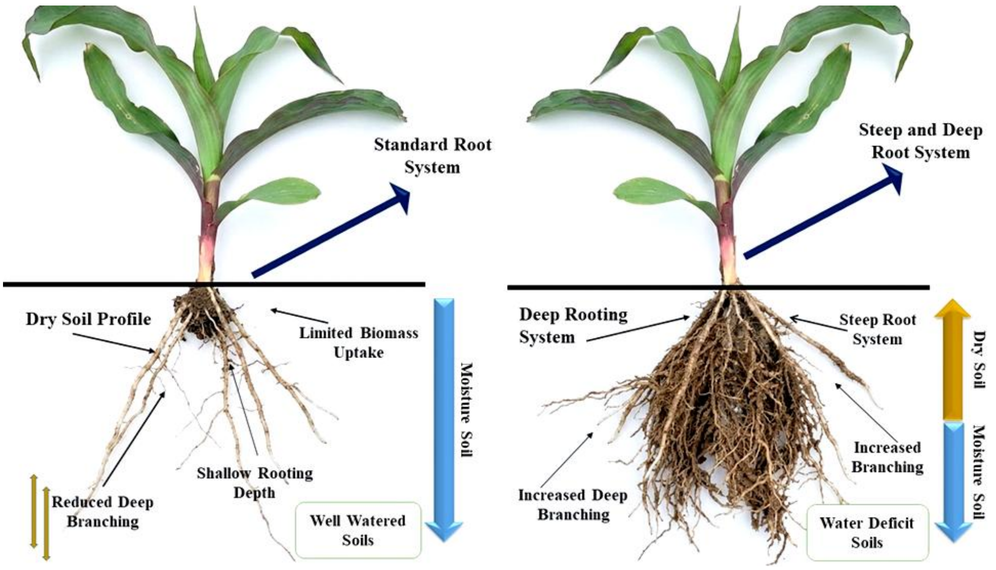

Fig. 1: Spatiotemporal Dynamics of Root System Architecture (RSA) Under Water Deficit.

Root cortical aerenchyma (RCA) further enhances drought resilience by replacing living cortical tissues with air-filled spaces, thereby reducing root respiration and nutrient requirements (Zhu et al., 2010). According to Chimungu et al. (2014), RCA lowers the carbon cost of soil exploration and allows greater assimilate allocation toward root elongation and reproductive development. Enhanced RCA formation has also been associated with improved penetration into compact soils and superior nitrogen acquisition efficiency (Liu et al., 2021). These anatomical

Citation: Hayat MK, Ijaz H, Jamali S, Zafar S, Ashraf ZU, Shahriyar S, Cengiz R, Öten M, Akter A and Mahmud MN, 2026. Global research trends in enhancing maize productivity under water scarcity: A bibliometric analysis of molecular and physical interventions (1984-2026). Agrobiological Records 24: 252-276. https://doi.org/10.47278/journal.abr/2026.042

modifications collectively improve hydraulic connectivity and soil moisture extraction under drought stress.

Shoot and canopy morphologies also play fundamental roles in drought avoidance mechanisms. Leaf rolling is a critical adaptive response that reduces transpiration loss by minimizing exposed leaf surface area during high evaporative demand (Tardieu, 2013; Ali et al., 2022). Similarly, upright leaf angles improve radiation use efficiency and optimize light distribution within the canopy, reducing canopy temperature and maintaining photosynthetic stability (Slattery & Ort, 2021). These canopy traits significantly improve water-use efficiency under drought conditions. Another important physical trait is the reduction of the anthesis-silking interval (ASI), which is strongly associated with reproductive success during water deficit (Welcker et al., 2022). Drought stress delays silk emergence relative to pollen shedding, resulting in poor fertilization and kernel abortion. The shorter ASI values are directly correlated with enhanced drought tolerance and higher grain yield under stress environments (Li et al., 2025; Wang et al., 2025b; Li et al., 2026b).

Hydraulic conductance represents the integrated physical regulation of water flow from soil to atmosphere through roots, stems and leaves (Wang et al., 2023). Efficient hydraulic conductance maintains leaf water potential, stomatal function and transpiration balance during drought episodes (Chen et al., 2023). Xylem vessel architecture, root hydraulic conductivity and aquaporin-mediated membrane transport collectively determine water transport efficiency in maize (Suslov et al., 2024). Genotypes possessing optimized hydraulic architecture can sustain photosynthetic activity and reproductive development even under declining soil moisture conditions (Wang et al., 2025a). Therefore, integrating RSA optimization, canopy adaptation and hydraulic regulation provides a robust physical blueprint for developing climate-resilient maize cultivars capable of sustaining productivity under increasing global water scarcity (Ahmed et al., 2025; Olarewaju et al., 2025).

1.2. Physiological Mechanisms: The Internal Balance

Physiological mechanisms play a central role in determining maize drought tolerance by regulating the internal balance between water conservation, photosynthetic efficiency and reproductive success (Tang et al., 2025). Under drought stress, maize plants activate a complex network of physiological responses that maintain cellular homeostasis and minimize yield losses (Aslam et al., 2015). Among these responses, stomatal governance is one of the most important adaptive strategies because stomata regulate the balance between carbon dioxide (CO_2) uptake and transpiration-driven water loss (Zarrin Ghalami et al., 2026). During water deficit, abscisic acid (ABA)-mediated signaling induces stomatal closure to reduce transpiration and preserve leaf water potential (Hsu et al., 2021). However, excessive stomatal closure restricts CO_2 diffusion into mesophyll tissues, thereby reducing photosynthetic carbon assimilation and biomass accumulation (Singh et al., 2013). Drought-tolerant maize genotypes possess optimized stomatal sensitivity that maintains partial stomatal conductance while minimizing unnecessary water loss. This balance enhances water-use efficiency and delays dehydration under prolonged drought conditions (Franco-Navarro et al., 2025; Takács et al., 2025).

Metabolic priming is another crucial physiological adaptation that enables maize plants to tolerate osmotic stress. Drought stress disrupts cellular water balance and causes loss of turgor pressure, leading to impaired growth and metabolic dysfunction (Aslam et al., 2015; Rafique, 2023). To counteract this effect, maize accumulates osmo-protectants such as proline, glycine betaine, soluble sugars, and polyamines (Kaur et al., 2024). Proline functions as an osmotic regulator, molecular chaperone, and reactive oxygen species (ROS) scavenger, thereby protecting cellular membranes and proteins during dehydration stress (Ghosh et al., 2022). Similarly, polyamines stabilize membrane structures, regulate ion transport and contribute to antioxidant defense mechanisms under drought conditions (Du et al., 2024; Tyagi et al., 2023). Studies have demonstrated that drought-tolerant maize hybrids accumulate significantly higher concentrations of proline and polyamines compared with susceptible genotypes, allowing maintenance of cellular turgor and metabolic activity during severe water limitation (Peer et al., 2024).

Photosynthetic stability is particularly important in maize because it is a C4 crop that depends heavily on the coordinated functioning of phosphoenolpyruvate carboxylase (PEPCase), Rubisco and associated enzymes, Fig. 2. Drought and high-temperature stress reduce chlorophyll content, impair electron transport chains, and destabilize C4 metabolic pathways (Karami et al., 2025). Among these effects, inhibition of PEPCase activity is especially critical because this enzyme catalyzes the initial fixation of CO_2 in mesophyll cells (Ren et al., 2026). Under drought conditions, oxidative stress and thermal injury reduce enzyme efficiency and ATP availability, ultimately lowering carbon assimilation and grain productivity (Li et al., 2026c). However, tolerant maize genotypes maintain higher PEPCase activity, chloroplast integrity and photochemical efficiency under stress, thereby preserving photosynthetic capacity and biomass production (Qu et al., 2023).

Source-sink dynamics also determine maize yield stability under drought stress. The “source” refers to photosynthetically active tissues producing assimilates (Yan et al., 2022). Whereas, the “sink” includes developing kernels and reproductive organs requiring carbohydrates for growth (Rafique, 2020). Drought stress disrupts assimilate transport by reducing photosynthesis, phloem loading and sucrose translocation to kernels (Du et al.,

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

2024). This imbalance often leads to kernel abortion, reduced grain filling and lower harvest index. Drought-tolerant maize lines maintain stronger sink strength through improved carbohydrate remobilization and efficient carbon partitioning during reproductive development (Aslam et al., 2015; Rafique, 2023). Enhanced sucrose synthase activity, stable phloem transport and delayed leaf senescence collectively contribute to effective kernel filling under water-deficit environments (Panozzo et al., 2025). Therefore, stomatal regulation, osmotic adjustment, photosynthetic stability and efficient source-sink coordination together form the physiological foundation of maize drought resilience (Aslam et al., 2015; Qi et al., 2021).

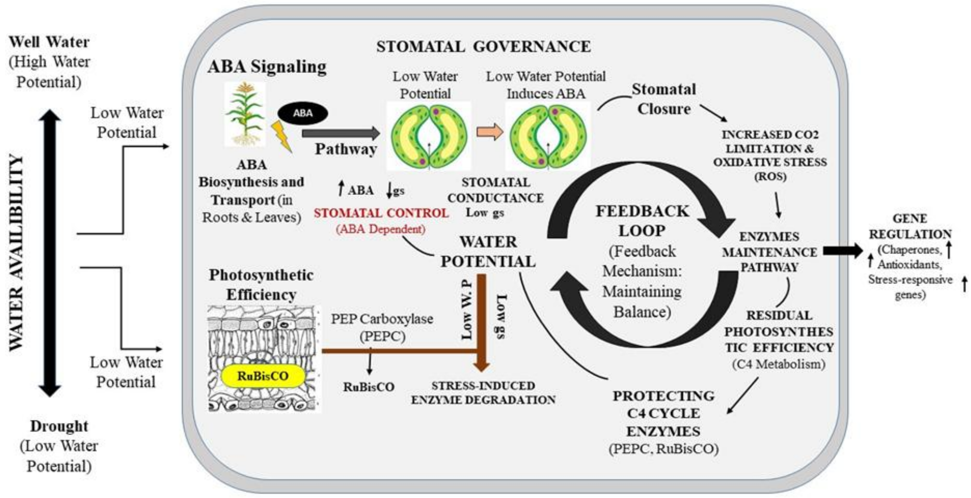

Fig. 2: The Interplay between Photosynthetic Efficiency and Stomatal Governance in C4 Metabolism.

1.3. Targeted Molecular Strategies

Targeted molecular strategies have become fundamental for improving drought tolerance in maize because they directly manipulate stress-responsive genes, signaling pathways and regulatory networks involved in water-deficit adaptation (Singh et al., 2023; Peer et al., 2024). Among these mechanisms, the abscisic acid (ABA) signaling pathway serves as the central molecular hub regulating drought perception and adaptive responses. Under drought stress, ABA accumulates rapidly in plant tissues and activates the PYL-PP2C-SnRK2 signaling cascade (Shen et al., 2022; Iglesias-Moya et al., 2024). In this pathway, pyrabactin resistance-like receptors (PYL/PYR) bind ABA molecules and inhibit type 2C protein phosphatases (PP2Cs), in Fig. 3. Thereby, releasing SNF1-related protein kinases 2 (SnRK2s) from repression (Daszkowska-Golec, 2016; Fidler et al., 2022). Activated SnRK2 kinases phosphorylate downstream transcription factors and stress-responsive proteins that regulate stomatal closure, osmoprotectant biosynthesis, antioxidant defense and drought-responsive gene expression (Soma et al., 2021). Manipulation of this signaling cascade through genetic engineering and CRISPR-mediated editing has shown significant potential for enhancing drought sensitivity and water-use efficiency in maize (Feng et al., 2025). Fine tuning ABA signaling can improve stress adaptation without severely compromising plant growth under normal conditions (Thilakarathne et al., 2025).

Transcription factor (TF) engineering represents another powerful molecular strategy for broad-spectrum stress tolerance (Wu et al., 2026). TFs regulate large networks of downstream genes involved in stress signaling, osmotic adjustment, detoxification and cellular protection (Imran et al., 2025). Among these, dehydration-responsive element-binding (DREB), NAC and WRKY transcription factor families have received major attention in drought-tolerance research. DREB proteins activate stress-inducible genes through ABA-independent pathways and enhance osmo-protectant accumulation, ROS scavenging and membrane stability (Feng et al., 2023). NAC transcription factors regulate root development, senescence and water-use efficiency. While, WRKY proteins coordinate hormonal signaling and defense-related gene expression under combined abiotic stresses (Yang et al., 2025). Overexpression studies in maize have demonstrated that DREB- and NAC-based transgenic lines maintain higher chlorophyll content, improved stomatal regulation, and greater grain yield under drought conditions (Fuertes-Aguilar & Matilla, 2024). These TF families therefore function as master regulators of drought adaptation and represent promising targets for climate-resilient crop engineering (Wang et al., 2025c; Wu et al., 2026).

The integration of "omics" technologies has revolutionized the understanding of maize drought responses by enabling genome-wide analysis of genes, proteins, metabolites and epigenetic modifications (Zhang et al., 2025; Rautela et al., 2026). Transcriptomics has identified numerous drought-responsive gene networks associated with ABA signaling, osmotic regulation, antioxidant defense and photosynthetic maintenance. RNA sequencing technologies have revealed that drought-tolerant maize genotypes exhibit stronger induction of stress-responsive transcription factors, aquaporins, late embryogenesis abundant (LEA) proteins and heat shock proteins compared with susceptible lines (Zenda et al., 2019; Peer et al., 2024). Additionally, systems biology approaches have enabled the identification of co-expression networks and candidate genes controlling drought resilience (Bano et al., 2022).

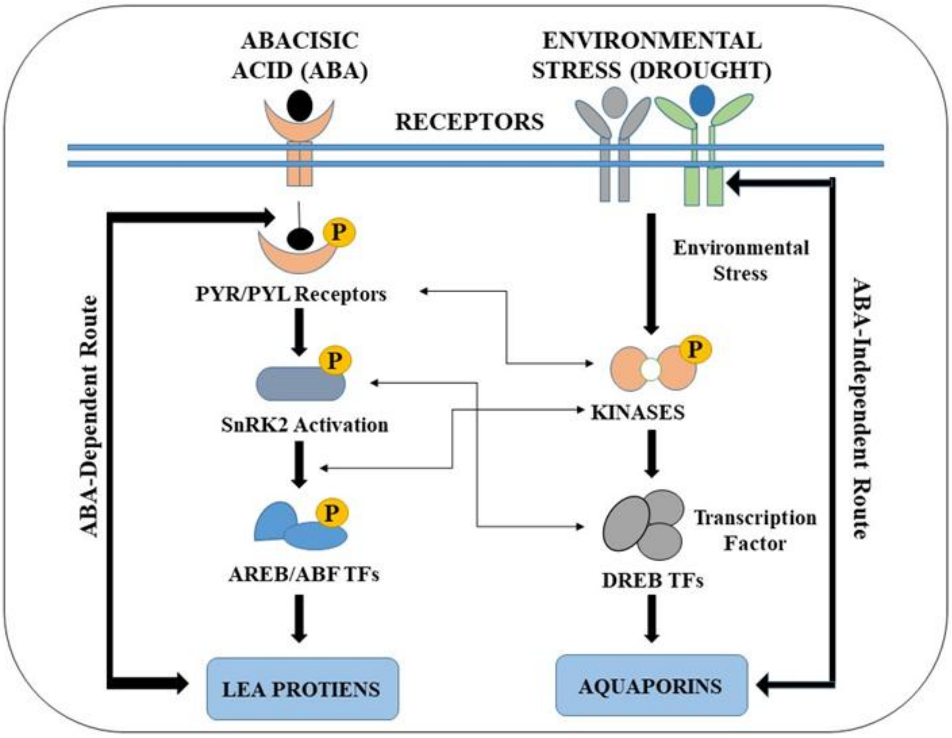

Fig. 3: The Molecular Signaling Cascade: From Perception to Gene Expression.

