Contents lists available at GrowingScience

Scientometrica

homepage: www.GrowingScience.com/sci

Scientometric survey: The evolving landscape of climate-resilient biotechnology research

Kouroush Jenab[a*]

[a]*Associate Professor, Department of Engineering Sciences, College of Science and Engineering, Morehead State University, United States*

C H R O N I C L E

Article history:
Received: November 5, 2025
Received in revised format: November 5, 2025
Accepted: November 31, 2025
Available online:
November 31, 2025

Keywords:
Climate-Resilient Agriculture
Agricultural Biotechnology
CRISPR-Cas9
Abiotic Stress Tolerance
Plant-Microbe Interactions
Scientometric Analysis
Sustainable Crop Production
Genome Editing
Omics Technologies
Food Security

A B S T R A C T

Climate change that is happening all around the world and is global that way poses a great threat to the productivity of agriculture and therefore the need for both resilient crops and sustainable farming systems is very strong. Climate-resilient biotechnology has become a major field that is dealing with this issue through the use of the most advanced genetic, microbial, and molecular tools. The present study is a scientometric one and it makes use of data from the Scopus database consisting of 122 scientific publications to map the research field, find the main trends and specify the intellectual structure of this area from 2013 to 2026. The research shows the existence of a very fast-growing field where the main focus of the research is on genome editing especially CRISPR-Cas9 for introducing tolerance to abiotic and biotic stress, the use of plant-growth-promoting microbes for the purpose of improving the plant's resilience, and the combination of omics for trait discovery. The major research areas are: the staples such as wheat, rice and maize, the underutilized nature-resilient crops, and the coming together of biotechnology with AI (artificial intelligence) and models of sustainable systems. The results of the study give evidence of a change in paradigm moving towards precision breeding and biological control measures, and this change is accompanied by the highlighting of the role of biotechnology as critical in securing future food supply under the conditions of volatile climate.

© 2025 by the authors; licensee Growing Science, Canada.

1. Introduction

Climate change, the main driver of the not-so-predictable weather, is now rewriting the agriculture contract from the foundation up—giving up on predictable seasons, stable temperatures, and sufficient rainfall among others. Although greenhouse gases are still rising, the global climate system is responding with a high level of volatility, which is characterized by extreme, weather events of higher frequency and intensity, erratic precipitation patterns, and the rise in average temperatures (IPCC, 2022). With this new climate pattern, global food security is threatened like never before, and to make matters worse, a global population that is already very high is expected to increase to 9.7 billion by 2050 (United Nations, 2019). It is our ability to adapt that will determine the stability of our agricultural systems and thus, the well-being of human societies. In this unstable situation, the area of climate-tolerant biotechnology has come up as a scientific frontier that is no longer just a hope but the only way of securing our food production against the future challenges.

The climate change effects on agriculture, though diverse, are very disruptive. Non-living environmental factors have practically taken over as the foremost muggles to crop harvest worldwide. Among these, drought stress, which is most feared, weakens water relations in the plant causing reduced cell turgor, closing off stomata and thus leading to reduced photosynthetic efficiency and undergrowth (Ngongolo & Mmbando, 2024). On the other hand, heat stress, especially at critical reproductive periods, i.e. flowering and grain filling, makes pollen not viable, kills seeds, and results in astonishingly high losses of rice and maize alongside wheat (Pandey et al., 2024; Senguttuvel et al., 2022). The salinity, often worsened by

* Corresponding author.
E-mail address: k.jenab@moreheadstate.edu (K. Jenab)

ISSN ISSN 3115-8455 (Online) - ISSN 3115-8447 (Print)
© 2025 by the authors; licensee Growing Science, Canada
doi: 10.5267/j.sci.2025.4.001

irrigation techniques and rise in sea level, causes ionic and osmotic stress, hindering nutrient uptake and metabolic processes (Alotaibi, 2023). Not to say that the waterlogging and flooding could create hypoxic conditions in the root zone, which would then lead to rotting and killing of the plants (Gondalia et al., 2024). These non-biotic stress factors are not self-sufficient; they usually come together, forming complicated, multi-stress situations that are even harder to manage (Liu et al., 2023).

At the same time, climate change is influencing the biotic stresses. The phenomenon of global warming with its factors such as increased CO2 levels and warmth may change the metabolic processes of host plants making them more prone to diseases and pests. Besides, global warming could also change the meteorological patterns in which the different insects, fungi, and bacteria grow and produce new diseases and infestations of greater magnitude in areas that were previously not affected (Castroverde et al., 2024; Prabhakaran et al., 2025). The continuous www.theplantfuture.org interplay between these stresses in nature results in a vicious cycle; for example, a plant that has been weakened by water shortage becomes an easier target for fungal infection, thus reinforcing the loss of the harvest (Kashyap et al., 2017). This combination of challenges brings out the limitations of normal agricultural methods and the use of traditional crops, which were meant for a climate that was stable and predictable. The demand of the day for a drastic shift in our thinking regarding crop enhancement has never been stronger.

The endeavor for climate resilience in agriculture is not a new idea; rather, it is a continuous process that has been happening for centuries through the selection of crops by farmers and breeders for their ability to tolerate local environmental stressors. Nonetheless, today's climate change is so fast that it has already gone beyond the limit of traditional breeding methods' adaptive capacity. Even though conventional breeding is the mainstay of agricultural improvement, it is a slow and labor-intensive process that can be further challenged by the limited genetic diversity within sexually compatible species and the long generation times of crops (Akhatar et al., 2022). The traits sought after are in some cases, particularly for complex quantitative traits like drought tolerance, hindered by the environment's strong influence (G x E interaction) which, in turn, renders the overall process of selection rather inefficient (Dwivedi et al., 2020). It is in the interstice of the growing menace and traditional approaches' limitations that the agricultural biotechnology has carved out its powerful mandate. Biotechnology for climate-resilient crops can be characterized as the use of a range of modern biological tools—including genetic engineering, genome editing, molecular marker-assisted selection, and microbial biotechnology—to study, develop, and apply the genetic mechanisms that give crops the ability to endure being stressed by climate factors. The ultimate aim is to produce new crop varieties and develop related management practices that will not only be able to withstand but also even enhance productivity, quality, and sustainability during climate adversities (Riaz et al., 2025; Munawar et al., 2020). This represents a dramatic shift in the approach taken to the problem, as the whole system goes from a reactive to a proactive approach thereby, not just cutting losses but also doing the opposite and actively making resilience by engineering.

