Shahid Bahonar University of Kerman
Agricultural Biotechnology Journal
Iranian Biotechnology Society
Print ISSN: 2228-6705 Online ISSN: 2228-6500

Advancing crop-climate resilience through plant biotechnology for sustainable agriculture

V. Ramesh Kumar
*Corresponding author. Associate Professor, Department of Biotechnology, Sathyabama Institute of Science and Technology, Chennai, Tamil Nadu, India. E-mail: rameshkumar.biotech@sathyabama.ac.in

Subhaprada Dash
Associate Professor, Department of Agronomy, Faculty of Agricultural Sciences, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha, India. E-mail: subhapradadash@soa.ac.in

Ranganathaswamy Madihalli Kenchappa
Associate Professor, Department of Mechanical Engineering, Faculty of Engineering and Technology, JAIN (Deemed-to-be University), Ramanagara District, Karnataka, 562112, India. E-mail: mk.ranganatha@jainuniversity.ac.in

Kanchan Awasthi
Associate Professor, Department of Science, Maharishi University of Information Technology, Lucknow, Uttar Pradesh, India. Email: kanchan.awasthi@muit.in

Takveer Singh
Centre of Research Impact and Outcome, Chitkara University, Rajpura- 140417, Punjab, India. E-mail: takveer.singh.orp@chitkara.edu.in

Lovish Dhingra
Chitkara Centre for Research and Development, Chitkara University, Himachal Pradesh-174103 India. E-mail: lovish.dhingra.orp@chitkara.edu.in

Umesh Daivagna
Professor, ISME, ATLAS SkillTech University, Mumbai, India. E-mail: umesh.daivagna@atlasuniversity.edu.in

Abstract

Objective

The article talks about how modern plant biotechnology can be used to make crops more resilient to climatic changes and other environmental pressures. It focuses on coming up with sustainable models to increase agricultural productivity and food security through the combination of genetic, molecular and agronomic information. As the conventional agricultural crop improvement methods are proving not to be effective in ensuring that crops are stress-resistant and yield consistent results, this review outlines the way in which biotechnology may be scaled to improve crop-climate resilience.

Materials and methods
The present study has its methodology grounded on a systematic review inspired by an analytical synthesis of peer-reviewed articles published between 2015-2025. The information was obtained in the popular scientific databases, i.e., Scopus, Web of Science, and PubMed. The review will cover the experimental findings of the recent applications of genome editing systems (CRISPR/Cas9, TALENs), transgenic crop research, and systems of integrated molecular models. Gene changes that raised abiotic and biotic stress tolerance, yield stability, and nutrient efficiency were compared to analyze the changes.
Results
The results show that biotechnological developments have greatly improved the flexibility and yield of plants. This is through genome editing tools and, in particular, CRISPR/Cas9, which made it possible to conduct specific alterations to genes that are involved in disease-causing stress, resulting in improved drought and heat resistance and pests in staple food crops such as rice, maize, and soybean. Moreover, the omics-artificial intelligence approach in crop modeling has also increased the development of production sustainability and optimal resource usage predictive models. As the key to the reduction of the ecological footprints, the collaboration of biotechnological inventions with sustainable agricultural practices, such as precision irrigation and enhancement of the soil microbiome, are also developed in the research.
Conclusions
Last but not least, this paper outlines how biotechnology can transform the future to foster a strong sustainable future of agriculture. In addition to the fact that genetic innovation, in combination with eco-centric farming technology ensures not only a higher level of crop productivity and more stable environment but also promotes the evolution of agriculture in the most ethical and inclusive manner. There will be a need to invest more in precise gene editing, bioinformatics and sustainability orientated technology to enable world food security goals to be attained without interfering with the ecosystem integrity.
Keywords: agriculture, crop-climate resilience, plant biotechnology, sustainable

Paper Type: Review Paper.
Citation: Kumar, V. R., Dash, S., Kenchappa, R. M., Awasthi, K. Singh, T., Dhingra, L., & Daivagna, U. (2026). Advancing crop-climate resilience through plant biotechnology for sustainable agriculture. *Agricultural Biotechnology Journal,* 18(1), 363-380.

Agricultural Biotechnology Journal, 18(1), 363-380. DOI: 10.22103/jab.2025.25119.1689
Received: September 20, 2025. Received in revised form: December 05, 2025.
Accepted: December 06, 2025. Published online: January 15, 2026.
Publisher: Shahid Bahonar University of Kerman & Iranian Biotechnology Society.