Epigenetics has emerged as an important area of drought research because environmental stress can induce heritable modifications in gene expression without altering DNA sequences (Banerjee & Roychoudhury, 2017; Yadav et al., 2024). DNA methylation, histone modification and small RNA-mediated regulation contribute to “stress memory,” enabling plants to respond more effectively to repeated drought exposure (Rao et al., 2024; Rahman et al., 2025). Evidence suggests that some epigenetic marks associated with drought tolerance may persist across generations, contributing to transgenerational stress adaptation in maize (Nguyen et al., 2022). Aquaporin modulation further enhances drought resilience by regulating cellular water transport across membranes. Aquaporins are membrane channel proteins that facilitate rapid water movement between cells and tissues (Zargar et al., 2017; Patel & Mishra, 2021). Under drought conditions, selective regulation of plasma membrane intrinsic proteins (PIPs) and tonoplast intrinsic proteins (TIPs) controls root hydraulic conductivity, leaf water status and stomatal behavior (Danelia et al., 2024). Optimized aquaporin expression improves water-use efficiency and maintains cellular hydration during severe drought stress (Li et al., 2024). Therefore, integrating ABA signaling engineering, transcription factor regulation, omics technologies, epigenetic memory and aquaporin modulation provides a comprehensive molecular framework for enhancing drought resilience in maize (Peer et al., 2025; Han et al., 2026).

1.4. Next-Generation Solutions for Global Water Scarcity

Next-generation technologies are revolutionizing maize improvement by integrating molecular biology, digital agriculture and microbial engineering to address the growing challenge of global water scarcity, in Fig. 4. Traditional breeding approaches have significantly improved drought tolerance. However, climate change and increasing frequency of extreme drought events require faster, more precise and multidisciplinary solutions (Srivastava et al., 2022; Ma & Ling, 2026). Modern innovations such as CRISPR/Cas9 genome editing, speed breeding, GeoAI-driven precision agriculture and microbiome engineering are now considered critical tools for developing climate-resilient maize hybrids capable of maintaining productivity under water-limited environments, in Fig. 4. Genome editing through CRISPR/Cas9 technology has emerged as one of the most powerful approaches for improving drought resilience in maize (Namata et al., 2025). Unlike conventional transgenic methods that often involve single-gene insertion, CRISPR enables targeted and multiplex editing of multiple genes simultaneously (Lin et al., 2026). This strategy is particularly important because drought tolerance is a polygenic trait controlled by interconnected regulatory pathways. Recent studies have focused on editing negative regulators of drought

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

signaling pathways, including PP2C phosphatases and stress-suppressing transcriptional repressors, to enhance stress responsiveness without severe yield penalties (Mubarik et al., 2021). CRISPR/Cas systems provide unprecedented precision in modifying stress-responsive loci associated with ABA signaling, root development, and osmotic regulation (Khalid et al., 2026). Multiplex editing has also enabled simultaneous improvement of root architecture, stomatal regulation and antioxidant defense systems in maize. Thereby, accelerating the development of drought-resilient genotypes (Qiao et al., 2026).

Fig. 4: Global overview of maize cultivation, physiological and molecular responses to drought stress, and key adaptation strategies across major producing nations. Regional profiles break down the specific physiological effects, molecular defense mechanisms, yield impact percentages, and primary adaptation strategies (such as climate-smart breeding and water-management systems) implemented by leading global producers.

Citation: Hayat MK, Ijaz H, Jamali S, Zafar S, Ashraf ZU, Shahriyar S, Cengiz R, Öten M, Akter A and Mahmud MN, 2026. Global research trends in enhancing maize productivity under water scarcity: A bibliometric analysis of molecular and physical interventions (1984-2026). Agrobiological Records 24: 252-276. https://doi.org/10.47278/journal.abr/2026.042

Speed breeding further complements genome editing by drastically reducing generation turnover time (Pandey et al., 2022). Traditional maize breeding cycles often require several years to develop stable hybrids. Whereas speed breeding integrates controlled environmental conditions, extended photoperiods and optimized growth chambers to accelerate flowering and seed production (Hayat & Öten, 2026). This approach enables multiple generations per year, significantly shortening the breeding pipeline for climate-ready cultivars. When combined with genomic selection and marker-assisted breeding, speed breeding allows rapid fixation of drought-tolerant alleles and early selection of superior phenotypes (Zhao et al., 2026). The integration of CRISPR editing with speed breeding can reduce the development time of improved maize hybrids by nearly 50%, offering an efficient pathway for responding to rapidly changing climatic conditions (He et al., 2024).

GeoAI and precision agriculture technologies are transforming drought management through real-time monitoring of crop and soil conditions (Hayat et al., 2026). GeoAI integrates artificial intelligence, satellite imaging, unmanned aerial vehicles (UAVs) and geospatial analytics to optimize irrigation scheduling, soil moisture management, and drought forecasting. Satellite-based multispectral and thermal imaging systems can detect early physiological signs of drought stress, including canopy temperature changes, chlorophyll decline and reduced transpiration rates (Gerhards et al., 2019). Soil sensors and IoT-enabled platforms further improve irrigation efficiency by providing real-time information on soil water availability and nutrient dynamics, in Fig. 5. Remote sensing technologies can significantly reduce water wastage while improving crop productivity under limited water resources. Precision agriculture therefore enables the integration of molecular resilience traits with field-scale environmental monitoring systems (Liang et al., 2025).

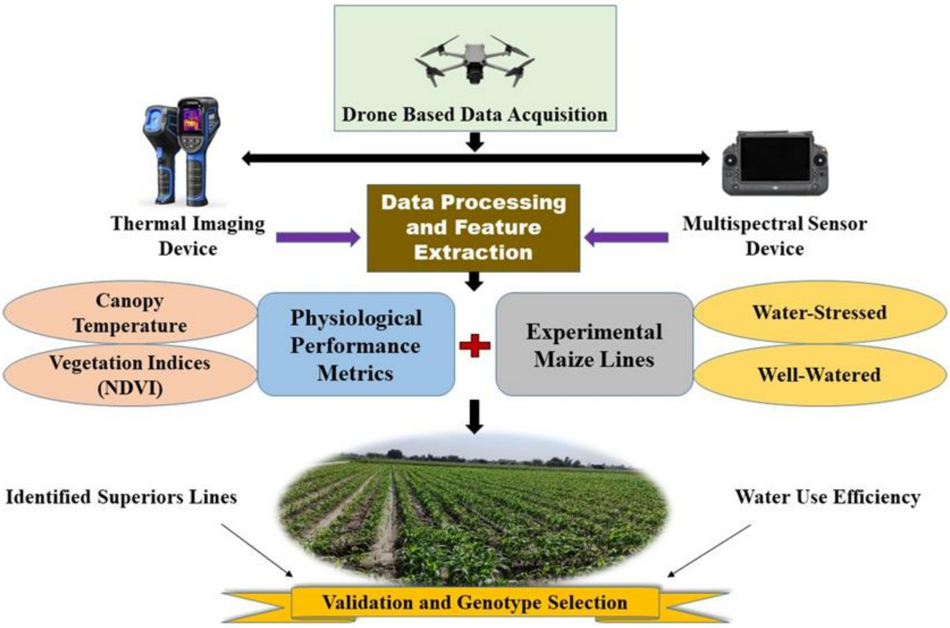

Fig. 5: Conceptual workflow for UAV-based remote sensing and high-throughput phenotyping. This figure depicts the integration of thermal and multispectral data acquisition with physiological performance metrics to select superior, water-efficient experimental maize genotypes.

Microbiome engineering has also emerged as a promising strategy for enhancing maize drought resilience. Drought-tolerant plant growth-promoting rhizobacteria (PGPR) and beneficial fungi establish synergistic interactions with maize roots, improving nutrient acquisition, hormonal balance, and water uptake (Meel & Saharan, 2024; Mikiciuk et al., 2024). Certain rhizobacteria stimulate root elongation, increase osmoprotectant production and induce systemic stress tolerance through phytohormonal signaling pathways (Das et al., 2025). Microbial inoculation can also improve soil aggregation and rhizosphere moisture retention under drought conditions. According to Microbiology research, microbiome-assisted drought adaptation represents a unique convergence of physical and molecular resilience mechanisms (Zhang et al., 2026). Consequently, the integration of genome editing, accelerated breeding systems, GeoAI technologies and microbiome engineering offers a comprehensive next-generation framework for sustaining maize productivity under increasing global water scarcity (Thingujam et al., 2025).

2. MATERIALS AND METHODS

The Web of Science Core Collection, which is one of the most comprehensive and internationally recognized transdisciplinary citation databases, was used as the primary data source for this bibliometric analysis. These databases were selected due to their extensive coverage of peer-reviewed literature in environmental sciences, plant biology and physiology and agricultural sciences, thereby ensuring a robust and representative dataset for research on maize production systems. The Clarivate Analytics Web of Science (WoS) is one of the most widely used platforms for academic citation searches and bibliometric analyses and constitutes one of the largest scientific databases worldwide, encompassing a broad range of high-impact scholarly publications (Pranckutė, 2021). Publication records were retrieved from the WoS Core Collection, including the following indices: Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Emerging Sources Citation Index (ESCI) and Index Chemicus (IC). Data collection was completed on November 20, 2025, to minimize potential database update bias. The search was conducted using the topic-based keywords "maize," "abiotic stress," "drought" and "abiotic stresses." In total, 2860 publications related to the impact of drought on maize were identified. Out of these 2860 papers only 853 paper were selected on the base criterias were selected for the recent publications on this top, which highlights the significance of this research. All records were exported in "full record and cited references" format and saved as RIS, EndNote, plain text data, Excle and tab-delimited files. The retrieved data were subsequently imported into VOSviewer for further bibliometric visualization and network analysis, in Fig. 6.

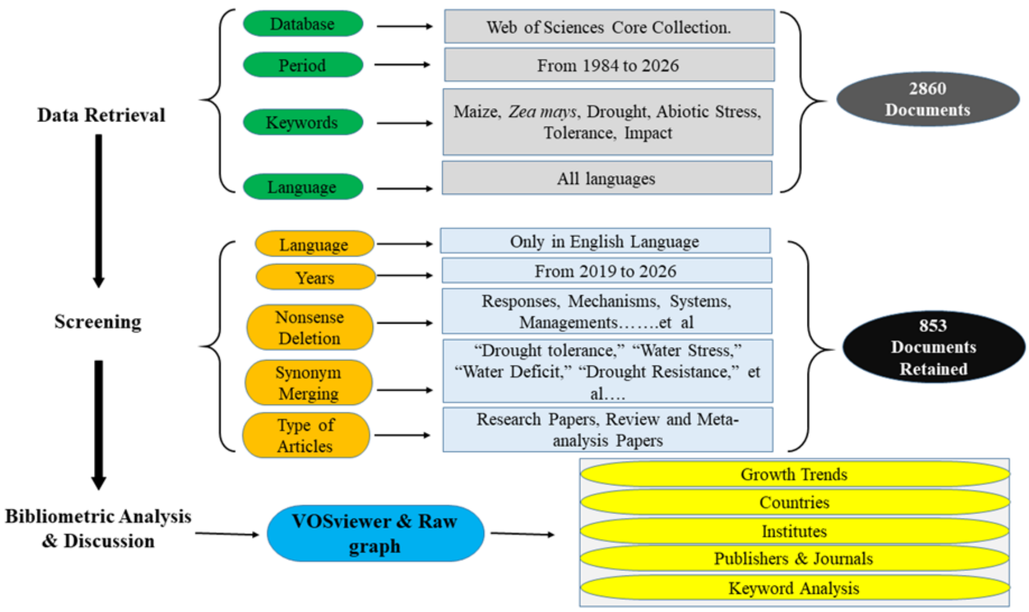

Fig. 6: A summary of bibliometric analysis procedures through this PRISMA flowchart.

2.1. VOSviewer

The datasets obtained from this search were analyzed and visualized using VOSviewer, a user-friendly, freely available bibliometric visualization software. This tool was chosen for its extensive analytical capabilities, ability to handle large datasets and its capacity to create intuitive visualizations that enhance data interpretation (Van Eck & Waltman, 2010; McAllister et al., 2022). In this study, VOSviewer was used to assess the extent of international collaboration among authors, institutions, countries and to identify research trends through keyword analysis. The software also facilitated cluster and network analyses. All analyses were performed using the default parameters provided by VOSviewer (Suryantoro et al., 2023). In the network visualizations, items are depicted as circles, with the size of each circle indicating the relative weight or importance of the item. Different colors represent clusters of related elements. The spatial distance between circles reflects the strength of their relationships, where closer proximity indicates stronger associations.

3. RESULTS

3.1. Type of Document and Publication Language

A total of 853 papers on the imapct of drought stress on maize, published between 1984 and 2026 were identified through keyword-based searches. The publications were indexed in several Web of Science databases, including the Science Citation Index Expanded (SCI-EXPANDED: 771 records), Social Sciences Citation Index (SSCI: 78 records), Emerging Sources Citation Index (ESCI: 68 records) and Index Chemicus (IC: 1 record). Regarding publication language, the vast majority of the papers (852) were published in English, while 1 paper was published in the French Language. Thus, English was the predominant language of publication in this research field.

3.2. Publications Trend

The quantification of academic publications is an important indicator for identifying trends and developments within specific scientific fields. Fig. 7 illustrates the number of scholarly publications related to maize stress studies published between 1984 and 2026. In 2024, the highest annual publication output was recorded, with 186 papers. Overall, the number of research articles addressing the impact of drought stress on the physiological, molecular and yield of maize has shown a marked increase since 2019. These trends indicate that this research area has attracted increasing scientific attention over the past 10 years, keeping in view the number of papers published and number citations per year.