The toolkit of climate-smart biotechnologies is composed of many different techniques and is changing very quickly, while a few key technological pillars are still in the spotlight. One of these pillars is the emergence of precision genome editing, especially the CRISPR-Cas9 system, which is the most revolutionary among others. It grants the researchers the opportunity to conduct very accurate and targeted alterations to the DNA of the plants; either deactivating negative regulator genes, adjusting the expression of positive regulators, or even adding new genetic sequences, without the random insertion and accompanying regulatory issues of traditional transgenics (Ponnurangan et al., 2025; Reed et al., 2025). The uses of the new method are limitless: including breeding rice with higher resistance to both bacterial blight and blast diseases (Ponnurangan et al., 2025), making heat-responsive genes in tomatoes and other vegetables (Saeed et al., 2023), and even designing the process of apomixis, or "clonal seeds," which will permit farmers to steadily produce high-yielding, resilient hybrids without losing their genetic superiority in the following generation (Reed et al., 2025). CRISPR's main strength is its rapidity, accuracy, and ability to operate on the plant's genetic map, thus it is the key technology for the swift creation of climate-resistant cultivars.

A second pillar of equal importance is the inclusion of "omics" technologies—genomics, transcriptomics, proteomics, and metabolomics—into the breeding cycle. This have been the time when sequencing entire plant genomes was just the beginning of a series of information flows from one plant to other plants' reactions to stress (Singh et al., 2021; Pudake et al., 2022). The analyses of genomes in association studies (GWAS) and quantitative trait locus (QTL) mapping can land on the exact genetic loci that characterize traits such as the drought-avoiding deep root systems or the heat-tolerant membrane stability (Kencharaddi et al., 2024; Shamanin et al., 2025). For example, in the case of neglected crops like finger millet and proso millet, which possess a high level of resistance but are not well researched, genomic techniques are employed to uncover and exploit their throughputs of stress-resistance mechanisms (Mane et al., 2024; Francis et al., 2023). The Knowledge of the molecular processes governing stress tolerance, combined with high-throughput phenotyping, leads to the implementation of marker-assisted selection (MAS), which hurries up the breeding process by the selection of the desired genes in the lab, even during the seedling stage and thus, not having to wait for the showing of mature plants' traits in the field (Ahmed et al., 2023).

The third method, which is biologically-based, utilizes the plant microbiome. Soil is not only a surface for growing but a very diverse ecosystem consisting of micro-organisms that have been evolving along with plants. Research done recently

is highlighting the importance of good microbes that are the main agents for plant resilience, for example, PGPR such as Bacillus and fungi like Trichoderma (Patani et al., 2024; Kashyap et al., 2017). These microbial allies are perceived as bio-fertilizers for their roles of fixing nitrogen from the atmosphere, solubilizing phosphorus, and as bio-pesticides, they enable the plant to gain strong immunity against the pathogens or such as theirs. The aspect of stress alleviation is the one that the contributors hugely promote: they can create exopolysaccharides which will keep the soil moisture during the drought, develop phytohormones that regulate plant metabolism under the stress, and strengthen antioxidant scavenging systems to counter the oxidative damage inflicted by the heat, salinity, and heavy metals (Tan et al., 2022; Bîrgovan et al., 2025). The use of microbial inoculants or the “bio-priming” of seeds with these helpful organisms, signifies an eco-friendly, low-input method to enhance plant health and yield while at the same time reducing the use of synthetic fertilizers and pesticides (Devika & Rakshit, 2019).

The use of biotechnology in agriculture is not limited to the improvement of specific crops only but also plays a major role in the sustainability of the whole system, which is a vital part of the resilience in the long run. One of the examples of this is the creation of bioremediation methods involving genetically modified plants or microorganisms to detoxify soils polluted by heavy metals, a situation which may be worsened by industrial waste and erosion caused by climate change (Sarma et al., 2021). Another example is the utilization of agricultural leftovers via bioprocessing, making what was once a waste problem a source of new products, as in the case of turning fish waste into highly nutritious peptone (Lee et al., 2025), or utilizing microalgae in fish farming for carbon capture and wastewater treatment (Dasari et al., 2025). Such practices coincide with the tenets of the circular bioeconomy, hence bringing about agricultural systems that are more resilient and sustainable.

The research emphasis has also been extended to encompass a wide range of underutilized species that have been rejected by modern agriculture but are resilient by nature. The past few years have seen an increasing interest in crops such as millets (Thakur et al., 2025; Singh et al., 2021), amaranth (Segura-Jiménez & Jacobo-Velázquez, 2025), bambara groundnut (Soumare et al., 2022), and African yam bean (Oluwole et al., 2021). These plants usually have great natural resistance against drought, heat, and poor soil. Eventually, the biotechnological tools are being applied to erase their restraints like low yield or anti-nutritional factors, thus "mainstreaming" them into the global food system to increase dietary diversity and act as buffers against climate shocks.

The future of the field looks very bright as it is just about to witness a new wave of innovations that will be characterized by the combination of the biology and the digital world. The fusion of artificial intelligence (AI) and machine learning with biotechnology is all set to change the whole paradigm of the area (Wang et al., 2025). The power of AI lies in its ability to process and analyze huge amount of multidimensional data coming from genomics and phenomics in such a way that the functions of genes can be predicted, best gene editing targets can be found and plant responses to complicated environmental stresses can be simulated. Moreover, the use of technologies such as extended reality (XR) is opening up new possibilities for applications in the visualization of intricate biological structures and processes, which in turn may lead to faster research and education in the field of molecular biology (Na-khle & Harfouche, 2023).

Nonetheless, the promising pathway has certain difficulties. The process through which laboratory triumphs reach the level of the solution that is widely accepted in the field is fraught with socio-economic and regulatory complexities. On the one hand, public opinion, intellectual property rights, and science-based regulatory frameworks for new breeding techniques such as genome editing are among the major obstacles (Archibald et al., 2023; Lassoued et al., 2023; Ojeih et al., 2024). On the other hand, it is of utmost ethical and practical importance to ensure that the climate-resilient technologies are made available and affordable to smallholder farmers who are usually the ones most affected by climate change (Shilomboleni & Ismail, 2023).