Introduction

The weather conditions which are becoming unpredictable, erosion of soil, and scarcity of valuable resources are straining the global agriculture industry. Despite years of breeding, advancement in breeding of stress-tolerant crops has been minimal. The following review addresses this critical issue, which is the low adaptability of crops to rapid climatic change, and how the biotechnology of plants can provide a new solution to these issues, overcoming these challenges via genetic, molecular, and bioinformatics-related methods. Rapid changes can be found in plant biotechnology (PBT) (Nahar, 2025). There are biological and technical ideas that will be used to make farming more productive, resistant, and able to adapt to new circumstances (Rivero et al., 2022; Topalova et al., 2024). These findings are meaningful in that world agriculture is struggling with two things namely, satisfying the increasing food demand and adjusting to environmental changes due to global warming. The duration of crops growing in case of changes in weather is determined by their crop resiliency or ability to absorb shocks such as pests, diseases, and drought. Primarily, the objective of PBT-mediated achievement of crop genomics and reproductive techniques is to achieve increased output also referred to as efficiency (Baggyalakshmi et al., 2024). The advances transform agriculture because they enable specialists to examine large volumes of data and make reasonable decisions (Priya and Mercy Gnana Rani, 2015). It applies machine learning and statistics to predictive analysis to examine the past and attempt to establish what is likely to occur in the future (Shinde et al., 2018). These models analyze various data such as genetic, physical, biological and data related to management to demonstrate the performance of the crops in various farming conditions. Scientists look at data to learn more about how plants and their surroundings affect each other. This helps them guess which natural traits will make crops stronger and produce more. Traditional crop growth, which is based on costly field testing and data from the real world, slows the progress of hardy varieties (Iyer & Deshpande, 2024). Breeders can focus on traits that make plants more resistant and productive by simulating genetic and environmental factors (Ahmad et al., 2022). The predictions are made with the data regarding the modeling of the response of plants on water, food, and exterior factors that can assist in more precise treatment, such as the addition of fertilizer, the control of pests, and the provision of water at the appropriate time. The process regulates unnecessary inputs that save resources and extend the life span of things. By using the genes and other genomic markers, breeders predict the success of a live thing in the future (Montesinos-Lopez et al., 2021). They do it through the use of statistical analysis. In the case of good traits, the probability of which can be determined using genomic analysis and machine learning (ML), it becomes easier to produce highly lucrative cultivars capable of withstanding stress. This is possible to many more breeders due to predictive analysis applied in genome selection in crops such as wheat corn and rice. By relying on forecasting tools to select the type of crop that will best suit the type of changes it anticipates in the environment, it is able to alleviate the impacts of climate change on agriculture. This is particularly important in areas where the weather is very fluctuating, temperature increases and severe storms are frequent. Predictive analysis will help the producer to know the features that will boost resilience and adaptability by predicting crop output in different climatic conditions. The main purpose of this study is to discuss and summarize the recent progress in the field of plant biotechnology that can help to strengthen crop-climate resilience and sustainable agricultural production. It aims at establishing the most important genetic, molecular, and agronomic mechanisms that allow plants to acclimate to environmental stresses and also stresses the incorporation of biotechnology and sustainable agriculture practices. Still, by synthesizing the results of current studies, the review is expected to give a broad outlook of how the use of biotechnological innovations can aid global food security and environmental sustainability in changing climatic conditions.

Methodology

Climate-smart farming (Kakamoukas et al., 2021) and sustainability aim to enhance agroecosystems by incorporating highly resilient species capable of enduring severe climatic events. This review aims to assess the claim by examining the amalgamation of methodologies outlined in prior publications and elucidating the advancements in microbial bioengineering. Every record (documents, reviews, studies) obtained in the initial phase was screened for relevance based on the subject, investigation type, and emphasis of the current investigation. The research received most of the literature from widely recognized, accessible, and verified databases. Initially, the study sought to obtain the most recent literature from the past five years and extended the search to include works from 2010. The literature obtained was evaluated for relevance to the title of this study and its keywords. The research categorized the pertinent material according to temporal relevance and removed the extraneous records, as referenced further in this review. Figures 1, 2, and 3 illustrate the number of publications across several subject groups from 2010 to 2025. This review presents the most recent information regarding microbes in several sectors of agriculture, the field of Biotechnology (BT) (Tyczewska et al., 2023), primarily utilized as bio-fertilizers and bio-pesticides, along with numerous papers in environmental studies. In this century, the application of microorganisms has markedly risen over the past decade in study. The qualifying records were extracted and imported into the EndNote program (reference management tool). All duplicate and misleading records were eliminated as outlined in the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) (O'Dea et al., 2021). Following the screening, a bibliography was assessed based on the subject matter, retrieved reports, types of research, and year of release (Figure 4).

Genetic construction and genome revision

Genome editing technologies: The emergence of CRISPR-Cas9 (Du et al., 2023) has initiated a novel phase in PBT sciences, providing unparalleled accuracy and efficacy in genome modification. This revolutionary method has significantly increased the prospects of crop improvement, which enable an accurate modification of a particular gene with a high level of accuracy. Crops now have improved attributes, including increased yield, resistance to abiotic diseases, and resistance to diseases because CRISPR-Cas9 (CC9) can be modified (Kazemipour et al., 2025). This precision of CC9 allows researchers to make it easier to make intricate modifications in genes with decreased adverse effects (Pant et al., 2021). This is a giant leap in comparison with the older Genetic Engineering (GE) techniques as illustrated in Figure 5.