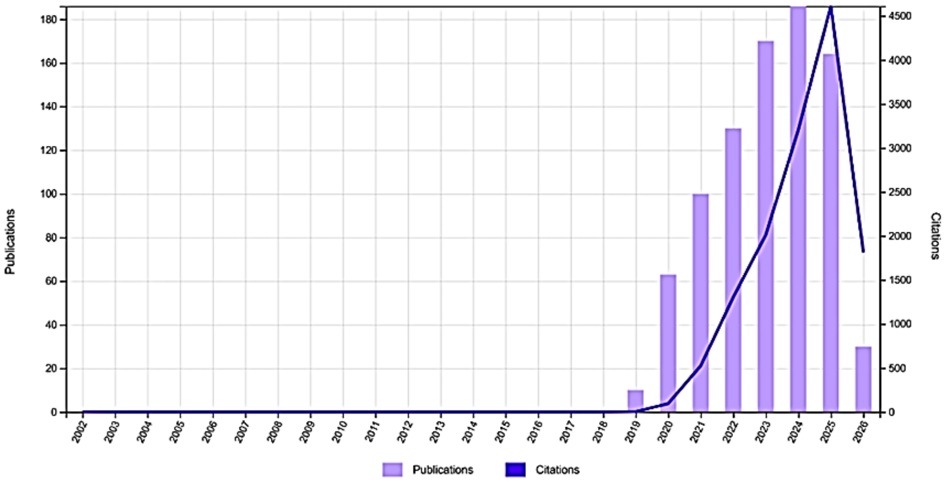

Fig. 7: Scholarly article publication trends concerning impact of drought on maize research between 2002 and 2026.

The influence of a scientific publication is commonly assessed by the number of citations it receives, while the overall quality and impact of published research are often evaluated using quantitative indicators such as the h-index. The h-index, originally proposed to measure a researcher's productivity and citation impact, is defined as the number of publications that have received at least the same number of citations (Hirsch, 2005). The 853 papers analyzed from 2019 to 2026 had an h-index of 51 and received a total of 13,590 citations during the study period, with an average of 15.93 citations per publication.

3.3. Web of Science Categories and Research Areas

According to the Web of Science (WOS) classification system, the search terms maize and drought were associated with 46 research subjects and 67 subject categories. The ability of WOS to classify journals and publications into multiple categories highlights the interdisciplinary nature of this field of study. Within the WOS platform, documents may be assigned to one or more research domains. Table 1 presents the top 15 WOS subject categories and research areas related to maize and stress studies published between 1984 and 2026. Among the subject categories 1349 papers were analyzed, the most frequent with at least 10 papers in these categories were

Table 1: The most important 15 WOS categories and research areas about the impact of drought on Maize

Sr. No.	WOS categories	Total Papers	% of papers	Research areas	Total Papers	% of papers
1	Plant Sciences	280	19.59	Plant Sciences	280	20.75
2	Environmental Sciences	209	14.62	Agriculture	240	17.79
3	Agronomy	171	11.96	Environmental Sciences Ecology	227	16.82
4	Meteorology Atmospheric Sciences	100	6.99	Meteorology Atmospheric Sciences	100	7.41
5	Water Resources	57	3.98	Science Technology Other Topics	98	7.26
6	Multidisciplinary Sciences	56	3.91	Water Resources	57	4.22
7	Environmental Studies	51	3.56	Food Science Technology	51	3.78
8	Food Science Technology	51	3.56	Geology	47	3.48
9	Soil Science	50	3.49	Microbiology	29	2.14
10	Geosciences Multidisciplinary	47	3.28	Chemistry	27	2.00
11	Green Sustainable Science Technology	40	2.79	Remote Sensing	24	1.77
12	Agriculture Multidisciplinary	30	2.09	Imaging Science Photographic Technology	20	1.48
13	Microbiology	29	2.02	Business Economics	18	1.33
14	Remote Sensing	24	1.67	Biochemistry Molecular Biology	16	1.18
15	Imaging Science Photographic Technology	20	1.39	Biotechnology Applied Microbiology	14	1.03

Citation: Hayat MK, Ijaz H, Jamali S, Zafar S, Ashraf ZU, Shahriyar S, Cengiz R, Öten M, Akter A and Mahmud MN, 2026. Global research trends in enhancing maize productivity under water scarcity: A bibliometric analysis of molecular and physical interventions (1984-2026). Agrobiological Records 24: 252-276. https://doi.org/10.47278/journal.abr/2026.042

Plant Sciences (280 papers: 20.75%), Agriculture (240 papers: 17.79%), Environmental Sciences Ecology (227 papers: 16.82%), Meteorology Atmospheric Sciences (100 papers: 7.41%), Science Technology Other Topics (98 papers 7.26%), Water Resources (57 papers: 4.23%), Food Science Technology (51 papers: 3.78%), Geology (47 papers 3.48%), Microbiology (29 papers: 2.15%), Chemistry (27 papers: 2%), Remote Sensing (24 papers: 1.78%), Imaging Science Photographic Technology (20 papers: 1.48%), Business Economics (18 papers: 1.33%), Biochemistry Molecular Biology (16 papers: 1.18%), Biotechnology Applied Microbiology (14 papers: 1.04%), Life Sciences Biomedicine Other Topics (11 papers: 0.82%) and Engineering and Genetics Heredity (10 papers: 0.74%).

3.4. Core Journals and Publishers

The top 15 core journals are listed in Table 2. These journals were shortlisted from the top 201 journals based on a minimum threshold of 10 articles, total citations and average citations per publication. The proportion of total papers published by the leading journals shows that *Agronomy Basel* accounted for 6.28% of the publications, followed by *Frontiers in Plant Science* (5.78%), *Plants Basel* (4.65%), *Environmental Research Letters* (3.90%), *Sustainability* (3.52%) and *Scientific Reports* (3.27%).

Table 2: List of the 15 most important journals pertaining to impact of drought on maize.

Sr. No.	Journals	Total Papers	% of papers	Journals	Total citations	Avg. citations of top cited papers
1	Agronomy Basel	50	6.28	Scientific Reports	264	37.71
2	Frontiers in Plant Science	46	5.78	Nature Food	247	41.17
3	Plants Basel	37	4.65	Nature Communication	182	45.5
4	Environmental Research Letters	31	3.90	Environmental Research Letters	176	25.14
5	Sustainability	28	3.52	BMC Plant Biology	129	21.5
6	Scientific Reports	26	3.27	Plant and Soil	125	25
7	Water	23	2.89	Agronomy Basel	119	19.83
8	Agriculture Basel	21	2.64	Archives of Agronomy and Soil Science	116	16.57
9	Frontiers in Sustainable Food Systems	18	2.26	Agricultural and Food Economics	97	19.4
10	Plant and Soil	18	2.26	Journal of Soil Science and Plant Nutrition	84	12
11	Remote Sensing	18	2.26	Plant Physiology	82	20.5
12	BMC Plant Biology	16	2.01	Agronomy Journal	81	11.57
13	Journal of Agronomy and Crop Science	14	1.76	Microbiome	80	11.43
14	Theoretical and Applied Climatology	14	1.76	Plant Direct	78	15.6
15	Journal of Soil Science and Plant Nutrition	11	1.38	Physiologia Plantarum	74	10.57

Table 2 also presents the top 20 journals with the highest citation impact, of which the top 10 are illustrated in Fig. 8. These journals include the *Journal of Experimental Botany* (average citations: 70.63), *Environmental Health* (63.70), *Veterinary Journal* (42.89), *Agronomie* (42.67), *Environmental Microbiology* (41.31), *Journal of Dairy Science* (38.25), *Nature Reviews Microbiology* (36.21), *Ecotoxicology & Environmental Safety* (32.70), *Trends in Plant Science* (29.93), and *Microbiology & Molecular Biology Reviews* (27.23). Fig. 8 highlights the leading journal categories with the highest number of recorded citations.

Similarly, a wide range of publishers contribute to publications across different research fields. Out of 36 publishers, among these publishers MDPI, Springer Nature, Wiley, Frontiers Media and Elsevier were the top 5, with 239 i.e., 30% papers, 159, 20% papers, 119, 15% papers, 87, 11% papers and 42, 5% publications, respectively. Each of these publishers produced approximately 10 or more articles, as shown in Fig. 9.

3.5. Authors and Co-authorship Analysis

The contribution of researchers from different countries and their collaborative networks, as illustrated in Fig. 10, represents a crucial component of this research field. Highly productive researchers often play a significant role in shaping research directions and advancing scientific knowledge within their disciplines. Out of a total of 853 publications, 710 highly ranked papers were shortlisted based on citation counts and the number of publications per author. These papers involved a total of 4399 authors. Using VOSviewer, co-authorship and citation analyses were conducted on the selected 710 papers, of which 613 authors met the threshold for the highest number of papers in Fig. 10, while the citation impact 721 authors out pf 3919 were grouped into 26 clusters based on data retrieved from the Web of Science, in Fig. 11.

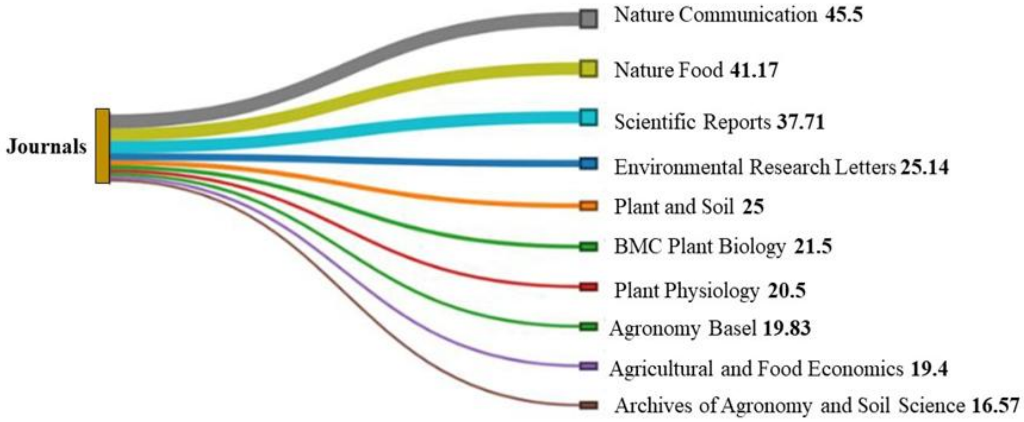

Fig. 8: Most highly rated journals in which the most papers were cited with an average citation.

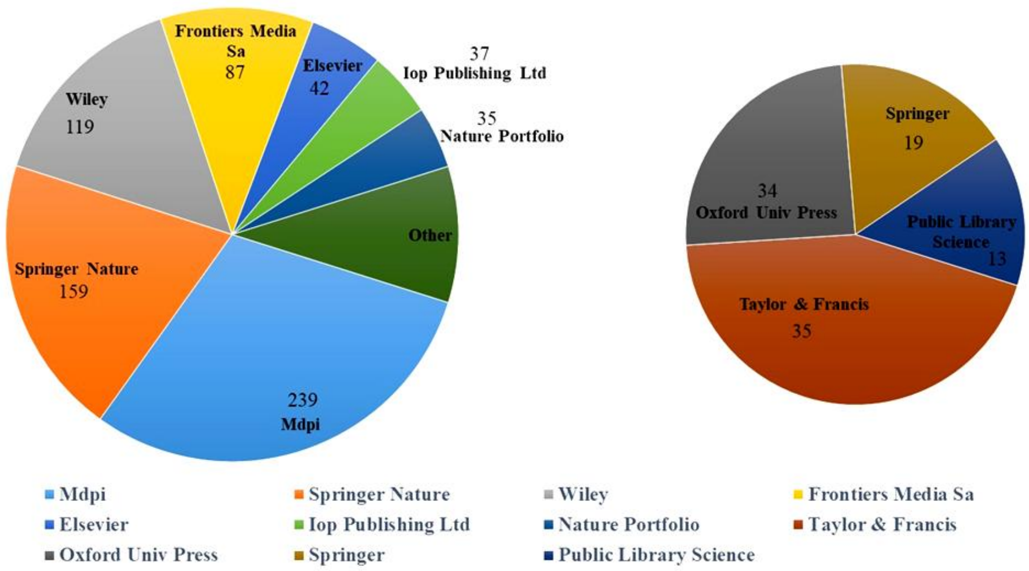

Fig. 9: Publication Sources and Citation Impact.

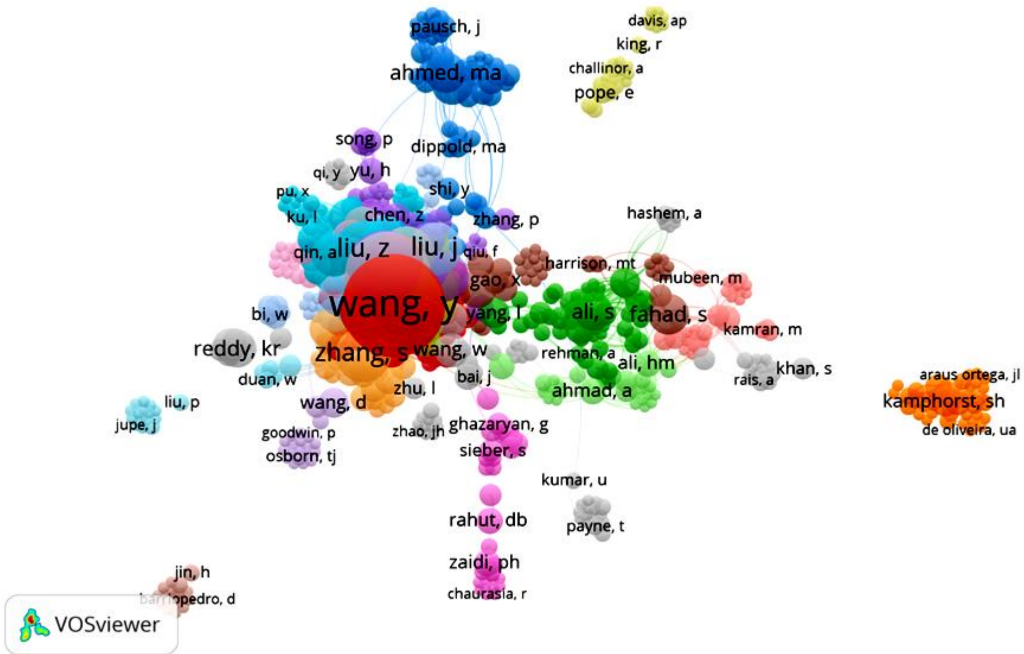

Fig. 10: Authors met the threshold for the highest number of papers.