To sum up, the dramatic and integrative biotechnological revolution is the main driving force of the scientific approach to the climate crisis in agriculture. and This introduction gives a preview of a thorough scientometric analysis of this topic. The mapping of the academic literature published between 2013 and 2026 will be done in a systematic way by the review which seeks to measure the field’s growth, pinpoint its major research themes and intellectual roots, bring to light the main crops and technologies under consideration, and depict the emerging trends that will determine the future of climate-resilient agriculture. The outcome of this analysis will be a comprehensive picture of biotechnology's role in our agricultural future, not just as an adaptation to a changing climate but as a major driver of change.

2. Methodology

The study relies on a carefully selected set of 122 documents obtained from Scopus using the keyword "Climate-Resilient Biotechnology" which was the main focus of the search. The selected documents comprise journal articles, reviews, book chapters, and books. Moreover, through a qualitative approach, various scientometric aspects, like the rate of publication over time, the main authors and institutions who contributed, thematic groupings, and the co-occurrence of keywords were subjected to analysis.

The domain is witnessing a fast-paced development, as shown by the fact that most of the identified articles (more than 80%) were published between 2023 and 2026. This increase in numbers is a clear indication of the worldwide research and development focus on the adoption of climate resistant practices in agriculture. A great part of this literature consists of review articles, which points to a period of collecting and organizing knowledge that is often followed by substantial empirical and technological breakthroughs. The examination of 122 publications unraveled a detailed and interrelated research landscape that was depicted through five main thematic clusters. These clusters are the major intellectual concerns of the field of climate-resilient biotechnology and they are not separate from each other; on the contrary, they often share and contribute to each other, forming a united front that is directed towards stronger agricultural systems.

2.1. Cluster 1: Precision Gene Editing and Functional Genomics

This cluster is the liveliest and fastest growing one, which stands for the very top of the genetic modification of crops. The introduction of CRISPR-Cas9 has radically changed the whole scenario from random mutation and old-school trans-genics to accurate and targeted genome altering. The studies taking place in this cluster are defined by a concentration on identifying major genetic determinants of stress tolerance and then applying editing tools to alter them with utmost precision. A major use case is in the reduction of vulnerability. A lot of plants have some genes that are responsible for imposing negative feedback on the defense pathways. CRISPR-Cas9 technique is applied to "knock out" these susceptibility (S) genes, thus enabling the plants to have broad-spectrum and long-lasting resistance. For example, Ponnurangan et al. (2025) present a detailed account of how CRISPR is used in rice for targeting the genes that render the plant susceptible to the most devastating fungal and bacterial diseases such as blast and blight. By doing edits at these particular sites, the scientists can develop rice that has improved innate immunity without the yield loss that is usually linked with the use of traditional resistance genes.

The technology is being applied beyond disease and rewiring a plant's reaction to death. Mushtaq et al. (2025) summarize the application of CRISPR and other molecular tools in enhancing transcription factors (e.g., DREB, AREB) and heat shock proteins (HSPs) and late embryogenesis abundant (LEA) proteins by strengthening their expression. The goal is to produce drought, heat, or salinity tolerant crops that can still keep their cells alive. For instance, making the promoters of stress-responsive genes more active during the stressful condition is a good technique to increase tolerance with no impact on the growth under optimal conditions. The synthetic apomixis, discussed by Reed et al. (2025), is probably the most revolutionary idea coming out of this area. Apomixis is the asexual production of seeds that results in the creation of genetically identical offspring to the mother plant. The researchers are using CRISPR to alter the genes that control meiosis and fertilization in order to "fix" hybrid vigor in crops. The effect of this manipulation would allow farmers to plant the seeds of a high-yielding, climate-resilient hybrid year after year without losing their superior genetic traits (this would be a big change that could take place in the developing world where improved varieties would be super-fast adoption).

The study in this cluster comes with its own difficulties, which are also being analyzed. One major area of concern is the importation of editing efficiency, multiplex editing (editing of multiple genes at one go) and the creation of new ways of editing without any transgenes that would make it easier for the regulatory authorities to approve dealing with the public as mentioned in the regulatory reviews e.g. Lassoued et al. (2023).

2.2. Cluster 2: Microbial Biotechnology and the Phytomicrobiome

This cluster directs the spotlight not the plant's internal genome but towards the external ecosystem that is associated with the plant - the microbiome. It is based on the perception that a plant is not a single organism but a holobiont, a complex community of millions of microbes living in symbiosis with each other. The main idea is that through the management of this phytomicrobiome, a plant's resilience can be significantly enhanced with a lower environmental footprint. The studies in this area are mainly focused on the characteristics of plant-growth-promoting (PGP) microbes. Patani et al. (2024) provide an extensive paper discussing the mechanisms by which Bacillus species, along with other PGP bacteria, act as bio-fertilizers by fixing atmospheric nitrogen, solubilizing insoluble phosphate, and sequestering iron. They also function as bio-pesticides by generating antibiotic substances and activating systemic resistance (ISR) in the plant. This, in turn, allows the plant to respond to pathogen attacks faster and with a stronger immune system. Moreover, their involvement in stress alleviation is paramount; they might produce exopolysaccharides that encompass the roots and form protective biofilms, thus minimizing water loss, and they might also adjust plant hormone levels (e.g., ACC deaminase decreases ethylene, which is a stress hormone) to facilitate the plant's resilience against abiotic stress.

The existence of this cluster is mostly due to the great role played by fungi, especially Trichoderma. Kashyap et al. (2017) provide a comprehensive account of how this fungus can be called a "superhero" biocontrol agent since it not only feeds on plant pathogens but also promotes root growth, increases the efficiency of nutrient uptake, and even manages to make plants resistant to drought and salinity. Tan et al. (2022) in their review classify these microbial technologies as the very basis of “climate-resilient microbial biotechnology” and recommend their adoption as the most important part of the sustainable agricultural sector. The current research trends under consideration in this cluster are those that take into account the shift from the use of a single strain to the formulation of synthetic microbial communities (SynComs). Aiming for the formation

of a cohort of microbes that would be mutually beneficial and hence provide the plant with a stronger and more functional benefit is the direction researchers are taking, as predicted in the progressive review by Bîrgovan et al. (2025). Yet another active area of research is the unveiling of the plant's core microbiome under stress conditions to discover keystone species with the goal of producing next-generation, precision probiotics for crops.