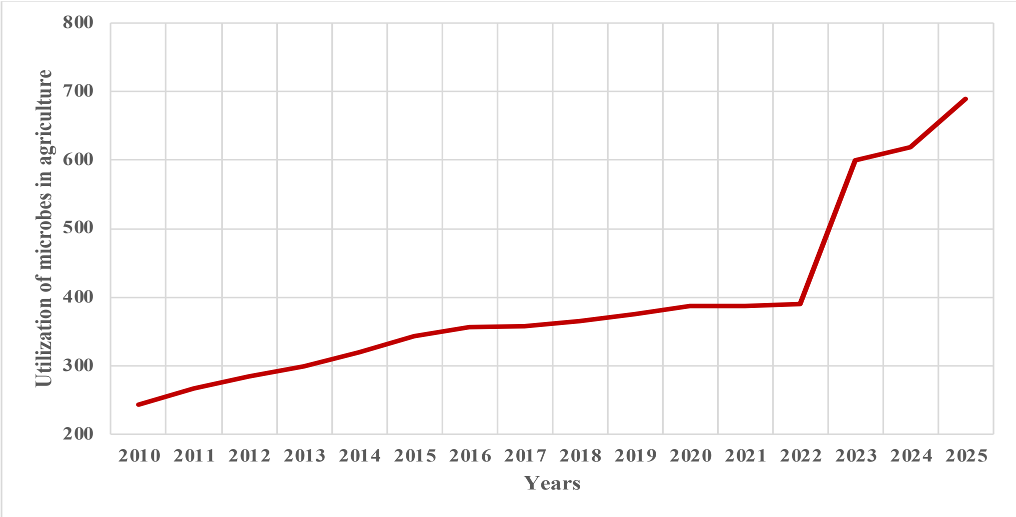

Figure 1. Utilization of microbes in agriculture

The study changed a gene that controls how the plant reacts to insufficient water with CC9. This made wheat more immune to drought. It was found that CC9 could help farmers deal with the effects of global warming. It also shows that the technology can precisely control complicated body processes. By going after the gene, CC9 was used in the study to make different types of rice less likely to get blight from bugs. This proved that the method makes plants stronger against biotic factors.