Citation: Hayat MK, Ijaz H, Jamali S, Zafar S, Ashraf ZU, Shahriyar S, Cengiz R, Öten M, Akter A and Mahmud MN, 2026. Global research trends in enhancing maize productivity under water scarcity: A bibliometric analysis of molecular and physical interventions (1984-2026). Agrobiological Records 24: 252-276. https://doi.org/10.47278/journal.abr/2026.042

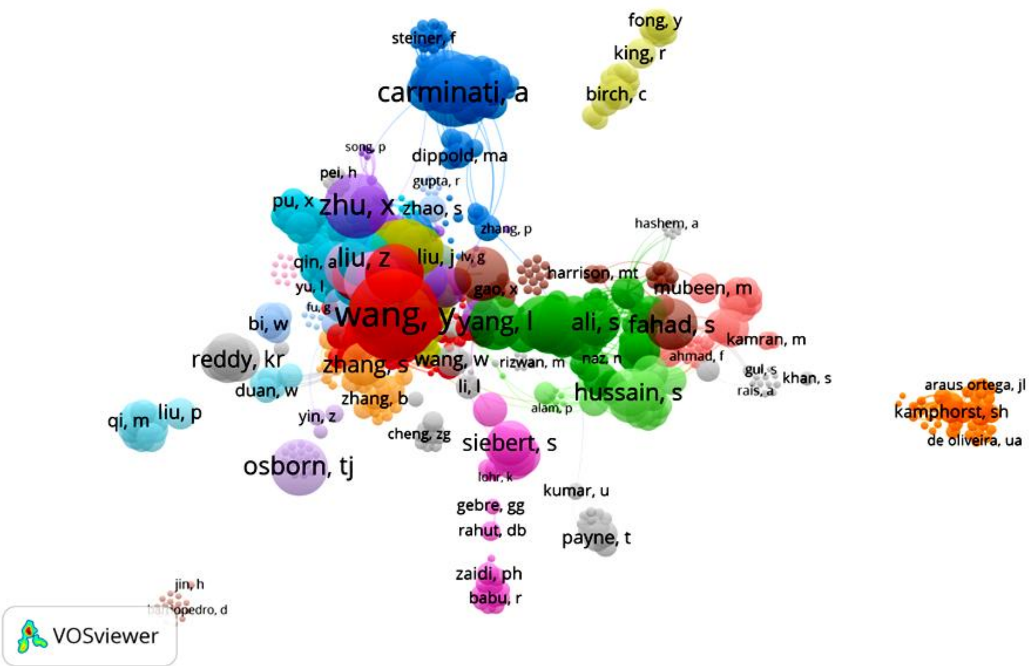

Fig. 11: Authors met the threshold for the at least 5 citations.

Similarly, institutional-level data obtained from the Web of Science were analyzed to identify the top 200 researchers with 609 papers were affiliated with 42 international institutions worldwide out 201, each with a minimum of 10 publications per institution. From these data, the top 126 researchers were further analyzed based on citation counts derived from the 853 shortlisted papers (Fig. 12). Among these researchers, the top ten authors with at least 5 papers were Zhang, Jiquan with 9, Fahad, Shah and Ahmed, Mutez with 8, Liu, Xingpeng with 7, Reddy, K. R., Tong, Zhijun and Bheemanahalli, Raju with 6, Rahman, Muhammad Habib-Ur-, de Lima, Valter Jário, Carminati, Andrea with 5 papers were shortlisted.

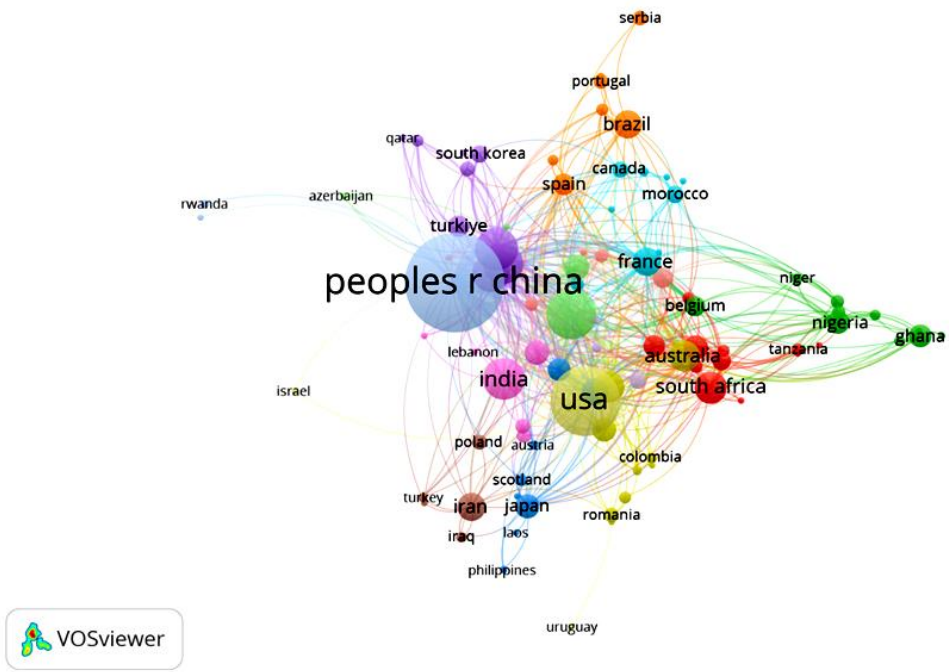

Fig. 12: Network of country co-authorship working on maize based on number of papers.

These 853 papers were published by 106 countries with minimum 1 paper by each country. Amoung these countries China was leading in both number of papers Fig. 12 and citations Fig. 13, followed by USA, Germany, Pakistan and Saudi Arabia, are well demonstrated. Till 2026, China 311 papers with 4648 citations, USA 152

Citation: Hayat MK, Ijaz H, Jamali S, Zafar S, Ashraf ZU, Shahriyar S, Cengiz R, Öten M, Akter A and Mahmud MN, 2026. Global research trends in enhancing maize productivity under water scarcity: A bibliometric analysis of molecular and physical interventions (1984-2026). Agrobiological Records 24: 252-276. https://doi.org/10.47278/journal.abr/2026.042

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

papers with 3098 citations, Germany 80 papers with 2247 citations, Pakistan 60 papers with 1295 citations and Saudia Arabia 53 papers with 1349 citations are dominating in this research domain.

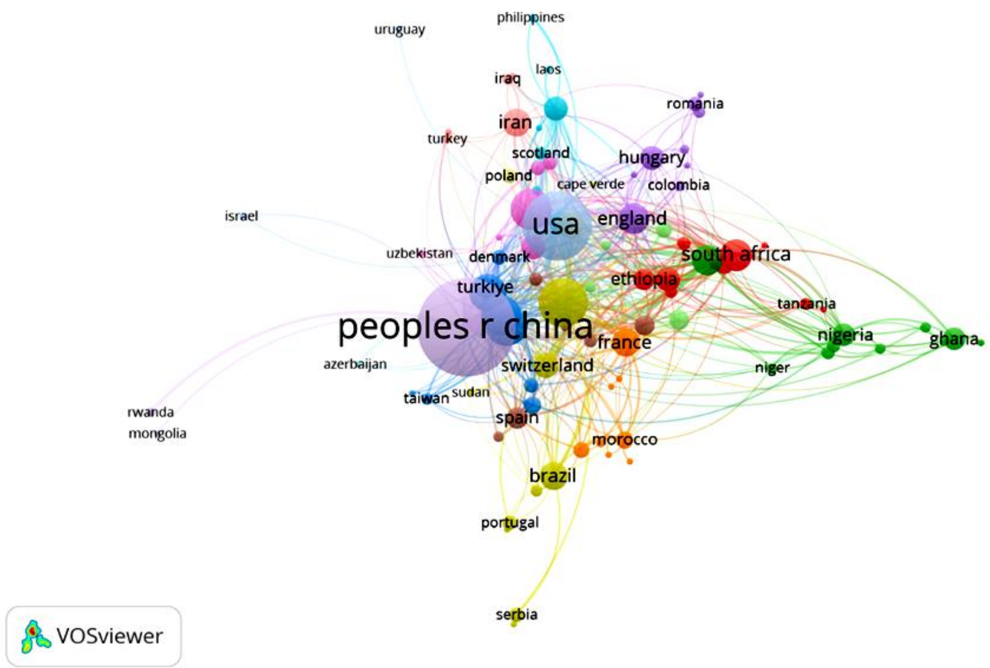

Fig. 13: Network of country co-authorship working on maize based on number of citations.

3.6. Organizations Co-authorship Analysis

An analysis of research organizations, as illustrated in Fig. 14 and 15, provides insight into the institutions leading this field of study. The publication data indicate that a total of 201 organizations contributed to 853 papers. The top 30 institutions and organizations, ranked by total number of publications, are presented in Table 3. These fifteen organizations are distributed across several countries, including the China (11 organizations) is leading followed by, United States Germany, Australia, France, Saudi Arabia, Pakistan India and Switzerland. In addition, the five most productive organizations worldwide the Chinese Academy of Sciences (China), CGIAR System Organization (France), the United States Department of Agriculture (USDA; USA), University of Agriculture Faisalabad (Pakistan), the Swiss Federal Institutes Of Technology Domain (Switzerland) and the Indian Council Of Agricultural Research ICAR (India), each institute published more than 12 papers. These institutions demonstrate a high level of prominence and influence in the scholarly literature related to impact of drought and its significance on maize.

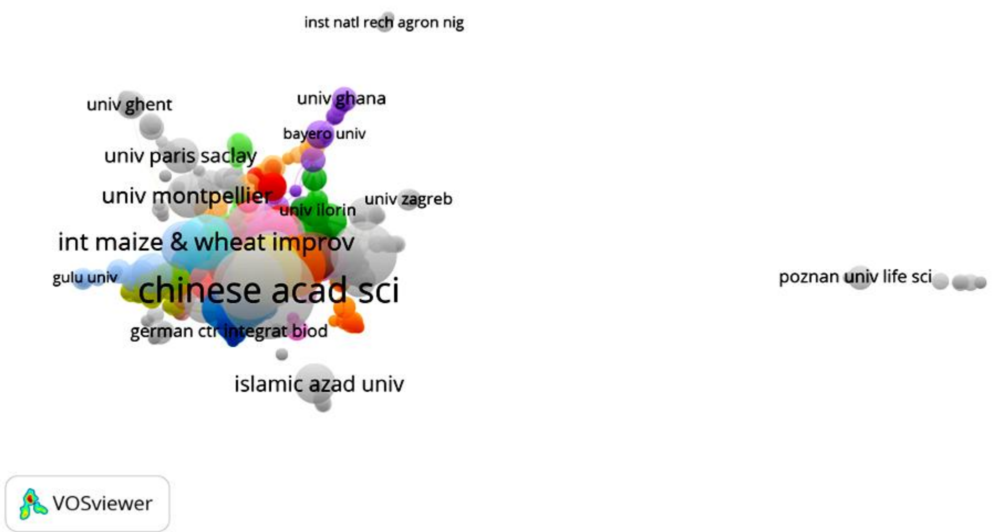

Fig. 14: Top Research Organizations Institutes on the base of number of papers.

Citation: Hayat MK, Ijaz H, Jamali S, Zafar S, Ashraf ZU, Shahriyar S, Cengiz R, Öten M, Akter A and Mahmud MN, 2026. Global research trends in enhancing maize productivity under water scarcity: A bibliometric analysis of molecular and physical interventions (1984-2026). Agrobiological Records 24: 252-276. https://doi.org/10.47278/journal.abr/2026.042

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

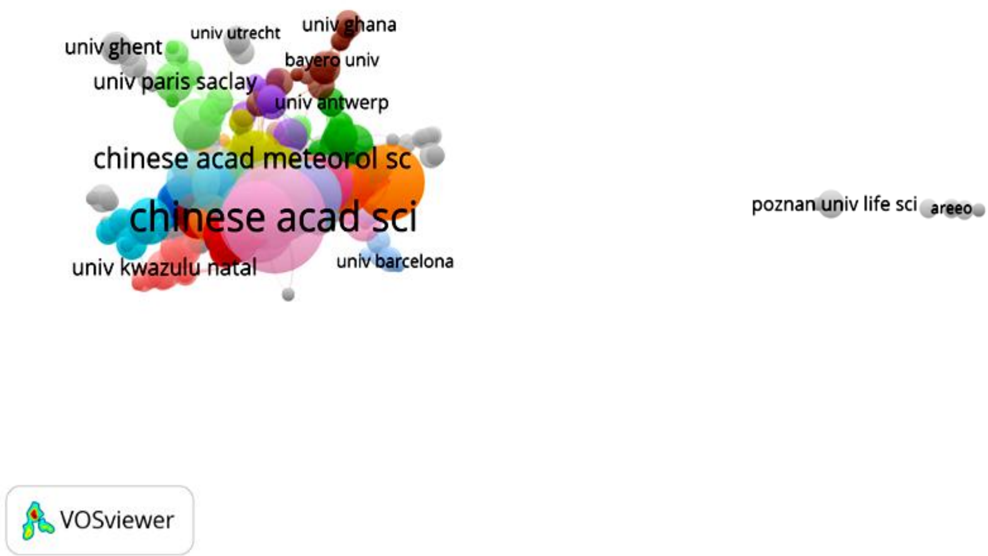

Fig. 15: Top Research Organizations Institutes on the base of number of citations.

Table 3: List of top 30 most influential organizations working on maize.

Sr. No.	Universities and Institutes	Papers	Countries
1	Chinese Academy of Sciences	62	China
2	CGIAR System Organization	44	France
3	Egyptian Knowledge Bank EKB	44	Egypt
4	University of Chinese Academy of Sciences CAS	32	China
5	China Agricultural University	29	China
6	China Meteorological Administration	29	China
7	King Saud University	26	Saudi Arabia
8	Northwest A F University China	24	China
9	International Maize Wheat Improvement Center CIMMYT	23	Mexico
10	Chinese Academy of Agricultural Sciences	21	China
11	University of California System	21	USA
12	United States Department Of Agriculture USDA	19	USA
13	Helmholtz Association	18	Germany
14	INRAE	18	France
15	Chinese Academy of Meteorological Sciences Cams	17	China
16	University of Agriculture Faisalabad	16	Pakistan
17	University of Bonn	16	Germany
18	Kansas State University	15	USA
19	Swiss Federal Institutes of Technology Domain	15	Switzerland
20	Institute of Geographic Sciences Natural Resources Research CAS	14	China
21	Islamia University of Bahawalpur	14	Pakistan
22	Nanjing University of Information Science Technology	14	China
23	ETH Zurich	13	Switzerland
24	Gansu Agricultural University	13	China
25	Universite De Montpellier	13	France
26	Henan Agricultural University	12	China
27	Indian Council of Agricultural Research ICAR	12	India
28	Leibniz Association	12	Germany
29	Leibniz Zentrum Fur Agrarlandschaftsforschung Zalf	12	Germany
30	Technical University of Munich	12	Germany

Total 1434 organizations were recoreded from these paper, from which only 1332 organizations meet the thresholds level of at least one citation with at least one paper. While 1064 organizations meet the thrshold level of at least 5 citations and have at leat one publication on this research. So, out of these 1064 organizations, top 1000 organizations were selected on the base maximum citations and number of papers. In Fig. 14, 858 organziations were grouped in 42 different groups with the 3288 links, while the total strenght among them was 3666. Once again, co-occurrence analysis method was used for the organizations with full fraction counting method and ignored the papers co-authored large number of organizations. In this analysis, maximum 25 number

Citation: Hayat MK, Ijaz H, Jamali S, Zafar S, Ashraf ZU, Shahriyar S, Cengiz R, Öten M, Akter A and Mahmud MN, 2026. Global research trends in enhancing maize productivity under water scarcity: A bibliometric analysis of molecular and physical interventions (1984-2026). Agrobiological Records 24: 252-276. https://doi.org/10.47278/journal.abr/2026.042

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

of papers were selected for each organization and 1434 organizations meet the criteria. While only 836 organizations meet the threshold level of having minimum 10 number of citations by each organization with at least one paper (Fig. 15).