2.3. Cluster 3: Multi-Omics and Data-Driven Breeding

The current technologies for crop improvement heavily rely on the collection of such information, which is the cluster of modern crop improvement methods. The cost of high-throughput sequencing has decreased dramatically and, consequently, "omics" technologies have been born that produce huge, multi-layered datasets describing the molecular makeup of plants. This cluster of research aims to bring together these datasets to analyze the complex biological networks that are responsible for stress resilience. Genomics is the main source of the foundation. For instance, the research conducted by Shamanin et al. (2025) makes use of genotyping-by-sequencing (GBS) to spot single nucleotide polymorphisms (SNPs) that are linked to winter wheat yield and agronomic traits. This method leads to genomic selection, in which the entire genome of a plant gives rise to a model that predicts the breeding value of that plant, thereby speeding up the breeding cycle significantly.

Transcriptomics, proteomics, and metabolomics incorporate activity and give a functio-nal view of the genome while still being static. They show the genes that are turned on, the proteins that are made, and the metabolites that are produced as the plant's response to a particular stress like heat or drought. In this regard, Mane et al. (2024) discuss extensively how these multi-omics tactics are being utilized on finger millet, a crop that has the ability to withstand climate change, but has a complex genetic make-up, to unearth the genes and pathways that are responsible for its toughness. By using the profiles of tolerant and susceptible varieties, the researchers can accurately spot the important molecular players; this could be a certain transporter protein for salinity tolerance or a biosynthetic pathway for a protective antioxidant. The translational research is the final aim of this research cluster. The quantitative trait loci (QTLs), candidate genes, and molecular markers that are discovered through omics tools are directly pipelined into the marker-assisted selection (MAS) and genomic selection (GS) methods. This is powerfully demonstrated in the pulses work by Kumar et al. (2019), who explain how the omics-driven mining of alleles from wild relatives and landraces is supplying a rich source of genetic diversity for breeding climate-smart varieties. The problem, which is a big concern of research, is the creation of complex bioinformatics tools and machine learning algorithms to merge and pull out the useful biological insights from these huge, multi-dimensional omics datasets.

2.4. Cluster 4: Systemic Sustainability and Circular Bioeconomy

The research cluster takes a wider view of not just the resilience at the level of crops but also the sustainability of the whole agricultural ecosystem. The main focus of this research is the use of biotechnologies to develop eco-friendly agricultural systems that are crop protection-free, thus making the farms more sustainable and easily integrated into a circular bioeconomy. Bioremediation and pollution prevention are among the key themes. Sarma et al. (2021) published an important review regarding the application of CRISPR-Cas9 to improve phytoremediation—the process wherein plants are used to remove heavy metals and other pollutants from contaminated soil and water. Scientists aim to breed "super-remediator" plants by altering the genes responsible for plant uptake, transport, and sequestration of heavy metals; they would then be able to restore degraded areas that are becoming increasingly susceptible to the effects of climate change. Another important theme revolves around the issue of waste valorization. A notable study is that of Lee et al. (2025), which proposed a method of turning fish head waste into nitrogen-enriched nutrients through life-cycle assessment. This research exemplifies how biotechnology can convert an environmental burden of the aquaculture sector into a marketable product, thus lessening the waste and making the system more circular. Likewise, Dasari et al. (2025) provide a review of microalgae usage in aquaculture not only as an eco-friendly feed source but also as a nutrient-rich wastewater bioremediation tool, thereby completing the cycle and minimizing eutrophication.

The creation of new biomaterials also falls within this cluster. The work of Mânica et al. (2025), dealing with a Bacillus strain that can dissolve urea used in the production of self-healing concrete ("bioconcrete"), though not directly linked to crop production, is a good example of a wider application of biotechnology in making sustainable infrastructure for a climate-resilient future. The basic idea here is to make use of biological processes to lessen the environmental impact of human activities, agriculture included.

2.5. Cluster 5: Underutilized Crops and Diversification

The cluster is based on the idea that one of the best ways to develop resilience is to have a variety of species for food that we can depend on. It is mainly oriented towards "orphan crops"—species that are more robust than others in terms of being able to live in harsh environments and are forgotten by the mainstream research and global market at the same time. This multidisciplinary research cluster is supported by extensive scientific and technological resources to fully characterize the biotechnology potentials of those crops. A significant contribution to this theme is through the systematic study of millets carried out by Singh et al. (2021) and Thakur et al. (2025), which shows that genomics and molecular breeding techniques

are being used to upscale these drought-tolerant and poor-soil-tolerant nutrient-rich grains. Likewise, Oluwole et al. (2021) give a full account of the technological uplift of African yam bean, a highly rated legume as far as protein content is concerned; and on the other hand, Soumare et al. (2022) have come up with a very strong argument in support of the Bambara groundnut crop. The whole undertaking involves germplasm conservation and evaluation, meaning that capturing the genetic diversity among those species could be done only for a short time before the diversity is lost. Deepana et al. (2025) talk about this in the case of the Dolichos bean, underlining the need to keep landraces that might be the home of the rare stress-adaptive alleles.

One of the main goals in this context is the improvement of the traits. It means bringing the quality of the crops to such a level that they do not have any of the restrictions preventing them from being widely adopted, such as low yield, seed shattering, or the presence of anti-nutritional factors. For example, Francis et al. (2023) applied mutagenesis and genotyping-by-sequencing in proso millet to obtain high-yielding mutants, thus showing how modern tools can effectively upgrade such former unnoticed species in a short time. Such a long-term vision would not only allow for more varieties of staple foods but also the creation of a global food system that would be less dependent on a few types of crops and therefore more resilient to climate shocks.

3. Key Crops and Organisms

The research area of climate-resilient biotechnology is skewed towards places where its application will be most necessary and where the greatest benefits can be expected, in terms of both nutrition and economy. The main target is very much at staple cereals, which provide the decarbonized and most indispensable caloric foundation for a large part of the world's population. For that reason, rice, wheat, and maize have been the objects of very close scrutiny, mainly due to their vulnerability to adverse climate and their crucial role in food security. For example, a lot of research on rice is going into genetic and biotechnological solutions to prevent heat-induced damage during the delicate flowering period and to improve water efficiency under drought conditions. Likewise, in the case of wheat and maize, the aspect of breeding resistant cultivars to heat and water shortage is by far the most concentrated effort, employing all tools available from molecular breeding to state-of-the-art genome editing. Besides the major three cereals, other places where significant research interest producing legumes like soybeans, chickpeas, and sorghum has been shown. These plants are not only great sources of plant protein but also their ability to take up nitrogen from the atmosphere increases the output of the soil. So, one of the goals for biotechnology is to plant them for fungal diseases, strengthen their drought resistance, and ultimately raise the production potential under less-than-ideal conditions. Also, non-vegetative high-value crops like citrus and papaya are included among the top research areas. This research usually revolves around developing resistance to diseases and improving the quality and shelf-life of fruits, which are directly affected by climate problems, thereby safeguarding both economic and nutritional diversity.