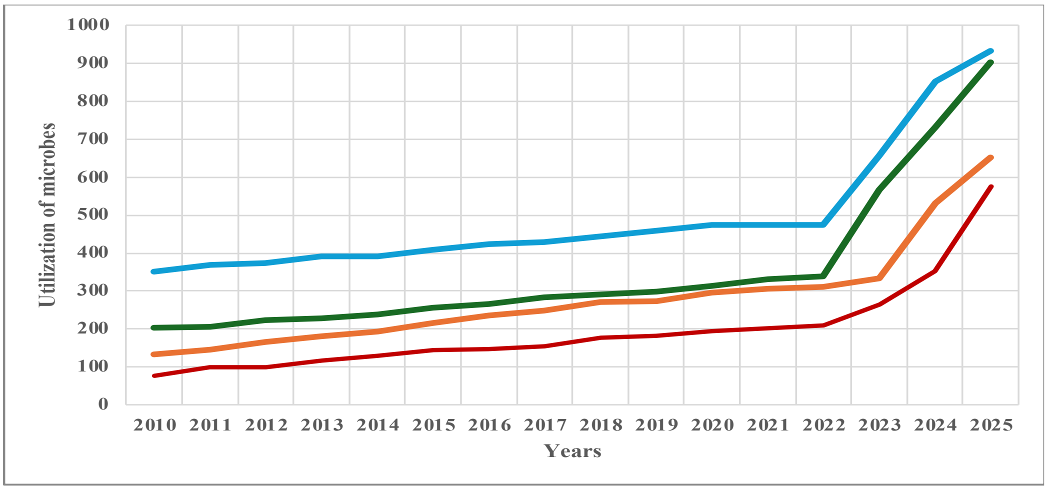

Figure 2. Utilization of microbes

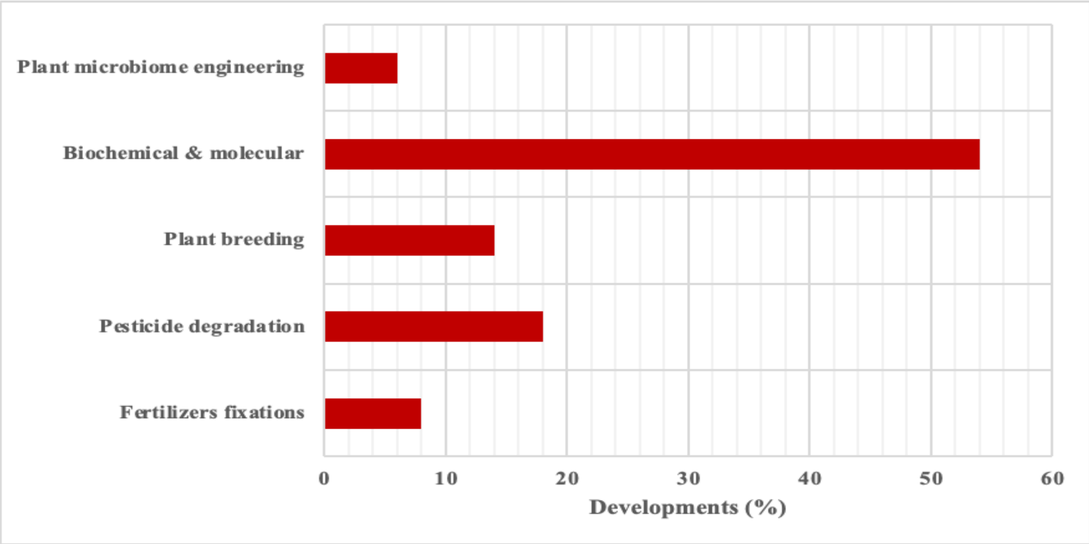

Figure 3. Recent utilization of microbial development

Many places have very different rules about GE crops that are very hard to understand. Different countries have different rules about CRISPR-edited plants (Kazemipour et al., 2025). Some have less strict rules, while others have strict rules. This variety of regulations makes it harder for GE plants to be used and sold worldwide. These regulatory flaws must be fixed for these methods to help solve global food security problems, and science-based methods must be fully implemented to analyse GE crops. Even though CC9 has already contributed significantly to PBT, it will always be necessary to understand the advantages and disadvantages of various GE tools. Improving these methods is always going on and the knowledge of agriculture, genetics and biology is increasing. This should accelerate the process of bettering crops. To unlock the full potential of GE in agricultural application scientific development, proper examination of ethical concerns, popular acceptance, and suitable legislation and regulations are all necessary.

Genetically modified (GM) crops: The GM crops are a major advancement in biotechnology within the agricultural industry as they bring alternatives to some of the greatest problems in this industry (Brookes, 2022). Through gene interventions scientists have bestowed qualities like herbicides resistance and nutritiousness to crop plants. Among the most prominent ones is Bt cotton that produces a toxin of the bacteria Bt. This is because this genetic modification is very resistant to major insects' pests and the result has brought great savings in the use of pesticides and also, great yield has been achieved. Bt cotton success shows the importance of genetic engineering in improving the sustainability of the farming methods by eliminating the adverse effects of chemical insecticides on the environment. The herbicide-resistant soybean is known as the soybean that contains a gene of Agrobacterium tumefaciens and this herb offers immunity to the herbicides and this benefit assists in effective control of the weeds. The Hawaiian papaya industry was rescued by a new breed papaya virus-resistant that was developed by insertion of the coat protein gene into the genome of the Papaya Ringspot Virus (PRSV), and this prevented the epidemic of PRSV. The other one is the brinjal that has been modified to contain the protein Cry1Ac which is known to attack the brinjal berries and shoot borer which significantly reduces the number of insect damages in South Asia.