3.7. All Keywords Co-occurrence Analysis

The use of keywords is crucial in a given scientific field since they reflect the major ideas of academic publications. It is possible to identify the patterns and trends that define a certain academic subject of study by creating a list of keywords. Using the full counting approach, the current study chose author keywords for co-occurrence analysis and examined the co-occurrence patterns of each term. The full counting method was used to conduct co-occurrence analysis for each keyword. According to the data with 3981 co-occurring keywords were selected with a total link strength of 36229, with 22858 links and 1000 of the 3981 keywords satisfied the minimal criteria of 90% most relevant terms in full counting method are given in 15 different clusters (Fig. 16). With a total link strength of 36229, the top 1000 co-occurring keywords were drought, tolerance, impact, maize, yield, adaptability, growth, temperature, management, food security, cereals, grain yield, variability, model, genes, soil, responses and biotic abiotic stresses. While in Fig. 17, fractional counting method was used to conduct the co-occurrence analysis for the keywords. According to this data, 4096 keywords were shortlisted and 315 keywords meet the criteria while considering minimum number of occurrences of a keywords should be five. It was discovered that each of these important terms appeared at least nine times. Fields from which these terms were extracted were the title and abstract fields from which structured abstract labels and copyright statements were ignored during the analysis through VOSviewer. The network map of 2 clusters illustrates the relationships between each keyword. A keyword is represented by each node on the base of its occurrence in the Fig. 18, 336 items were recorded with 26789 links and 98296 total link strengths. The network reveals two primary thematic clusters mapping the research landscape: the red cluster primarily represents macro-level, environmental, and socio-economic dimensions (e.g., *data*, *region*, *model*, *rainfall*, *policy*, *farmer*), while the green cluster focuses on micro-level, physiological, and biological mechanisms (e.g., *growth*, *plant*, *treatment*, *root*, *chlorophyll*, *proline*). The size of the nodes corresponds to the term occurrence frequency, and the thickness of the connecting lines indicates the strength of the co-occurrence links between terms.

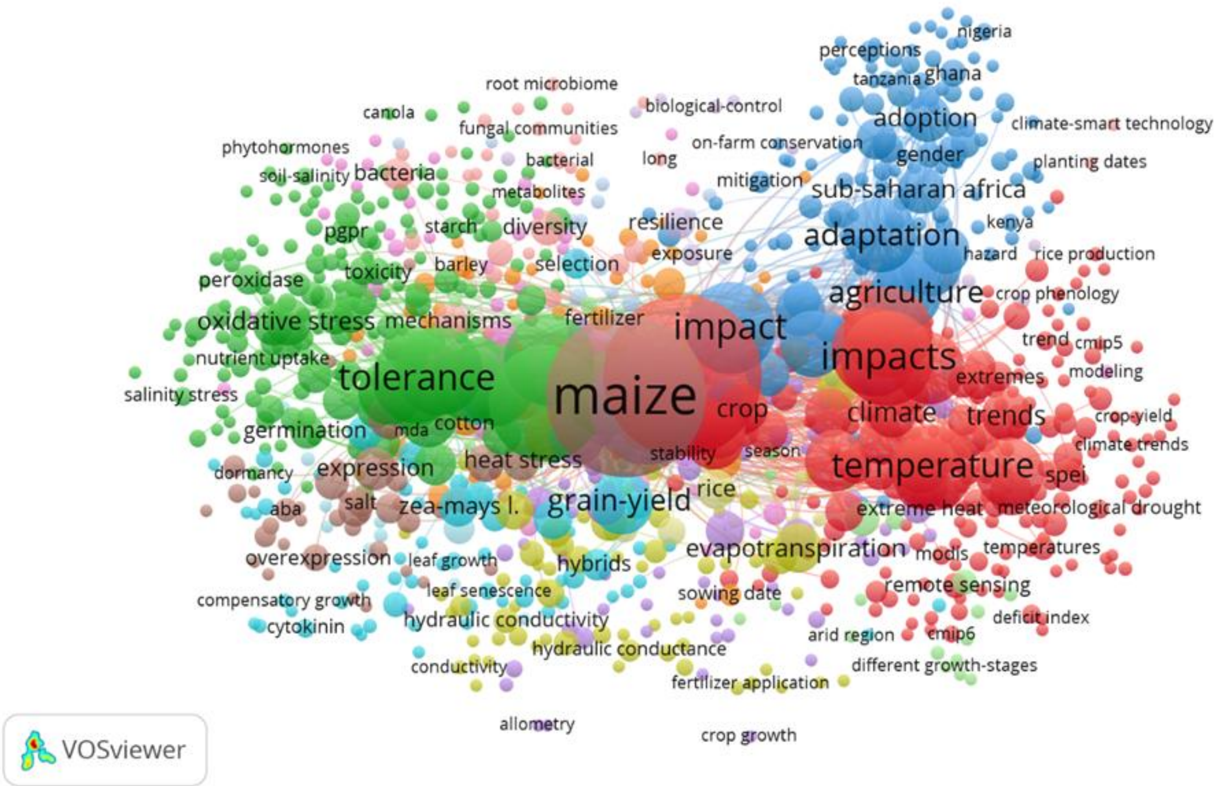

Fig. 16: Co-occurrence network visualization diagram of the most frequently occurring keywords in full counting, pertaining to stresses impacting maize. Clusters of related terms are represented by nodes that share the same color.

Citation: Hayat MK, Ijaz H, Jamali S, Zafar S, Ashraf ZU, Shahriyar S, Cengiz R, Öten M, Akter A and Mahmud MN, 2026. Global research trends in enhancing maize productivity under water scarcity: A bibliometric analysis of molecular and physical interventions (1984-2026). Agrobiological Records 24: 252-276. https://doi.org/10.47278/journal.abr/2026.042

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

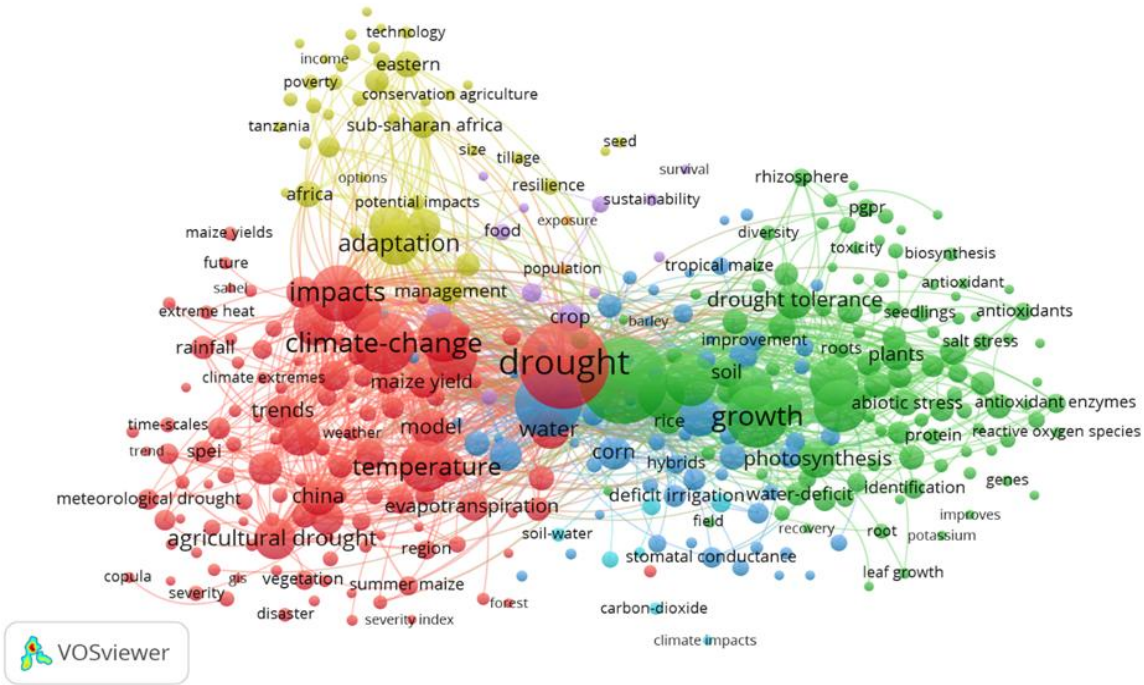

Fig. 17: Co-occurrence network visualization diagram of the most frequently occurring keywords in fractional counting, pertaining to stresses impacting maize. Clusters of related terms are represented by nodes that share the same color.

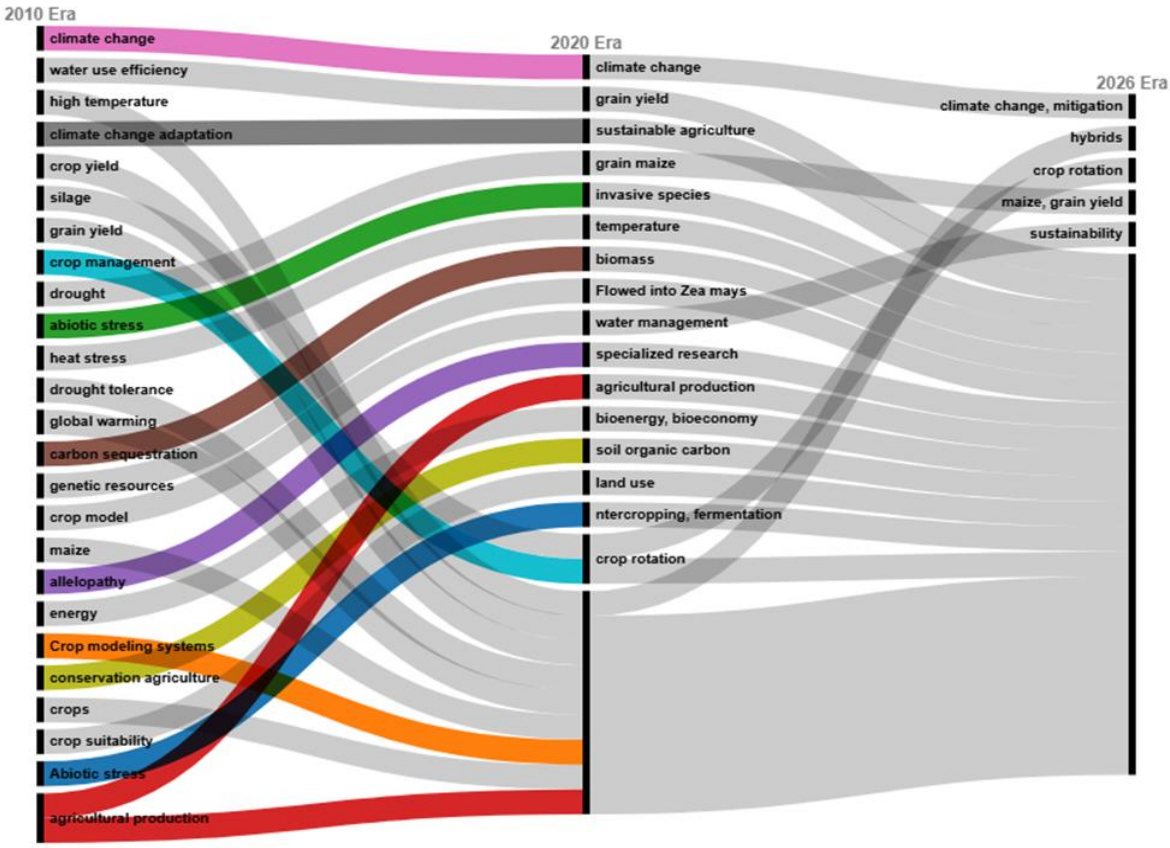

Fig. 18: Thematic evolution of paper's keywords. Evolution of research themes in crop science from 2000 to 206, visualized through a multi-period Sankey diagram. This figure illustrates how key topics such as drought, heat stress, crop yield, fertilization, and pest management emerged, transformed, and interconnected across four timeframes (2000-2010, 2011-2020 and 2021-2026).

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

4. DISCUSSION

The present bibliometric analysis provides a comprehensive picture of how global maize drought research has transitioned from descriptive agronomic observations to an integrated science that combines plant physiology, molecular genetics, environmental modeling, and digital agriculture. The identification of 853 relevant publications from an initial pool of 2860 records demonstrates both the maturity and the rapid expansion of this research domain. The pronounced acceleration in publication output after 2019, culminating in the highest annual output in 2024, reflects the increasing urgency created by climate change, recurrent drought events, and growing competition for freshwater resources (Pandit & Sharma, 2024; Li et al., 2026c). Similar surges in research activity have been reported across climate-resilient agriculture and crop stress physiology, where drought tolerance has become a central target for ensuring future food security (Pranckutė, 2021; McAllister et al., 2022).

The distribution of articles by discipline also shows the development of maize drought research into a highly interdisciplinary field. Although Plant Sciences and Agronomy are still the dominant fields, the high number of papers in Environmental Sciences, Remote Sensing, Biotechnology, Microbiology and Imaging Science shows that drought resistance is now beyond the breeding scope. Rather, it is increasingly being tackled through systems-level approaches that integrate crop physiology, genomics, geospatial analytics, and socio-environmental modelling (Liang et al., 2025; Seraj & Vafaee, 2026). Such a transition is critical when maize is exposed to drought stress, from cellular metabolism to regional food systems, requiring integrative solutions that combine laboratory discoveries and field management strategies.

The analysis of keyword co-occurrence supports further this interpretation. The strong clustering of "drought", "maize", "yield", "tolerance", "adaptability", and "genes" suggests that the main scientific goal remains to achieve grain productivity under water limitation. Similarly, the co-occurrence of physiological terms like "root," "chlorophyll," and "proline" with broader terms such as "food security," "policy," and "climate" points to a growing integration of biological mechanisms with sustainability frameworks (Peer et al., 2024; Peer et al., 2025; Thingujam et al., 2025). Such integration is essential, because in the end improvements in drought tolerance must lead to stable yields, resilient farming systems and reduced vulnerability for regions dependent on maize.

A prominent theme identified in the investigation is the enduring significance of physical and morphological features for drought adaptation. The architecture of the root system is fundamental to drought tolerance since it directly influences access to deep soil moisture. The significant bibliometric predominance of research on steep, deep, and metabolically efficient root systems aligns with findings indicating that deeper nodal roots can greatly enhance water acquisition and yield stability during drought conditions (Lynch, 2013; Gao & Lynch, 2016). Research on root cortical aerenchyma has garnered interest due to its role in diminishing the carbon expenditure associated with soil exploration, thus facilitating increased allocation of assimilates for root elongation and reproductive development (Zhu et al., 2010; Chimungu et al., 2014). The focus on anthesis-silking interval, canopy structure, and hydraulic conductance underscores that effective drought breeding relies significantly on traits that sustain reproductive synchronization and facilitate water transport amid diminishing soil moisture (Qi et al., 2021; Welcker et al., 2022).