In the parallel and complementary area of microbial biotechnology, a selective group of organisms has turned out to be the potential biological partners. The bacterium Bacillus and the fungus Trichoderma are the most studied organisms due to their multi-faceted advantages. They act as biofertilizers by increasing the availability of nutrients, as biopesticides by preventing soil-borne pathogens, and as stress-relievers by enhancing the plants' immune systems and making them more tolerant to abiotic stresses like salinity and drought. Moreover, cyanobacteria are being researched for their role in nitrogen fixation as well as being a sustainable source of biofertilizers and biostimulants which is a more holistic and ecological way of coping with a challenge like crop resilience. This explicit orientation towards particular crops and microbes is a deliberate strategy to ensure global food production through genetic and biological alteration.

4. Integration of Frontier Technologies

One of the most impressive and game-changing trends in the industry is the unification of the main biotechnological instruments with, previously, the other disruptive technologies. This coming together of forces is paving the way for a new order of "digital biological agriculture," where the distinctiveness between the digital and biological spheres is getting less and less sharp. This overlap is gaining a lot of power and, therefore, able to manage and create plant resilience faster than ever. The cross-technique is already beyond mere robotics and is turning the research and development cycle upside down.

The convergence between biotechnology and artificial intelligence (AI) is absolutely the most revolutionary of all others, especially when it comes to machine learning (ML) and data analysis. The scale and intricacy of biological data—whole-genome sequences (genomics), gene expression (transcriptomics), protein interaction (proteomics), and metabolic profiles (metabolomics)—have posed a "big data" issue that cannot be dealt with by traditional methods any longer. AI is presented as a very strong ally in this case. The work of Wang et al. (2025) underscores this idea; namely, that AI algorithms can be fed on these vast, multilayered datasets so as to spot concealed patterns and links that are beyond the detection of human researchers. For example, in their research on cold stress in legumes, ML models are capable of combining genomic data with past phenotypic responses to the exposure to low temperatures. This synergistic effort leads to the predictive identification of key genetic loci and complicated gene networks that are responsible for cold tolerance. In addition, AI can process high-throughput phenotyping data, such as the ones generated by drones or sensors that measure plant growth, canopy

temperature, and chlorophyll fluorescence, and connect these physical characteristics directly with their genetic basis. As a result, the rapid screening of thousands of plant lines for stress-resilient traits is made possible, which is a process known as genomic selection, and this in turn significantly shortens the breeding cycle. Not only that, but AI also has the capability of predicting the likely outcomes of particular gene edits, such as off-target effects or unintended consequences in the metabolic network of the plant, even before laboratory work starts, hence making CRISPR-Cas9 editing more effective and precise.

At the same time, another frontier is being opened up through the integration of Extended Reality (XR)—which is a term used to refer to various technologies such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) as a whole. According to Nakhle & Harfouche (2023), XR technologies are likely to change the whole scenario of the way scientists interact with biological data and intricate molecular structures. Picture a plant geneticist donning a VR headset and being able to "walk" through a 3D, interactive model of a chromosome where he can see the promoter regions and the gene clusters that are good candidates for editing, all visually identified. This whole situation would give him an instantaneous comprehension of the spatial relationships that would otherwise not be available on a 2D computer screen. In educational settings, AR could add a layer of digital information to the physical plants in a greenhouse; when a researcher holds up a tablet to a seedling, he can see real-time information about its genetic makeup, stress response transcripts, or nutrient levels as a digital overlay being displayed. Such a combination of the physical and digital worlds can make the whole process of conducting experiments faster and also make training more effective. In addition, XR can create "digital twins" of whole crops or ecosystems and allow scientists to experiment and watch how modified plants would react under various climate scenarios in the future, such as a long drought or a sudden heat wave, all this in a risk-free virtual environment and only after that, decide whether to carry out the more expensive and time-consuming field trials or not. Thus, the use of XR in such a way becomes a very effective and powerful one in the case of planning and de-risking biotechnological interventions.

Essentially, the merging of AI and XR with biotechnology is to establish a scientific discipline that is more predictive, precise, and intuitive. The artificial intelligence gives the power of computation to unravel the complexity of life and to steer the engineering feats so as XR offers the facility of an immersive interface for the visualization and interaction with that complexity. The AI and XR combination are speeding up the movement from discovering genes to producing strong, climate-resistant plants, thus marking a crucial change in the way we deal with global food supply security.

5. Geographical and Institutional Contributions

The affiliations of the corresponding authors imply that the research is distributed all over the world and that there are major contributions from China, India, Pakistan, the USA, and some countries in Europe and the Middle East. International collaboration is evident, it is even between institutions in developed and developing nations, thus emphasizing the global character of the climate issue (See Fig. 1).