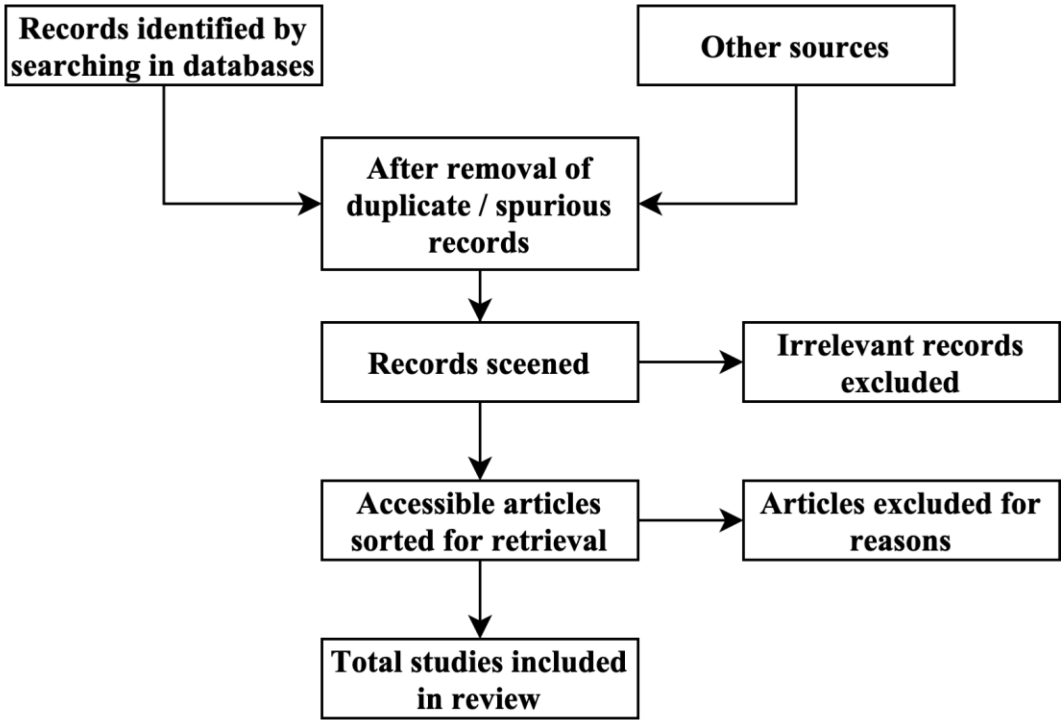

Figure 4. PRISMA chart of the resource

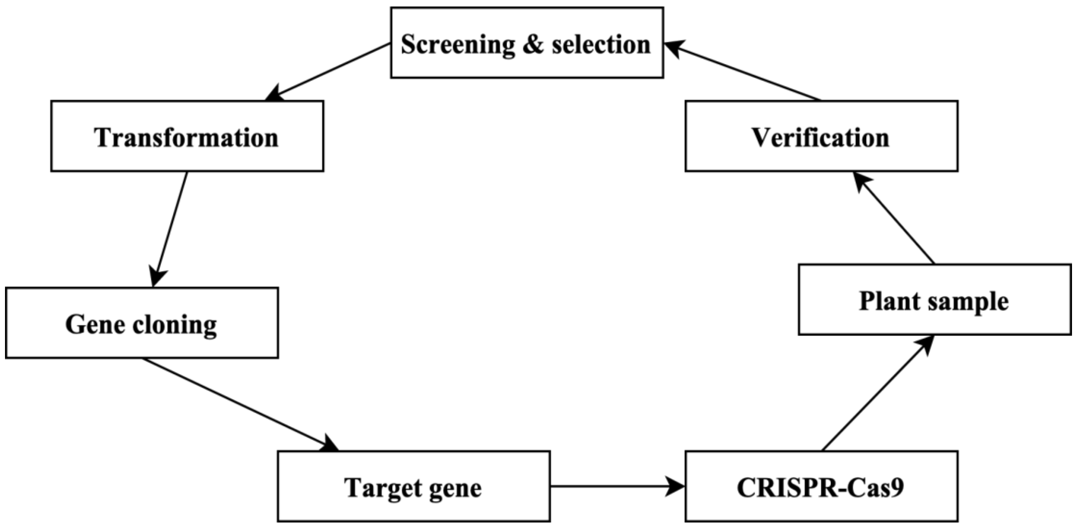

Figure 5. GE and the genomic editing process

Case analyses: There have been some remarkable success stories, as a result of using gene editing and BT in agriculture. An example of how this can be done is to develop maize resistant to drought by introducing into it the cold-shock protein B (CspB) gene of Bacillus subtilis. This

GM type of maize has a high output under water-limiting conditions, which depicts the ability of GM to mitigate global warming impact on agriculture. One good case study focuses on the use of CC9 in designing tomato plants that are more resistant against the Tomato Yellow Blotch Virus (Du et al., 2023). Through gene targeting, scientists have produced tomatoes that are much less infected by viruses and have better fruit production which depicts the possible advantages of CC9 in curbing the agricultural diseases issue. The article widely discusses the applications of CRISPR to making agrarians resistant to disease and tolerant to stress. The article demonstrates the importance of CRISPR in enhancing tolerance to biotic stressors, such as bacterial and fungal diseases, through modulated deletion of genes and regulatory methods (Kazemipour et al., 2025). In Brazilian experiments, transgenic sucrose with the Arabidopsis thaliana genes as shown has shown a 25 per cent increase in production in drought conditions, which is the evidence of the augmented resistance of the crop. A permanent solution to the malnourished population is bio-fortified bananas aimed at producing high levels of beta-carotene, which is a dietary intervention in regions with serious vitamin A deficiency.

Sustainable agricultural methodologies

Conservation tillage and soil integrity: Conservation tillage/no-till and reduced-till is a factor that is significant to agricultural sustainability because it helps to minimize the disturbance of the soil. The practice will reduce soil erosion, increase water uptake and increase the organic contents of the soil that increases health of the soil. Regular cultivation causes the soil structure to change as well as decreasing the amount of organic matter in the soil; conservation cultivation does not do this. Instead, it preserves the natural soil ecosystem, which enhances more bacteria and biodiversity (Tyczewska et al., 2023). This is very much needed in order to keep the earth healthy and also to allow the earth to produce more as time progress. Conservation farming happens to be a nice idea. According to no-till farming, the levels of organic nitrogen and carbon were significantly increased in the soil compared with the conventional methods of plowing. This makes the ground stronger and able to hold water that is important in sustaining the crops as the weather changes. They need to be taught that conservation tillage can be affected by the nature of the soil applied, weather patterns and approach taken in the farm. It means that different sites to grow must be provided with different alternatives.