Physiological resilience is another major research frontier. The high frequency of terms associated with stomatal regulation, osmotic adjustment, antioxidant defense and photosynthetic stability shows that the understanding is that drought tolerance is essentially a problem of maintaining internal equilibrium when a water deficit occurs. Optimized stomatal sensitivity in drought-tolerant maize genotypes conserves water without completely suppressing carbon assimilation and thus improves water-use efficiency during prolonged stress (Franco-Navarro et al., 2025; Takács et al., 2025). The accumulation of osmoprotectants like proline, glycine betaine and polyamines has also been identified as a consistent marker of stress adaptation, as these compounds stabilize proteins, membranes and cellular hydration (Ghosh et al., 2022; Tyagi et al., 2023). More importantly, the bibliometric prominence of photosynthesis-related keywords reveals that maintaining C4 photosynthetic efficiency is still a major challenge. Drought causes a reduction in chlorophyll content, electron transport and phosphoenolpyruvate carboxylase activity, which directly limits biomass production and kernel filling, while tolerant genotypes maintain higher photochemical efficiency and carbon assimilation under stress (Qu et al., 2023; Ren et al., 2026).

The data indicate a major shift in the direction of precision crop improvement at the molecular scale. The growing importance of ABA signaling, DREB, NAC and WRKY transcription factors has pushed drought research from phenotype selection to modification of regulatory networks that control stress responses (Singh et al., 2023; Yang et al., 2025). The ABA-mediated PYL–PP2C–SnRK2 pathway is a key target as it integrates drought perception with stomatal closure, osmoprotectant production and stress-responsive gene expression (Shen et al., 2022; Iglesias-Moya et al., 2024). Recent advances in transcriptomics and systems biology enabled us to find candidate genes, co-expression networks, aquaporins, LEA proteins and heat-shock proteins associated with drought tolerance (Zenda et al., 2019; Bano et al., 2022). Particularly noteworthy is the increasing focus on

Citation: Hayat MK, Ijaz H, Jamali S, Zafar S, Ashraf ZU, Shahriyar S, Cengiz R, Öten M, Akter A and Mahmud MN, 2026. Global research trends in enhancing maize productivity under water scarcity: A bibliometric analysis of molecular and physical interventions (1984-2026). Agrobiological Records 24: 252-276. https://doi.org/10.47278/journal.abr/2026.042

epigenetic regulation and stress memory, indicating that some drought-adaptive responses could be inherited through generations through DNA methylation, histone modification and small-RNA pathways (Banerjee & Roychoudhury, 2017; Rao et al., 2024; Rahman et al., 2025).

Also important is the geographical distribution of research output. China's dominance in both the volume of publications and their citation impact reflects sustained national investment in climate-resilient agriculture, genomic breeding and agricultural biotechnology. The strength of the United States and Germany and the high-profile roles of institutions like the Chinese Academy of Sciences, CGIAR and CIMMYT underscore the fact that international collaboration continues to be a significant driver of innovation in maize drought research. The participation of countries like Pakistan and Saudi Arabia further highlights the increasing involvement of regions that are experiencing severe water scarcity and therefore have strong incentives to develop drought-resilient cropping systems.

Perhaps the most forward-looking finding is that next-generation technologies are emerging as a distinct research cluster. CRISPR/Cas9 genome editing is being more and more considered as a practical tool to simultaneously modify several drought-related genes to improve in a targeted manner ABA signaling, root development and antioxidant pathways (Namata et al., 2025; Khalid et al., 2026). Speed breeding complements this approach by reducing the duration of the generation cycle and hastening the deployment of climate-ready hybrids (He et al., 2024; Zhao et al., 2026). The rapid emergence of GeoAI, UAV-based phenotyping, satellite imaging, and IoT-enabled irrigation management is also of equal importance, enabling real-time detection of drought stress and more efficient use of limited water resources (Gerhards et al., 2019; Hayat et al., 2026). Another dimension to the solution space is the increasing interest in microbiome engineering. Beneficial rhizobacteria and fungi can be harnessed to enhance root growth, nutrient acquisition, osmotic adjustment and moisture retention in the rhizosphere (Meel & Saharan, 2024; Mikiciuk et al., 2024).

However, the bibliometric evidence also indicates several remaining gaps despite these advances. In many studies drought responses are still assessed in controlled conditions that do not fully represent the complexity of field conditions, heat-drought interactions, or flash-drought dynamics (Christian et al., 2024). Therefore, future research must focus on multi-environment validation, integration of omics data with high-throughput phenotyping and stronger linkages between molecular discoveries and farmer-scale management practices. In conclusion, the present analysis suggests that the future of maize drought resilience will rely on integrating physical traits, physiological regulation, molecular engineering, digital agriculture, and microbial alliances into integrated climate-smart breeding and production systems capable of supporting global food security in the face of increasing water scarcity.

5. CONCLUSION

Drought stress, climate change and increasing global water scarcity pose growing threats to maize productivity; thus, the need to develop drought-resilient production systems is a critical priority for sustainable agriculture. A bibliometric analysis of 853 relevant publications from 1984 to 2026 revealed a significant increase in global scientific interest, particularly after 2019, emphasizing the urgent need to address water challenges in maize cultivation. The findings indicate that maize drought research has transitioned from conventional physiological investigations to multi-disciplinary approaches comprising plant physiology, molecular biology, genomics, artificial intelligence, precision agriculture, and microbiome engineering. The analysis showed that root system architecture, hydraulic conductance, stomatal regulation, photosynthetic stability and osmotic adjustment are important physiological determinants of drought tolerance. At the molecular level, research frontiers became major ABA signaling pathways, transcription factor engineering, omics technologies and epigenetic regulation. The fast adoption of CRISPR/Cas9 genome editing, speed breeding, GeoAI-based crop monitoring, and beneficial microbial interventions further emphasizes the transition to next-generation climate-smart agricultural technologies. Strong contributions from countries including China, USA and Germany and wide-ranging international collaborations highlight the global commitment to improve maize resilience. In summary, the integration of physical, physiological, molecular and digital innovations will be key to maintaining maize productivity, enhancing food security and bolstering agricultural resilience under future drought and climate uncertainty.

Declarations

Funding: This study did not get any financial support from any organization/agency.

Acknowledgement: We would like to thank Prof. Dr. Mustafa Yilmaz, Chairman of the Department of Field Crops, Faculty of Agriculture, Sakarya University of Applied Sciences, who helped us during this study.

Conflicts of Interest: None.

Data Availability: All the data is available in the article.

Ethics Statement: The authors have nothing to report.

Consent: The authors have nothing to report.

Author's Contributions: MKH, HI, SJ, SZ, ZUA, SS, RC, MÖ, MNM and AA did a significant contribution to this work. In the conception, study design, execution, and interpretation, or all these areas; took part in drafting, revising, or critically reviewing the article; gave final approval of the version to be published. Both of these (RC & MÖ) professors, along with all the authors are agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

Generative AI Statements: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

Publisher's Note: All claims stated in this article are exclusively those of the authors and do not necessarily represent those of their affiliated organizations or those of the publisher, the editors, and the reviewers. Any product that may be evaluated/assessed in this article or claimed by its manufacturer is not guaranteed or endorsed by the publisher/editors.

REFERENCES

Aarif, KO, M., Alam, A., & Hotak, Y. (2025). Smart sensor technologies shaping the future of precision agriculture: Recent advances and future outlooks. Journal of Sensors, 2025(1), 2460098. https://doi.org/10.1155/js/2460098

Abdullah, H. M., Atta, M., ul Haq, I., Shah, M. A. R., Mubashar, M., & Hayat, M. K. (2025). Soybean's Genetic Odyssey: Unveiling Diverse Transformation Strategies. In Policy Research Journal. Zenodo. https://doi.org/10.5281/zenodo.15679578

Ahmed, M., Abid, M., Malik, N. A., Ali, S., Zahid, A., Malik, A., & Cheema, M. (2025). Climate-Resilient Strategies for Sustainable Management of Water Resources and Agriculture. In Climate Resilient and Sustainable Agriculture: Volume 2: Social and Transformative Strategies (pp. 1-25). Springer. https://doi.org/10.1007/978-3-032-04141-8_1

Akram, A., Abdullah, M., Haider, D., Tariq, T., Ali, Q., Hayat, M., Haseeb, A., Yasin, F., & Iqbal, A. (2025). Thriving in adversity: quinoa's response to drought and the promise of optimized watering. Agrobiological Records, 21, 78-98. https://doi.org/10.47278/journal.abr/2025.035

Akram, H.M.B., Ullah. I., Nabi. H.G., Shahzad. N., Ahmad. M., & Farzand, A. (2023). Optimization of plant spacing for yield improvement in hybrid maize using DSSAT. Agrobiological Records, 14. 37-49. https://doi.org/10.47278/journal.abr/2023.036

Ali, Z., Merrium, S., Habib-ur-Rahman, M., Hakeem, S., Saddique, M. A. B., & Sher, M. A. (2022). Wetting mechanism and morphological adaptation; leaf rolling enhancing atmospheric water acquisition in wheat crop a review. Environmental Science and Pollution Research, 29(21), 30967-30985. https://doi.org/10.1007/s11356-022-18846-3

Aslam, M., Maqbool, M. A., & Cengiz, R. (2015). Drought stress in maize (Zea mays L.) Effects, resistance mechanisms, global achievements and. Cham: Springer. https://doi.org/10.1007/978-3-319-25442-5

Azrai, M., Bahrun, A. H., Efendi, R., Andayani, N. N., Jihad, M., Zainuddin, B., & Aqil, M. (2024). Global drought tolerant maize research and development: analysis and visualization of cutting-edge scientific technologies. Journal of Agriculture and Food Research, 18, 101323. https://doi.org/10.1016/j.jafr.2024.101323

Banerjee, A., & Roychoudhury, A. (2017). Epigenetic regulation during salinity and drought stress in plants: Histone modifications and DNA methylation. Plant Gene, 11, 199-204. https://doi.org/10.1016/j.plgene.2017.05.011

Bano, N., Fakhrah, S., Mohanty, C. S., & Bag, S. K. (2022). Transcriptome meta-analysis associated targeting hub genes and pathways of drought and salt stress responses in cotton (Gossypium hirsutum): a network biology approach. Frontiers in Plant Science, 13, 818472. https://doi.org/10.3389/fpls.2022.818472

Biswas, A., Sarkar, S., Das, S., Dutta, S., Choudhury, M. R., Giri, A., Bera, B., Bag, K., Mukherjee, B., & Banerjee, K. (2025). Water scarcity: A global hindrance to sustainable development and agricultural production–A critical review of the impacts and adaptation strategies. Cambridge Prisms: Water, 3, e4. https://doi.org/10.1017/wat.2024.16

Burlakoti, S., Devkota, A. R., Poudyal, S., & Kaundal, A. (2024). Beneficial plant-microbe interactions and stress tolerance in maize. Applied Microbiology, 4(3), 1000-1015. https://doi.org/10.3390/applmicrobiol4030068

Chen, S., Chen, Z., Kong, Z., & Zhang, Z. (2023). The increase of leaf water potential and whole-tree hydraulic conductance promotes canopy conductance and transpiration of Pinus tabulaeformis during soil droughts. Trees, 37(1), 41-52. https://doi.org/10.1007/s00468-022-02322-z

Chimungu, J. G., Brown, K. M., & Lynch, J. P. (2014). Large root cortical cell size improves drought tolerance in maize. Plant Physiology, 166(4), 2166-2178. https://doi.org/10.1104/pp.114.250449

Christian, J. I., Hobbins, M., Hoell, A., Otkin, J. A., Ford, T. W., Cravens, A. E., Powlen, K. A., Wang, H., & Mishra, V. (2024). Flash drought: A state of the science review. WIREs Water, 11(3), e1714. https://doi.org/10.1002/wat2.1714

Dai, J., Shi, Y., Zed, R., Sun, B., Shen, J., Zhang, F., & Jin, K. (2025). Adaptation of deep-rooted maize genotype to compacted soil: Synergy of root mechanical properties, anatomical traits, and PIEZO1 gene regulation. Soil and Tillage Research, 252, 106620. https://doi.org/10.1016/j.still.2025.106620

Danelia, G. V., Emelyanov, V. V., & Shishova, M. F. (2024). The role of water-transporting aquaporins of the PIP and TIP subfamilies in plant development and adaptation to stress factors. Ecological Genetics, 22(4), 343-368. https://doi.org/10.17816/ecogen637037

Das, S., Shil, S., Rime, J., Alice, A. K., Yumkhaibam, T., Mounika, V., Singh, A. P., Kundu, M., Lalhmangaihzuali, H., & Hazarika, T. K. (2025). Phytohormonal signaling in plant resilience: advances and strategies for enhancing abiotic stress tolerance. Plant Growth Regulation, 105(2), 329-360. https://doi.org/10.1007/s10725-025-01279-6

Daszkowska-Golec, A. (2016). The role of abscisic acid in drought stress: how ABA helps plants to cope with drought stress. In Drought stress tolerance in plants, Vol 2: Molecular and genetic perspectives (pp. 123-151). Springer. https://doi.org/10.1007/978-3-319-32423-4_5

Du, S., & Xiong, W. (2024). Weather extremes shock maize production: current approaches and future research directions in Africa. Plants, 13(12), 1585. https://doi.org/10.3390/plants13121585

Du, X., Zhang, X., Chen, X., Jin, W., Huang, Z., & Kong, L. (2024). Drought stress reduces the photosynthetic source of subtending leaves and the transit sink function of podshells, leading to reduced seed weight in soybean plants. Frontiers in Plant Science, 15, 1337544. https://doi.org/10.3389/fpls.2024.1337544

Erenstein, O., Jaleta, M., Sonder, K., Mottaleb, K., & Prasanna, B. M. (2022). Global maize production, consumption and trade: trends and R&D implications. Food Security, 14(5), 1295-1319. https://doi.org/10.1007/s12571-022-01288-7

Feng, C., Gao, H., Zhou, Y., Jing, Y., Li, S., Yan, Z., Xu, K., Zhou, F., Zhang, W., & Yang, X. (2023). Unfolding molecular switches for salt stress resilience in soybean: recent advances and prospects for salt-tolerant smart plant production. Frontiers in Plant Science, 14, 1162014. https://doi.org/10.3389/fpls.2023.1162014

Fidler, J., Graska, J., Gietler, M., Nykiel, M., Prabucka, B., Rybarczyk-Płońska, A., Muszyńska, E., Morkunas, I., & Labudda, M. (2022). PYR/PYL/RCAR receptors play a vital role in the abscisic-acid-dependent responses of plants to external or internal stimuli. Cells, 11(8), 1352. https://doi.org/10.3390/cells11081352

Franco-Navarro, J. D., Padilla, Y. G., Álvarez, S., Calatayud, Á., Colmenero-Flores, J. M., Gómez-Bellot, M. J., Hernández, J, A., Martínez-Alcalá, I., Penella, C., Pérez-Pérez, J. G., Sánchez-Blanco, M. J., Tasa, M., & Acosta-Motos, J. R. (2025). Advancements in Water-Saving strategies and crop adaptation to drought: A comprehensive review. Physiologia Plantarum, 177(4), e70332. https://doi.org/10.1111/ppl.70332