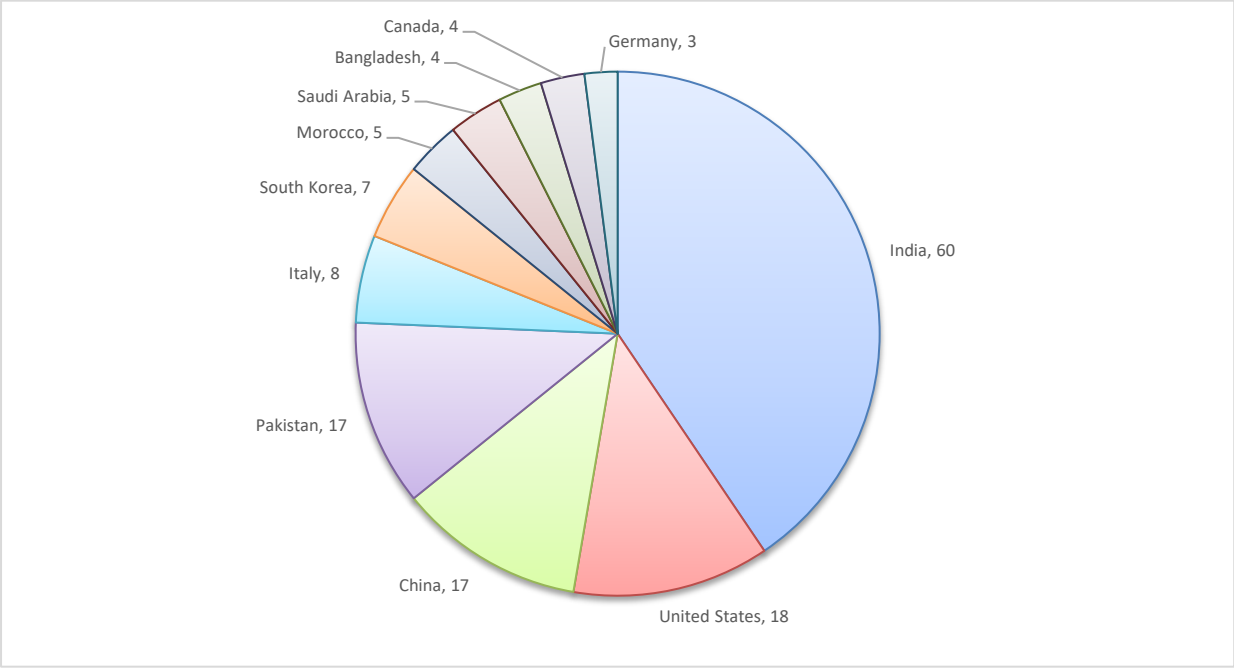

Fig. 1. Distribution of the countries

6. Conclusion and Future Directions

The scientometric analysis of the 122 publications conducted with no doubt shows that climate-resilient biotechnology has grown up from a baby field to a very active and key discipline in the worldwide endeavor to protect food security. The research landscape is not anymore characterized by isolated studies, but by a strong and integrative framework where different technology streams come together. The five clusters identified—precision gene editing, microbial biotechnology, multi-omics-driven breeding, systemic su-stainability, and the promotion of underutilized crops—are not parallel paths but connected routes of a shared strategy. The revolutionary precision of CRISPR-Cas9 is controlled by the deep mechanistic insights that omics technologies have revealed, while the protective advantages of microbial inoculants present a sustainable delivery system for the resilience that is coded in a plant's genes. This cooperation is even more reinforced by the coming of artificial intelligence and extended reality, which are giving the computing power and the interactive interfaces needed to deal with this new biological complexity. The main story is quite clear: the solution to the many-sided problem of climate change is not a single silver bullet, but rather a refined silver buckshot approach, that is, an integrating of genetic, biological, and digital innovations to fortify every layer of our agricultural systems, ranging from the molecular to the ecological.

The future of climate-resilient biotechnology is already mapped and will be marked by even closer integration and a few important challenges that are about to arise. Animal and plant engineering will be under-researched methods of working with living systems. The quality and yield of crops will be carefully monitored while combining the drought, heat, and disease-resistant traits through the application of highly sophisticated multiplex gene editing techniques to the stacking of multiple stress-tolerance genes. The idea of the 'phytobione' will be accepted and the research will progress from traditional bioinoculants to the creation of synthetic microbial communities (SynComs) that are specifically designed for particular crops and environmental conditions, so that a beneficial microbiome can be formed for every field. On top of that, the role of AI in the process will transform from an analytical support tool to a predictive and generative one. With AI models, we will be able to foresee the future when they will be able to talk about the best editing techniques for the genes of an organism or to give a pretty good prediction of the performance of a new variety of crops in a changed climate scenario. The current process of breeding will be cut down drastically by this "predictive breeding" invention from ten years to almost nothing at all. Nevertheless, this bright future still relies on the resolution of a lot of big problems. The legal regulations for the crops that are edited by gene remain a very complicated and diverse global pattern, which creates uncertainty and hinders innovation. Making the necessary leap from lab breakthroughs to total the adoption by farmers, especially for smallholders in developing countries, demands not only low-cost technologies but also good seed systems, extension services, and a profound understanding of socio-economic contexts. The public's perception and acceptance of these changing technologies will still be a determinant factor and will need to be supported by clear communication and inclusive dialogue about the risks and the very great risks of inaction.

In conclusion, the results of this review indicate that biotechnology has become an essential element of the agricultural sector’s climate adaptation strategy, and not just a supplementary tool. Researchers have jumped from pegging the understanding of biotic stress to actively and intentionally reshaping it. The teamwork illustrated by these publications is said to be a huge task in re-engineering food systems’ foundations that can handle the unprecedented pressure of the 21st century. Now, the challenge consists of making sure that the convergence of this remarkable technological development is accompanied by a similarly sophisticated and collaborative amalgamation of policy, economics, and ethics. By creating an atmosphere where scientific innovation can be responsibly transformed into available and practical solutions, we shall be able to use this knowledge not only to reduce the impacts of climate change but also to facilitate the arrival of a new age of productive, sustainable, and resilient agriculture that can feed a growing population living under stress. The review of progress in this paper provides not only data but also a strong and optimistic plan for the realization of this important objective.

References

Ahmed, H. G. M.-D., Zeng, Y., Fiaz, S., & Rashid, A. R. (2023). Applications of high-throughput phenotypic phenomics. In *[Book Title]* (pp. 119–134). Springer. https://doi.org/10.1007/978-3-031-15568-0_6

Akhatar, J., Kaur, H., & Kumar, H. (2022). Conventional plant breeding to modern biotechnological approaches in crop improvement. In *[Book Title]* (pp. 1–21). Springer. https://doi.org/10.1007/978-981-16-5767-2_1

Alotaibi, M. A. (2023). Climate change, its impact on crop production, challenges, and possible solutions. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 51*(1), 13020. https://doi.org/10.15835/nbha51113020

Archibald, B. N., Zhong, V., & Brophy, J. A. N. (2023). Policy makers, genetic engineers, and an engaged public can work together to create climate-resilient plants. *PLOS Biology, 21*(7), e3002208. https://doi.org/10.1371/journal.pbio.3002208

Asif, Z., Jabeen, A., Irfan, M., Khatoon, A., Bashir, A., & Malik, K. A. (2025). Stress-inducible IPT gene expression boosts antioxidant defense and grain production in heat-stressed maize. *Pakistan Journal of Agricultural Sciences, 62*(2), 359–375. https://doi.org/10.21162/PAKJAS/25.192

Bîrgovan, A. L., Lakatos, E. S., Cioca, L. I., Paul, N. L., Vatca, S. D., Kis, E., & Păcurariu, R. L. (2025). Harnessing microbial power for a sustainable future food system. *Microorganisms, 13*(9), 2217. https://doi.org/10.3390/microorganisms13092217