Crop rotation and diversity: Farming and the rotation and growth of various types of crops is a vital environmental-friendly aspect in farming. In addition to keeping out diseases, pests, they also enhance the health of the soil, support the environment and make farming tough. When it employs such approaches, it must strategize to have alternative crops grow during other seasons of the year and introduce other types of plants into the farms (Brookes, 2022). These instruments are grounded on the principles of green farming which are meant to utilize superior resources, reduce pollution of green-house gases, and ensure sustainable returns. When crops are move pests and diseases can not be left in one place. New meta-analyses provide that it can also be used to maintain the yields constant and reduce the population of pests inhabiting an area. An attentive examination of data on 2900 reports revealed that the yields increased by 4.7% by crop rotation in numerous various farming methods all over the world. This increase in production has been occasioned by a number of factors, including improvement in the soil structure, enhancement of nutrient cycles, and reduction in the disease burden. Its research was primarily on the merits of incorporating beans into rotational farming which may increase the yield of harvest by up to 14% of these kinds of wheat grains. Within the recent years, there has been an increased interest in the way in which crop diversity can be utilized to enhance soil fertility and offer ecological quality. Research has revealed that different methods of cultivating can significantly increase soil organic carbon confinement, which may help to prevent climate change (Rivero et al., 2022). Their meta-analysis with 97 trials showed that varied systems supplemented the organic matter in the soil with an average of 3.7% as compared to the simplified cycles. Improving the carbon content of soil has a positive effect on the composition of the soil, its ability to retain water and the variety of microorganisms, which contributes to the agricultural resilience. Legume crop rotation helps in increasing the level of turnover of nitrogen and the soil condition. Nitrogen fixation of various species of legumes in various agricultural system was also measured in another study. This implies that well-managed legume rotations can provide up to 250 kg N ha -1 yr -1 to the succedent. Biological fixation of nitrogen will decrease the use of manufactured fertilizers and reduce the environmental impact of the effect of nitrogen runoff and greenhouse emission by soils cultivation. The advantages of crop rotation and diversity are more advantageous than soil health, even in the context of ecosystem functions on large scale. The study has shown that crop diversification has a beneficial effect on the quantity and diversity of pollinators, which define the sustainability of crop production and resistance to exogenous shocks. They conducted a systematic review of 89 studies to demonstrate that either fire or landscape enhancement of the diversity of crops could provide pollination services by a maximum of 55 per cent. which is significant considering that geographic levels have been considered significant in the diversification of the agricultural strategies. In spite of the thoroughly reported advantages, the introduction of crop and diversity rotation is a serious challenge in the contemporary agricultural operations. The market issues, infrastructure constraints and the necessity to possess special expertise and equipment do not contribute to its adoption. The analysis conducted indicated that the decision to diversify the farming system by farmers is driven by important socio-economic and regulatory force. The paper has observed that there should be coherent policy actions to incorporate monetary incentives, technical support and market expansions to support the shift to more diversified and sustainable agricultural operations. Recently, technology has made significant progress in precision farming and remote sensing, and this has provided opportunities to enhance crop cycles and diversity. It was demonstrated that machine learning approaches and satellite data can be used to aid more precise planning of crop rotations regarding space, taking into account the alterations in the soil, the weather prognosis, and the market tendencies

(Mohammadabadi et al., 2025). With an improved technology and application of farming knowledge in participatory studies, it might be possible to achieve context-specific diversification approaches that strike the balance in making money, efficiency and long-term growth. Crops rotation and the addition of various products can be used to increase the resilience of agriculture to climate change. Scientific studies are increasingly demonstrating all their advantages, both in enhancing the well being of the soil, and in supplying ecological services. In order to maximize on such techniques, the study needs to examine the macro-level and examine how the numerous technical, economic and social drivers of farming choices all inter-play. In order to simplify the adoption of various farming techniques in diverse agricultural environments, research in the future should also be aimed at developing plans that exploit emerging technologies, legislative modifications, and involvement of the farmer.

Integrative pest management (IPM): Integrative Pest Management (IPM) is a way to eliminate pests that considers all of their needs. It uses biological, social, physical, and chemical methods to decrease environmental damage and costs. IPM reduces the need for man-made pesticides and promotes biological balance by using natural enemies, biocontrol substances, and strategies for managing habitats. IPM methods have been very successful with several crops in the real world (Kakamoukas et al., 2021). IPM application in cotton farming has using into drastic reductions in the application of pesticides and maintenance of high levels of crop and high levels of profits. This technique supports useful living organisms, reduces the residual chemicals and extends the lifespan of farming systems, as they would be less susceptible to attacks by bugs. IPM can be effective only in case it is able to diagnose the exact kind of pest, monitor everything closely, and respond promptly. These things require time and money to instruct farmers on how to do them.