Fuertes-Aguilar, J., & Matilla, A. J. (2024). Transcriptional control of seed life: new insights into the role of the NAC family. International Journal of Molecular Sciences, 25(10), 5369. https://doi.org/10.3390/ijms25105369

Gao, Y., & Lynch, J. P. (2016). Reduced crown root number improves water acquisition under water deficit stress in maize (Zea mays L.). Journal of Experimental Botany, 67(15), 4545-4557. https://doi.org/10.1093/jxb/erw243

Gerhards, M., Schlerf, M., Mallick, K., & Udelhoven, T. (2019). Challenges and future perspectives of multi-/Hyperspectral thermal infrared remote sensing for crop water-stress detection: A review. Remote Sensing, 11(10), 1240. https://doi.org/10.3390/rs11101240

Ghosh, U., Islam, M., Siddiqui, M., Cao, X., & Khan, M. (2022). Proline, a multifaceted signalling molecule in plant responses to abiotic stress: understanding the physiological mechanisms. Plant Biology, 24(2), 227-239. https://doi.org/10.1111/plb.13363

Guo, C., Bao, X., Sun, H., Zhu, L., Zhang, Y., Zhang, K., Bai, Z., Zhu, J., Liu, X., & Li, A. (2024). Optimizing root system architecture to improve cotton drought tolerance and minimize yield loss during mild drought stress. Field Crops Research, 308, 109305. https://doi.org/10.1016/j.fcr.2024.109305

Haghpanah, M., Hashemipetroudi, S., Arzani, A., & Araniti, F. (2024). Drought tolerance in plants: physiological and molecular responses. Plants, 13(21), 2962. https://doi.org/10.3390/plants13212962

Han, Y., Song, D., Zhou, R., & Yang, T. (2026). Molecular and physiological mechanisms of heat and drought stress tolerance in maize (Zea mays L.). Trends in Plant Biology, 3, 1-10. https://trendsacademics.com/tpb/index.php/ojs/article/view/10

Hayat M. K., & Öten M., (2026). Beyond the shell: a comprehensive review of physical and physiological barriers to seed germination. Plant & Crop Letter, 7: 1-19. https://doi.org/10.65822/j.pcl/2026.19

Hayat, M. K., Khan, A. R., Klutse, S., Rasool, M. W., & Mohsin, M. (2025). Empowering crops: How organic, agronomic practices and technology can fortify our fields. World News of Natural Sciences, 59, 358-383. https://psjd.icm.edu.pl/psjd/element/bwmeta1.element.psjd-cf75060d-f9f3-4657-bb74-976c1e58d295

Hayat, M. K., Muniza, N. T., Mahmud, M. N., Batool, R., Ullah, Q., Kafi, A. A., Haider, W., Ashraf, Z. U., Tahara, T., Raidah, R., Barman, M., & Bala, S. K. (2026). GeoAI Driven Precision Agriculture: Enhancing Crop Productivity and Sustainability in Changing Climate. World News of Natural Sciences, 66, 165–192. https://doi.org/10.5281/zenodo.20046275.

He, B., Pan, S., Zhao, J., Zou, X., Liu, X., & Wu, S. (2024). Maize improvement based on modern breeding strategies: progress and perspective. ACS Agricultural Science & Technology, 4(3), 274-282. https://doi.org/10.1021/acsagscitech.3c00427

Hirsch, J. E. (2005). An index to quantify an individual's scientific research output. Proceedings of the National Academy of Sciences, 102(46), 16569-16572. https://doi.org/10.1073/pnas.0507655102

Hsu, P. K., Dubeaux, G., Takahashi, Y., & Schroeder, J. I. (2021). Signaling mechanisms in abscisic acid-mediated stomatal closure. The Plant Journal, 105(2), 307-321. https://doi.org/10.1111/tpj.15067

Iglesias-Moya, J., Benítez, Á., Segura, M., Alonso, S., Garrido, D., Martínez, C., & Jamilena, M. (2024). Structural and functional characterization of genes PYL-PP2C-SnRK2s in the ABA signalling pathway of Cucurbita pepo. BMC Genomics, 25(1), 268. https://doi.org/10.1186/s12864-024-10158-9
Imran, M., Wu, Q., Guanming, C., & Zhou, L. (2025). Multifaceted roles and regulatory mechanisms of MYB transcription factors in plant development, secondary metabolism, and stress adaptation: Current insights and future prospects. GM Crops & Food, 16(1), 626-655. https://doi.org/10.1080/21645698.2025.2559489
Karami, S., Shiran, B., & Ravash, R. (2025). Molecular investigation of how drought stress affects chlorophyll metabolism and photosynthesis in leaves of C3 and C4 plant species: A transcriptome meta-analysis. Heliyon, 11(3). https://doi.org/10.1016/j.heliyon.2025.e42368
Kaur, G., Sanwal, S. K., Kumar, A., Pundir, R. K., Yadav, M., & Sehrawat, N. (2024). Role of osmolytes dynamics in plant metabolism to cope with salinity induced osmotic stress. Discover Agriculture, 2(1), 59. https://doi.org/10.1007/s44279-024-00070-x
Kaya, C. (2025). Molecular crosstalk of transcription factors and hormones in drought tolerance genes in plants. Turkish Journal of Botany, 49(3), 145-164. https://doi.org/10.55730/1300-008X.2852
Khalid, B., Javed, M. U., Ikram, M., Ateeq, M., Ashraf, M. A., Riaz, T., Nawaz, S., & Maqbool, R. (2026). Precision Rewiring of Stress-Responsive Gene Networks Via CRISPR: Mechanistic Pathways Toward Climate-Smart Agriculture. Journal of Crop Health, 78(1), 2. https://doi.org/10.1007/s10343-025-01273-y
Khamis, G., Alsherif, E. A., Korany, S. M., Aldailami, D. A., Aloufi, A. S., Khalaf, M. H., Hamed, S. M., Maridueña-Zavala, M. G., Al-Jaouni, S. K., & Selim, S. (2025). Drought stress differentially influences growth, physiology, and metabolite accumulation in Triticum aestivum (C3) and Amaranthus caudatus (C4) plants. BMC Plant Biology, 25(1), 1199. https://doi.org/10.1186/s12870-025-07022-7
Khan, A. A., Wang, Y. F., Akbar, R., & Alhoqail, W. A. (2025). Mechanistic insights and future perspectives of drought stress management in staple crops. Frontiers in Plant Science, 16, 1547452. https://doi.org/10.3389/fpls.2025.1547452
Kim, K. H., & Lee, B. M. (2023). Effects of climate change and drought tolerance on maize growth. Plants, 12(20), 3548. https://doi.org/10.3390/plants12203548
Kumar, A., Bharati, A., Chandra, A. K., Adhikari, S., Joshi, A., Kumar, L., Dinkar, V., Singh, A., & Kencharaddi, H. (2024). Breeding and Molecular Mechanism of Drought Stress in Maize. In Climate-Resilient Agriculture (pp. 481-508). Apple Academic Press. https://doi.org/10.1201/9781003455271-19
Li, H., Tang, Y., Meng, F., Zhou, W., Liang, W., Yang, J., Wang, J., Wang H., Guo J., Yang, Q., & Shao, R. (2025). Transcriptome and metabolite reveal the inhibition induced by combined heat and drought stress on the viability of silk and pollen in summer maize. Industrial Crops and Products, 226, 120720. https://doi.org/10.1016/j.indcrop.2025.120720
Li, L., Xu, J., Liu, J., Bi, W., Li, Y., He, A., Guo, X., & Ai, Z. (2026a). Combined Salt and Heat Stress Aggravates Oxidative Stress and Photosynthetic Damage, Disrupting Carbon and Nitrogen Metabolism and Yield in Rice. Antioxidants, 15(3), 308. https://doi.org/10.3390/antiox15030308
Li, N., Li, S., Zhao, B., Yuan, X., & Zhu, J. (2026b). Global Agricultural Drought Crisis: Synergistic Impacts of Climate Change and Human Activities and Their Feedback Mechanisms. Water, 18(6), 732. https://doi.org/10.3390/w18060732
Li, R., Yang, K., Feng, Z., Jia, M., Guo, H., Wei, Y., Yan, Z., Li, Y., Jia, X., & Wang, Q. (2026c). Low Grain Yield of Maize (Zea mays L) due to Stunted Tassel and Limited Sugar Transport Under Drought and Heat During Flowering. Journal of Agronomy and Crop Science, 212(1), e70147. https://doi.org/10.1111/jac.70147
Li, X., Guo, Y., Ling, Q., Guo, Z., Lei, Y., Feng, X., Wu, J., & Zhang, N. (2024). Advances in the structure, function, and regulatory mechanism of plant plasma membrane intrinsic proteins. Genes, 16(1), 10. https://doi.org/10.3390/genes16010010
Liang, X., Yu, S., Ju, Y., Wang, Y., & Yin, D. (2025). Multi-scale remote-sensing phenomics integrated with multi-omics: Advances in crop drought-heat stress tolerance mechanisms and perspectives for climate-smart agriculture. Plants, 14(18), 2829. https://doi.org/10.3390/plants14182829
Lin, J., Hazaisi, H., Guan, Y., & Bai, M. (2026). Multiplex gene editing drives revolution in crop breeding: overlaid editing of multiple genes and customization of complex traits. Advanced Biotechnology, 4(1), 5. https://doi.org/10.1007/s44307-026-00099-7
Liu, Z., Chin, C. S., & Xia, J. (2021). Improving recycled coarse aggregate (RCA) and recycled coarse aggregate concrete (RCAC) by biological denitrification phenomenon. Construction and Building Materials, 301, 124338. https://doi.org/10.1016/j.conbuildmat.2021.124338
Lynch, J. P. (2013). Steep, cheap and deep: an ideotype to optimize water and N acquisition by maize root systems. Annals of Botany, 112(2), 347-357. https://doi.org/10.1093/aob/mcs293
Ma, J., & Ling, X. (2026). Synergistic integration of gene editing and traditional breeding for water-saving and drought-resistant crop improvement: Progress and future prospects. Advances in Resources Research, 6(1), 81-109. https://doi.org/10.50908/arr.6.1_81
Maqbool, S., Hassan, M. A., Xia, X., York, L. M., Rasheed, A., & He, Z. (2022). Root system architecture in cereals: progress, challenges and perspective. The Plant Journal, 110(1), 23-42. https://doi.org/10.1111/tpj.15669
McAllister, J. T., Lennertz, L., & Atencio Mojica, Z. (2022). Mapping a discipline: a guide to using VOSviewer for bibliometric and visual analysis. Science & Technology Libraries, 41(3), 319-348. https://doi.org/10.1080/0194262X.2021.1991547
Meel, S., & Saharan, B. S. (2024). Enhancing crop resilience towards drought: by integrating nanotechnology, microbiomes, and growth-promoting rhizobacteria. Discover Agriculture, 2(1), 112. https://doi.org/10.1007/s44279-024-00131-1

Mikiciuk, G., Miller, T., Kisiel, A., Cembrowska-Lech, D., Mikiciuk, M., Łobodzińska, A., & Bokszczanin, K. (2024). Harnessing beneficial microbes for drought tolerance: a review of ecological and agricultural innovations. Agriculture, 14(12), 2228. https://doi.org/10.3390/agriculture14122228
Mubarik, M. S., Khan, S. H., Sajjad, M., Raza, A., Hafeez, M. B., Yasmeen, T., Rizwan, M., Ali, S., & Arif, M. S. (2021). A manipulative interplay between positive and negative regulators of phytohormones: A way forward for improving drought tolerance in plants. Physiologia Plantarum, 172(2), 1269-1290. https://doi.org/10.1111/ppl.13325
Namata, M. J., Xu, J., Habyarimana, E., Palakolanu, S. R., Wang, L., & Li, J. (2025). Genome editing in maize and sorghum: A comprehensive review of CRISPR/Cas9 and emerging technologies. The Plant Genome, 18(2), e70038. https://doi.org/10.1002/tpg2.70038
Nguyen, N. H., Vu, N. T., & Cheong, J. J. (2022). Transcriptional stress memory and transgenerational inheritance of drought tolerance in plants. International Journal of Molecular Sciences, 23(21), 12918. https://doi.org/10.3390/ijms232112918
Ojara, M. A., Yunsheng, L., Babaousmail, H., Sempa, A. K., Ayugi, B., & Ogwang, B. A. (2022). Evaluation of drought, wet events, and climate variability impacts on maize crop yields in East Africa during 1981–2017. International Journal of Plant Production, 16(1), 41-62. https://doi.org/10.1007/s42106-021-00178-w
Olarewaju, O. O., Fawole, O. A., Baiyegunhi, L. J., & Mabhaudhi, T. (2025). Integrating sustainable agricultural practices to enhance climate resilience and food security in Sub-Saharan Africa: a multidisciplinary perspective. Sustainability, 17(14), 6259. https://doi.org/10.3390/su17146259
Ortez, O. A., Lindsey, A. J., Thomison, P. R., Coulter, J. A, Singh, M. P., Carrijo, D. R., Quinn, D. J., Licht, M. A., & Bastos, L. (2023). Corn response to long-term seasonal weather stressors: A review. Crop Science, 63, 3210-3235. https://doi.org/10.1002/csc2.21101
Pandey, S., Singh, A., Parida, S. K., & Prasad, M. (2022). Combining speed breeding with traditional and genomics-assisted breeding for crop improvement. Plant breeding, 141(3), 301-313. https://doi.org/10.1111/pbr.13012
Pandit, J., & Sharma, A. K. (2024). Impact of Climate Change on Drought: A Comprehensive Review. International Journal of Agriculture, Environment and Biotechnology, 17(4), 749-763. https://doi.org/10.30954/0974-1712.04.2024.14
Panozzo, A., Bolla, P. K., Barion, G., Botton, A., & Vamerali, T. (2025). Phytohormonal regulation of abiotic stress tolerance, leaf senescence and yield response in field crops: a comprehensive review. BioTech, 14(1), 14. https://doi.org/10.3390/biotech14010014
Patel, J., & Mishra, A. (2021). Plant aquaporins alleviate drought tolerance in plants by modulating cellular biochemistry, root-architecture, and photosynthesis. Physiologia Plantarum, 172(2), 1030-1044. https://doi.org/10.1111/ppl.13324
Peer, L. A., Bhat, M. Y., Lone, A. A., Dar, Z. A., & Mir, B. A. (2024). Genetic, molecular and physiological crosstalk during drought tolerance in maize (Zea mays): pathways to resilient agriculture. Planta, 260(4), 81. https://doi.org/10.1007/s00425-024-04517-9
Peer, L. A., Wani, A. A., Lone, A. A., Dar, Z. A., & Mir, B. A. (2025). Drought stress memory in maize: understanding and harnessing the past for future resilience. Plant Cell Reports, 44(5), 101. https://doi.org/10.1007/s00299-025-03494-x
Pranckutė, R. (2021). Web of Science (WoS) and Scopus: The titans of bibliographic information in today's academic world. Publications, 9(1), 12. https://doi.org/10.3390/publications9010012
Qi, M., Liu, X., Li, Y., Song, H., Yin, Z., Zhang, F., He, Q., Xu, Z., & Zhou, G. (2021). Photosynthetic resistance and resilience under drought, flooding and rewatering in maize plants. Photosynthesis Research, 148(1), 1-15. https://doi.org/10.1007/s11120-021-00825-3
Qiao, X., Waheed, A., Dong, C., Aili, A., Muhammad, M., & Xu, H. (2026). Harnessing Genetic Innovations for Climate-Resilient and High-Yield Crops: A Pathway to Sustainable Agriculture. Plant and Soil, 1-27. https://doi.org/10.1007/s11104-025-08195-8
Qu, L., Gu, X., Li, J., Guo, J., & Lu, D. (2023). Leaf photosynthetic characteristics of waxy maize in response to different degrees of heat stress during grain filling. BMC Plant Biology, 23(1), 469. https://doi.org/10.1186/s12870-023-04482-7
Rabie, A. B., Elhag, M., & Subyani, A. (2025). Remote sensing, GIS, and machine learning in water resources management for arid agricultural regions: a review. Water, 17(21), 3125. https://doi.org/10.3390/w17213125
Rafique, S. (2020). Drought responses on physiological attributes of Zea mays in relation to nitrogen and source-sink relationships. In Abiotic Stress in Plants. IntechOpen. https://doi.org/10.5772/intechopen.93747
Rafique, S. (2023). Physiological and biochemical responses in maize under drought stress. In Maize improvement: current advances in yield, quality, and stress tolerance under changing climatic scenarios (pp. 117-136). Springer. https://doi.org/10.1007/978-3-031-21640-4_7
Rahman, M. M., Keya, S. S., Bulle, M., Ahsan, S., Rahman, M. A., Roni, M. S., Al Noor, M. M., & Hasan, M. (2025). Past trauma, better future: how stress memory shapes plant adaptation to drought. Functional Plant Biology, 52(6), FP24355. https://doi.org/10.1071/FP24355
Rao, X., Yang, S., Lü, S., & Yang, P. (2024). DNA methylation dynamics in response to drought stress in crops. Plants, 13(14), 1977. https://doi.org/10.1071/FP24355
Rautela, I., Chaurasiya, D. K., Singh, S., Pathak, S., Manjeet, Bhoomika, Prasad, R., Ahmed, M., Bhalerao, B. M., & Chettri, D. (2026). Harnessing Omics Technologies to Mitigate Drought Stress in Crop Plants. Journal of Agronomy and Crop Science, 212(1), e70135. https://doi.org/10.1111/jac.70135
Ravinandrasana, V. P., & Franzke, C. L. (2025). The first emergence of unprecedented global water scarcity in the Anthropocene. Nature Communications, 16(1), 8281. https://doi.org/10.1038/s41467-025-63784-6