Castroverde, C. D. M., Kuan, C., & Kim, J. (2024). Plant immune resilience to a changing climate: Molecular insights and biotechnological roadmaps. *Genome*. https://doi.org/10.1139/gen-2024-0088

Dasari, D., Dong, C.-D., Singhania, R. R., Tambat, V. S., Piechota, G., & Patel, A. K. (2025). Harnessing microalgae for sustainable aquaculture and mariculture: Marine pollution mitigation and circular economy strategies. *Marine Pollution Bulletin, 219*, 118292. https://doi.org/10.1016/j.marpolbul.2025.118292

Deepana, K., Geetha, K., Jeyaprakash, P., Sangeetha, M., & Govindan, K. (2025). The Dolichos bean: A versatile legume with potential to address food security challenges and strategies for improvement. *Genetic Resources and Crop Evolution, 72*(2), 1313–1331. https://doi.org/10.1007/s10722-024-02085-1

Devika, O. S., & Rakshit, A. (2019). Economic appraisal of bio-priming mediated stress moderation in crop plants. *Economic Affairs, 64*(3), 563–569. https://doi.org/10.30954/0424-2513.3.2019.12

Dwivedi, S. L., Goldman, I., Ceccarelli, S., & Ortiz, R. (2020). Advanced analytics, phenomics and biotechnology approaches to enhance genetic gains in plant breeding. *Advances in Agronomy, 162*, 89–142. https://doi.org/10.1016/bs.agron.2020.02.002

Francis, N., Rajasekaran, R., Veera Ranjani, V. R., Bakya, S. V., Raveendran, R., Kumar, A. G., Senthil, S., Krishnamoorthy, I., & Chitdeshwari, C. (2023). Molecular characterization and SNP identification using genotyping-by-sequencing in high-yielding mutants of proso millet. *Frontiers in Plant Science, 14*, 1108203. https://doi.org/10.3389/fpls.2023.1108203

Gondalia, N., Vashi, R., Barot, V., Sharma, F., Anishkumar, P. K., Chatterjee, M., Karmakar, N., Gupta, P., Sarker, A., Kumar, S., & Sarkar, A. (2024). Genomic designing for abiotic stress tolerance in pea (Pisum sativum L.). In *[Book Title]* (pp. 45–113). Springer. https://doi.org/10.1007/978-3-030-91039-6_3

Kashyap, P. L., Rai, P., Srivastava, A. K., & Kumar, S. (2017). *Trichoderma* for climate resilient agriculture. *World Journal of Microbiology and Biotechnology, 33*(8), 155. https://doi.org/10.1007/s11274-017-2319-1

Kencharaddi, H. G., Suresha, P. G., Soregaon, C. D., & Kumar, A. (2024). Breeding and molecular approaches for drought-resilient crops. In *[Book Title]* (pp. 227–265).

Kumar, J., Choudhary, A. K., Sen Gupta, D. S., & Kumar, S. (2019). Towards exploitation of adaptive traits for climate-resilient smart pulses. *International Journal of Molecular Sciences, 20*(12), 2971. https://doi.org/10.3390/ijms20122971

Lassoued, R., Smyth, S. J., & Phillips, P. W. B. (2023). Regulatory outlook of CRISPR-edited plants in Canada. In *[Book Title]* (pp. 231–250). Elsevier. https://doi.org/10.1016/B978-0-443-18444-4.00024-7

Lee, S., Ahn, S., Zong, J. H., Oh, C., Suh, S., & Hwang, D. S. (2025). Sustainable valorization of fish head wastes into nitrogen-based nutrients: A comparative life cycle assessment. *Journal of Biological Engineering, 19*(1), 87. https://doi.org/10.1186/s13036-025-00560-6

Liu, S., Zenda, T., Tian, Z., & Huang, Z. (2023). Metabolic pathways engineering for drought or/and heat tolerance in cereals. *Frontiers in Plant Science, 14*, 1111875. https://doi.org/10.3389/fpls.2023.1111875

Madale, V. A., Madamba, R. S., Salic-Hairulla, M. A., & Naquines, L. P. (2025). Enhancing rice for the future: Advances in yield, resistance, and climate adaptability. *Health Leadership and Quality of Life, 4*, 644. https://doi.org/10.56294/hl2025644

Mane, R. S., Prasad, B. D., Sahni, S., Quaiyum, Z., & Sharma, V. K. (2024). Biotechnological studies towards improvement of finger millet using multi-omics approaches. *Functional and Integrative Genomics, 24*(5), 148. https://doi.org/10.1007/s10142-024-01438-4

Mânica, G., Schmitz, C., Irazoqui, J. M., Amadio, A. F., Acevedo, M., Mascolo, R., Ehrenbring, H. Z., & Volken de Souza, C. F. (2025). Genomic and functional characterization of ureolytic Bacillus bombysepticus QCSJ3 and its application in self-healing cementitious composites through encapsulation. *World Journal of Microbiology and Biotechnology, 41*(10), 365. https://doi.org/10.1007/s11274-025-04585-3

Munawar, S., Tahir Ul Qamar, M. T., Mustafa, G., Khan, M. S., & Joyia, F. A. (2020). Role of biotechnology in climate resilient agriculture. In *[Book Title]* (pp. 339–365). Springer. https://doi.org/10.1007/978-3-030-49732-3_14

Mushtaq, W., Li, J., Liao, B., Miao, Y., & Liu, D. (2025). Unlocking crop resilience: How molecular tools enhance abiotic stress tolerance. *Plant Stress, 17*, 100950. https://doi.org/10.1016/j.stress.2025.100950

Nakhle, F., & Harfouche, A. L. (2023). Extended reality gives digital agricultural biotechnology a new dimension. *Trends in Biotechnology, 41*(1), 1–5. https://doi.org/10.1016/j.tibtech.2022.09.005

Ngongolo, K., & Mmbando, G. S. (2024). Harnessing biotechnology and breeding strategies for climate-resilient agriculture: Pathways to sustainable global food security. *Discover Sustainability, 5*(1), 431. https://doi.org/10.1007/s43621-024-00653-0

Ojeih, C. A., Ogidan, O., Oluwajobi, Y. F., & Adebayo, B. O. (2024). Biotechnology regulatory conundrum: Balancing innovation and oversight. *Journal of Sustainable Development Law and Policy, 15*(3), 120–144. https://doi.org/10.4314/jsdlp.v15i3.5