Organic agriculture: The definition of organic agriculture is the lack of artificial chemicals, the focus on natural inputs and methods that contribute to the diversity and the improvement of the environment. Organic systems make use of composting, organic fertilizer, and IPM in order to enhance soil fertility and control pests. Organic farming unlike the traditional farming methods improves soil health and reduces the greenhouse gases emissions since it promotes diversification of the soil. It has been shown that organic farming enhances soil fertility, soil biodiversity and reduces harmful emissions and resistance to climate shock. Organic matter constituted systems often have high adaptability to adverse weather conditions due to the improved soil composition and water retention. Organic farming has challenges, such as low productivity and high labor costs that need continuous research and development to optimize operations and enhance economic viability (Shinde et al., 2018).

Obstacles and Constraints

Various prediction methods demand large and high-quality datasets; there is dearth of data, anomalies and irregularities. Effective algorithms that predict resilience, production, and stress tolerance require plant genomes of high quality, phenomic data, and environmental data. Despite the recent development of data collection, predictive models still lack data. It is difficult to develop forecasting models in the regions that lack technological support and funds, genetic, physical, and ecological data (Figure 6).

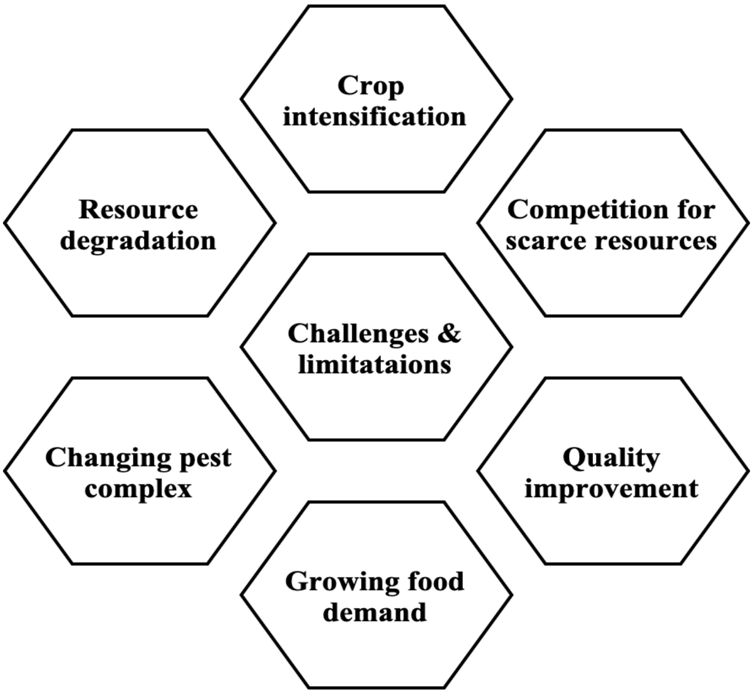

Figure 6. Challenges and limitations of BT

The fragmentation of data and limited access to some commodities, regions or attributes make it difficult to develop generalization frameworks. Data gaps, inaccuracies and deviations may impair the effectiveness of predictive models. The error of human data entry, the difference in measuring tools and discrepancy in procedures in different study groups may also affect the quality of data. To address these quality issues, data validation, consistency, and cleansing are required. This process is arduous. Many BT plant experts support the use of standardized data formats and processes to form consistency and comparison. The statistical modelling of PBT needs a lot of infrastructure and computing power, which is problematic when resources are limited. Multi-omics outcomes are extremely computational as the information on genomics, transcriptomics, proteomics, and behavior is numerous. Some countries or organisations do not permit a biological information storage and analysis system that is hosted in the cloud (Mohammadabadi et al., 2025). Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs) are able to evaluate data of high-dimensions that are not simple; it is difficult to explain them. Unlike linear regression, neural networks possess multiple layers and other attributes that hide the connections between the inputs and outputs (Ghotbaldini et al., 2019). Scientists had some challenges in trying to evaluate the conclusions made by the model and support the predictions. Predictive models require end-user trust and especially in farming.

Predictive models can be more useful and effective in agriculture, agricultural scientists, and legislators when they understand their operation and rationale (Mohammadabadi et al., 2024b). Understandable ML calculations, visualization tools, and importance of features tests will increase model acceptability and reliability. In high stakes disciplines such as agriculture, results of the models need to be simple to interpret so that they can be used in crop management. Such instruments can be used to make individuals familiar with complex models and verify whether agricultural forecasting is accurate (Mohammadabadi et al., 2024a). Crops can be made more resilient and productive by forecasting, but it must take into account the level of familiarity it has with the models, the computing power it has, and data quality. Such problems can be resolved through uniting individuals of other disciplines, investing in infrastructure and ensuring that the models are easy to understand and clear so that the farming consumers can have confidence in them.