Raza, A., Hassan, A., Abbas, S., Razzaq, W., Hazoor, S., Nosherwan, M., Rehman, A., & Ali, I. (2024). Effects of salinity on morpho-physiological traits in six maize hybrids at seedling stage. Agrobiological Records, 18, 41-53. https://doi.org/10.47278/journal.abr/2024.036

Ren, Y., Cheng, B., Khan, A., Chen, B., Zhang, J., Wang, W., Wang, C., Wang Z., & Xing, B. (2026). Polyethyleneimine-functionalized carbon dots boost maize (Zea mays. L) Resistance: Photochemistry improvement, carbon fixation, and signaling molecules regulation. Chemical Engineering Journal, 173021. https://doi.org/10.1016/j.cej.2026.173021

Seraj, R. G. M., & Vafaee, V. (2026). Data-Driven Genomic Design for Next-Generation Crop Breeding. In Plant Genomic Prediction: AI-Enhanced Models for Plant Genomics and Crop Improvement (pp. 68-107). CABI GB. https://doi.org/10.1079/9781836991328.0005

Shen, X., Nan, H., Jiang, Y., Zhou, Y., & Pan, X. (2022). Genome-wide identification, expression and interaction analysis of GmSnRK2 and type A PP2C genes in response to abscisic acid treatment and drought stress in soybean plant. International Journal of Molecular Sciences, 23(21), 13166. https://doi.org/10.3390/ijms232113166

Shoaib, M., Banerjee, B. P., Hayden, M., & Kant, S. (2022). Roots' drought adaptive traits in crop improvement. Plants, 11(17), 2256. https://doi.org/10.3390/plants11172256

Silva, P. C., Sanchez, A. C., Opazo, M. A., Mardones, L. A., & Acevedo, E. A. (2022). Grain yield, anthesis-silking interval, and phenotypic plasticity in response to changing environments: Evaluation in temperate maize hybrids. Field Crops Research, 285, 108583. https://doi.org/10.1016/j.fcr.2022.108583

Singh, A., Pandey, H., Pandey, S., Lal, D., Chauhan, D., Aparna, Antre, S. H., B, S., & Kumar, A. (2023). Drought stress in maize: stress perception to molecular response and strategies for its improvement. Functional & Integrative Genomics, 23(4), 296. https://doi.org/10.1007/s10142-023-01226-6

Singh, S. K., Badgujar, G., Reddy, V. R., Fleisher, D. H., & Bunce, J. A. (2013). Carbon dioxide diffusion across stomata and mesophyll and photo-biochemical processes as affected by growth CO2 and phosphorus nutrition in cotton. Journal of Plant Physiology, 170(9), 801-813. https://doi.org/10.1016/j.jplph.2013.01.001

Slattery, R. A., & Ort, D. R. (2021). Perspectives on improving light distribution and light use efficiency in crop canopies. Plant physiology, 185(1), 34-48. https://doi.org/10.1093/plphys/kiaa006

Soma, F., Takahashi, F., Yamaguchi-Shinozaki, K., & Shinozaki, K. (2021). Cellular phosphorylation signaling and gene expression in drought stress responses: ABA-dependent and ABA-independent regulatory systems. Plants, 10(4), 756. https://doi.org/10.3390/plants10040756

Srivastava, R. K., Yadav, O., Kaliamoorthy, S., Gupta, S., Serba, D. D., Choudhary, S., Govindaraj, M., Kholová, J., Murugesan, T., & Satyavathi, C. T. (2022). Breeding drought-tolerant pearl millet using conventional and genomic approaches: achievements and prospects. Frontiers in Plant Science, 13, 781524. https://doi.org/10.3389/fpls.2022.781524

Suryantoro, E., Udin, U., & Qamari, I. (2023). A bibliometric analysis using VOSviewer: Leadership in infection prevention and control. Multidisciplinary Science Journal, 5(2). https://doi.org/10.31893/multiscience.2023022

Suslov, M., Daminova, A., & Egorov, J. (2024). Real-time dynamics of water transport in the roots of intact maize plants in response to water stress: The role of aquaporins and the contribution of different water transport pathways. Cells, 13(2), 154. https://doi.org/10.3390/cells13020154

Takács, G., Gergely, I., Ördög, V., Vörös, L., & Iváncsics, J. (2025). Approaches to studying wheat and maize drought stress responses. Plant and Soil, 1-18. https://doi.org/10.1007/s11104-025-07789-6

Tang, H., Zhang, L., Xie, X., Wang, Y., Wang, T., & Liu, C. (2025). Resilience of maize to environmental stress: Insights into drought and heat tolerance. International Journal of Molecular Sciences, 26(11), 5274. https://doi.org/10.3390/ijms26115274

Tardieu, F. (2013). Plant response to environmental conditions: assessing potential production, water demand, and negative effects of water deficit. Frontiers in Physiology, 4, 17. https://doi.org/10.3389/fphys.2013.00017

Thilakarathne, A. S., Liu, F., & Zou, Z. (2025). Plant signaling hormones and transcription factors: key regulators of plant responses to growth, development, and stress. Plants, 14(7), 1070. https://doi.org/10.3390/plants14071070

Thingujam, D., Gouli, S., Cooray, S. P., Chandran, K. B., Givens, S. B., Gandhimeyyan, R. V., Tan, Z., Wang, Y., Patam, K., & Greer, S. A. (2025). Climate-resilient crops: Integrating AI, multi-omics, and advanced phenotyping to address global agricultural and societal challenges. Plants, 14(17), 2699. https://doi.org/10.3390/plants14172699

Tyagi, A., Ali, S., Ramakrishna, G., Singh, A., Park, S., Mahmoudi, H., & Bae, H. (2023). Revisiting the role of polyamines in plant growth and abiotic stress resilience: mechanisms, crosstalk, and future perspectives. Journal of Plant Growth Regulation, 42(8), 5074-5098. https://doi.org/10.1007/s00344-022-10847-3

Uga, Y., Sugimoto, K., Ogawa, S., Rane, J., Ishitani, M., Hara, N., Kitomi, Y., Inukai, Y., Ono, K., & Kanno, N. (2013). Control of root system architecture by DEEPER ROOTING 1 increases rice yield under drought conditions. Nature Genetics, 45(9), 1097-1102. https://doi.org/10.1038/ng.2725

Van Eck, N., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics, 84(2), 523-538. https://doi.org/10.1007/s11192-009-0146-3

Wang, G., & Zhang, X. (2024). Maize in global food security: Role and challenges. Field Crop, 7. https://cropscipublisher.com/index.php/fc/article/html/3937

Wang, H., Sun, J., Ren, H., Zhao, B., Li, Y., Zhang, Z., & Liu, P. (2025a). Increased hormone activity promotes silk development and heat tolerance during the floret differentiation stage in maize. The Crop Journal, 13(2), 545-555. https://doi.org/10.1016/j.cj.2024.12.019

Wang, M., Zhao, Y., Huang, Y., & Liu, J. (2025b). Integrating Drought Stress Signaling and Smart Breeding for Climate-Resilient Crops: Regulatory Mechanisms and Genetic Strategies. Plants, 14(24), 3714. https://doi.org/10.3390/plants14243714

Wang, R., Zhang, Z., Wang, H., Chen, Y., & Zhang, M. (2023). Soil water deficit reduced root hydraulic conductivity of common reed (Phragmites australis). Plants, 12(20), 3543. https://doi.org/10.3390/plants12203543
Wang, S., Zhu, L., Zhang, P., Wang, X., Sun, H., Zhang, K., Zhang, Y., Wang, G., Zhu, N., & Bai, Z. (2025c). Synergistic optimisation of root hydraulic architecture enhances drought tolerance in cotton. Plant, Cell & Environment, 48(9), 6662-6673. https://doi.org/10.1111/pce.15640
Welcker, C., Spencer, N. A., Turc, O., Granato, I., Chapuis, R., Madur, D., Beauchene, K., Gouesnard, B., Draye, X., & Palaffre, C. (2022). Physiological adaptive traits are a potential allele reservoir for maize genetic progress under challenging conditions. Nature Communications, 13(1), 3225. https://doi.org/10.1038/s41467-022-30872-w
Wu, W., Wang, R., Li, J., Zhang, Z., Yao, W., Zhang, N., & Xu, W. (2026). Engineering Climate-Resilient Horticultural Crops: Advances in Transcriptional Regulation, Genome Editing, and Synthetic Networks. Horticulture Research, uhag119. https://doi.org/10.1093/hr/uhag119
Xiong, H., He, H., Chang, Y., Miao, B., Liu, Z., Wang, Q., Dong, F., & Xiong, L. (2025). Multiple roles of NAC transcription factors in plant development and stress responses. Journal of Integrative Plant Biology, 67(3), 510-538. https://doi.org/10.1111/jipb.13854
Yadav, S., Meena, S., Kalwan, G., & Jain, P. (2024). DNA methylation: An emerging paradigm of gene regulation under drought stress in plants. Molecular Biology Reports, 51(1), 311. https://doi.org/10.1007/s11033-024-09243-9
Yan, S., Wu, Y., Fan, J., Zhang, F., Zheng, J., Guo, J., Zheng, J, Guo, J., Lu, J., Wu, L., Qiang, S., & Xiang, Y. (2022). Source-sink relationship and yield stability of two maize cultivars in response to water and fertilizer inputs in northwest China. Agricultural Water Management, 262, 107332. https://doi.org/10.1016/j.agwat.2021.107332
Yang, L., Fang, S., Liu, L., Zhao, L., Chen, W., Li, X., Xu, Z., Chen, S., Wang, H., & Yu, D. (2025). WRKY transcription factors: Hubs for regulating plant growth and stress responses. Journal of Integrative Plant Biology, 67(3), 488-509. https://doi.org/10.1111/jipb.13828
Zahedi, S. M., Karimi, M., Venditti, A., Zahra, N., Siddique, K. H., & Farooq, M. (2025). Plant adaptation to drought stress: the role of anatomical and morphological characteristics in maintaining the water status. Journal of Soil Science and Plant Nutrition, 25(1), 409-427. https://doi.org/10.1007/s42729-024-02141-w
Zargar, S. M., Nagar, P., Deshmukh, R., Nazir, M., Wani, A. A., Masoodi, K. Z., Agrawal, G. K., & Rakwal, R. (2017). Aquaporins as potential drought tolerance inducing proteins: towards instigating stress tolerance. Journal of Proteomics, 169, 233-238. https://doi.org/10.1016/j.jprot.2017.04.010
Zarrin Ghalami, R., Duszyn, M., & Karpiński, S. (2026). Absorption of Energy in Excess, Photoinhibition, Transpiration, and Foliar Heat Emission Feedback Loops during Global Warming. Cells, 15(1), 75. https://doi.org/10.3390/cells15010075
Zenda, T., Liu, S., Wang, X., Liu, G., Jin, H., Dong, A., Yang, Y., & Duan, H. (2019). Key maize drought-responsive genes and pathways revealed by comparative transcriptome and physiological analyses of contrasting inbred lines. International Journal of Molecular Sciences, 20(6), 1268. https://doi.org/10.3390/ijms20061268
Zhang, F., Jiang, R., Gao, X., & Wang, H. (2025). The research progress on maize drought resistance metabolic mechanisms: Systematic integration analysis based on gene regulation and metabolic networks. Advances in Resources Research, 5(3), 1698-1714. https://doi.org/10.50908/arr.5.3_1698
Zhang, H., Zhao, H., Qu, T., Jiang, H., Gao, S., Zhang, Y., & Zheng, C. (2026). Halotolerant PGPR at the Soil-Plant-Microbiome Interface: Microbial Strategies to Enhance Crop Adaptation to Salinity. Phyton, 95(3). https://doi.org/10.32604/phyton.2026.076579
Zhao, C., Harrison, M. T., Liu, K., Li, C., Chen, Z., Shabala, S., & Zhou, M. (2026). Fast Backcross Breeding for Climate-Resilient Cereals: Integrating Speed Breeding, Marker-Assisted Backcrossing and Genomic Selection. Biobreeding, 1(1), 10003. https://doi.org/10.70322/biobreeding.2026.10003
Zhu, J., Brown, K. M., & Lynch, J. P. (2010). Root cortical aerenchyma improves the drought tolerance of maize (Zea mays L.). Plant, Cell & Environment, 33(5), 740-749. https://doi.org/10.1111/j.1365-3040.2009.02099.x