Oluwole, O. O., Aworunse, O. S., Aina, A. I., Oyesola, O. L., Popoola, J. O., Oyatomi, O. A., Abberton, M. T., & Obembe, O. O. (2021). A review of biotechnological approaches towards crop improvement in African yam bean (Sphenostylis stenocarpa Hochst. Ex A. Rich.). *Heliyon, 7*(11), e08481. https://doi.org/10.1016/j.heliyon.2021.e08481

Pandey, S., Divakar, S., & Singh, A. (2024). Genome editing prospects for heat stress tolerance in cereal crops. *Plant Physiology and Biochemistry, 215*, 108989. https://doi.org/10.1016/j.plaphy.2024.108989

Patani, A., Patel, M., Islam, S., Yadav, V. K., Prajapati, D., Yadav, A. N., Sahoo, D. K., & Patel, A. (2024). Recent advances in Bacillus-mediated plant growth enhancement: A paradigm shift in redefining crop resilience. *World Journal of Microbiology and Biotechnology, 40*(2), 77. https://doi.org/10.1007/s11274-024-03903-5

Ponnurangan, V., Namachivayam, R., Pradeep, R. K. M., Jesudoss, D., Eswaran, K., Arul, A., Kumar, K. K., Paranidharan, P., Maduraimuthu, D., & Shanmugam, V. (2025). Biotechnological breakthroughs in rice disease management: An overview from transgenics to CRISPR. *Molecular Biology Reports, 52*(1), 616. https://doi.org/10.1007/s11033-025-10701-1

Prabhakaran, V. S., Noh, M.-Y., Park, K.-B., Kim, T.-Y., Jung, W.-J., Senthil-Nathan, S., & Han, Y. S. (2025). Plant immunity to insect herbivores: Mechanisms, interactions, and innovations for sustainable pest management. *Frontiers in Plant Science, 16*, 1599450. https://doi.org/10.3389/fpls.2025.1599450

Pudake, R. N., Solanke, A. U., Sevanthi, A. M., & Rajendrakumar, P. (2022). *Omics of climate resilient small millets*. Springer. https://doi.org/10.1007/978-981-19-3907-5

Reed, R. C., Iqbal, R., Sundaresan, V., & Khanday, I. (2025). Reinventing Inheritance: Clonal Propagation of Crops Through Seeds with Apomixis. *Critical Reviews in Plant Sciences*. https://doi.org/10.1080/07352689.2025.2519701

Riaz, M., Yasmeen, E., Saleem, B., Hameed, M. K., Saeed Almheiri, M. T., Saeed Al Mir, R. O., Alameri, G., Khamis Alghafri, J. S., & Gururani, M. A. (2025). Evolution of agricultural biotechnology is the paradigm shift in crop resilience and development: a review. *Frontiers in Plant Science, 16*, 1585826. https://doi.org/10.3389/fpls.2025.1585826

Saeed, F., Chaudhry, U. K., Raza, A., Charagh, S., Bakhsh, A., Bohra, A., Ali, S., Chitikineni, A., Saeed, Y., Visser, R. G. F., Siddique, K. H. M., & Varshney, R. K. (2023). Developing future heat-resilient vegetable crops. *Functional and Integrative Genomics, 23*(1), 47. https://doi.org/10.1007/s10142-023-00967-8

Sarma, H., Islam, N. F., Prasad, R., Prasad, M. N. V., Ma, L. Q., & Rinklebe, J. (2021). Enhancing phytoremediation of hazardous metal(loid)s using genome engineering CRISPR–Cas9 technology. *Journal of Hazardous Materials, 414*, 125493. https://doi.org/10.1016/j.jhazmat.2021.125493

Senguttuvel, P., Jaldhani, V., Raju, N. S., Balakrishnan, D., Beulah, P., Bhadana, V. P., Mangrauthia, S. K., Neeraja, C. N., Subrahmanyam, D., Rao, P. R., HariPrasad, A. S., & Voleti, S. R. (2022). Breeding rice for heat tolerance and climate change scenario; possibilities and way forward. A review. *Archives of Agronomy and Soil Science, 68*(1), 115–132. https://doi.org/10.1080/03650340.2020.1826041

Shamanin, V. P., Shepelev, S. S., Kovalchuk, A. M., Morgunov, A. I., Turuspekov, Y. K., & Pototskaya, I. V. (2025). SNP Effects on Yield and Agronomic Traits in an International Winter Wheat Collection Grown in Western Siberia. *Crops, 5*(4), 41. https://doi.org/10.3390/crops5040041

Shilomboleni, H., & Ismail, A. M. (2023). Gene-editing technologies for developing climate resilient rice crops in sub-Saharan Africa: Political priorities and space for responsible innovation. *Elementa, 11*(1), 00145. https://doi.org/10.1525/elementa.2022.00145

Singh, R. K., Muthamilarasan, M., & Prasad, M. (2021). Biotechnological approaches to dissect climate-resilient traits in millets and their application in crop improvement. *Journal of Biotechnology, 327*, 64–73. https://doi.org/10.1016/j.jbiotec.2021.01.002

Soumare, A., Diedhiou, A. G., & Kane, A. (2022). Bambara groundnut: a neglected and underutilized climate-resilient crop with great potential to alleviate food insecurity in sub-Saharan Africa. *Journal of Crop Improvement, 36*(5), 747–767. https://doi.org/10.1080/15427528.2021.2000908

Tan, C., Kalhoro, M. T., Faqir, Y., Ma, J., Osei, M. D., & Khaliq, G. (2022). Climate-Resilient Microbial Biotechnology: A Perspective on Sustainable Agriculture. *Sustainability, 14*(9), 5574. https://doi.org/10.3390/su14095574

Thakur, N., Dishri, M., Nath, A. K., Chahota, R. K., & Antony Ceasar, S. A. (2025). Millets as climate-resilient crops: mitigating food and nutrient insecurity. *Cereal Research Communications*. https://doi.org/10.1007/s42976-025-00680-1

Wang, K., Xia, L., Yang, X., Du, C., Tang, T., Yang, Z., Ma, S., Wan, X., Guan, F., Shi, B., Xie, Y., & Zhang, J. (2025). Integrating Artificial Intelligence and Biotechnology to Enhance Cold Stress Resilience in Legumes. *Plants, 14*(17), 2784. https://doi.org/10.3390/plants14172784

© 2025 by the authors; licensee Growing Science, Canada. This is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC-BY) license (http://creativecommons.org/licenses/by/4.0/).