Prospective developments and innovations in agricultural production: With the assistance of AI, multi-omics, and statistical analysis, things can be improved and become more permanent. Genetics, transcriptomics, proteomics and metabolomics are all part of crop biology. These facts allow the study to be better placed to understand the problematic relationships between genes, external factors and the nature of farming (Mohammadabadi et al., 2024b). This will help in better prediction of the breeding and crops. Drought resistance, disease pragmatism and yield growth are used in accurate breeding. In case of complex traits, it can be considered positively by AI. The algorithms to choose crops more quickly can be Deep Learning (DL) algorithms, which can find patterns of active gene expression that are suggestive of stress-tolerance in the genome and transcriptome data. The multi-dimensional multi-omics data cannot be discriminated in the other manner as it is in these models. Polygenic symptoms that are affected by multiple genes can be predicted using multi-omics data and the DL algorithms. Multi-omics, predictive modeling, and AI provide greater accuracy to farming (Ghotbaldini et al., 2019). AI may be used to evaluate multi-omics, environmental, and managerial information in order to make immediate decisions. The irrigation and fertilization could be handled in a manner that would avoid the waste of the resources and loss of productivity in the agricultural sector. Joint studies on the PBT are performed by countries, groups, and organizations. The blockchain open information ledger regulates access and information utilization, hence secure cooperation. Close information-sharing system is required to protect and approve proprietary information and to collaborate. Blockchain also helps to verify the identity of the user and safeguard confidential information. The research will be able to restrict the data utilization and encourage data creators using blockchain smart contracts (Mohammadabadi et al., 2024a). Decentralization architecture prevents data abuse and enhances confidence amongst the stakeholders in the agricultural enhancement research. Data analysts, agronomists, plant researchers, and engineers have to work together to enhance the productivity of agriculture through statistical analysis. Technical, biological and efficient prediction models depend on multidomain input. Plant and data scientists utilize agriculture and computational skills. Physiological systems necessitate knowledge from crop biological, genetic, and environmental information supplied by plant researchers. Data analysts create complex predictive instruments employing machine learning, integrating data, and model development. Farmers and scientists can create accessible, customized prediction tools. This partnership allows producers and agronomists to use predictive analytics for the data-driven management of crops. Multidisciplinary teams must transform complex forecasting models into ideas that improve productivity and ecology. Interdisciplinary research is crucial for addressing climate change in farming (Mohammadabadi et al., 2024b). Climate studies, genomics, information technology, and agricultural science enable teams to evaluate the impacts of climate on agriculture and develop adaptive methods for management. The models would allow breeders to create climate-resilient crops and aid farmers in adaptation.

Conclusion: The agricultural practice should also be sustainable to generate the increasing food demands of the world along with safeguarding the environment and securing crop yields in the future. In order to have good environment friendly to the climate, it is necessary to adopt modern methods of farming such as organic farming, crop rotation, conservation farming and integrated pest control. The diversity of soils is enhanced by such methods and crops are able to address issues that are a result of temperature and resources. Two of the most interesting biotechnological techniques that can cause plants to be less susceptible to stress and yield more food are genetic engineering and change. Precision farming and gardening technology assist in these activities since they optimize resource usage and crop management decisions with information about it. To make good use of these new ideas, researchers have to resolve social and legal dilemmas, make sure that everybody gets access to resources equally, and leave financial problems behind. Much work has already been done, but some of the issues are yet to be resolved. Some of these are the effects of climate change, the lack of resources, and the need for clear rules and market rewards. Many different types of people need to come together and think of new ways to solve these issues and promote gardening that is good for the earth. Researchers will need to look into more parts of hormone control in the future. They will also need to improve their predictions of crop hardiness and find new ways to use technology in farming. All these projects working together can help make farming stronger and better for the environment, so that future generations can have enough food and the environment will be safe.

Author Contribution

V. Ramesh Kumar conceptualized the study, supervised the manuscript structure, and coordinated the integration of biotechnological aspects, Subhaprada Dash contributed to the agricultural sustainability and crop management sections and validated agronomic data interpretations, Ranganathaswamy M. Kenchappa provided analytical support in the modeling of predictive and precision farming frameworks, Kanchan Awasthi contributed to data collection, literature review, and manuscript editing, Takveer Singh supported methodological validation and figure development, Lovish Dhingra contributed to reference management, formatting, and statistical data visualization, and Umesh Daivagna contributed to the synthesis of interdisciplinary insights and the final manuscript revision.

Data Availability Statement

All data supporting the findings of this study are available within the article and its referenced materials. Additional datasets generated or analysed during the current study are available from the corresponding author upon reasonable request.

Acknowledgements

The authors express their sincere gratitude to all individuals and organizations who provided valuable guidance, technical assistance, and access to research resources that supported this study. Special appreciation is extended to the peer reviewers and colleagues whose constructive feedback helped enhance the clarity, accuracy, and overall quality of this manuscript.

Ethical Considerations

This study did not involve human participants or animals. Ethical principles were followed throughout the literature review and data collection processes, ensuring proper attribution, transparency, and compliance with institutional ethical standards.

Funding

This study did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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مجله بیوتکنولوژی کشاورزی
انجمن بیوتکنولوژی ایران
دانشگاه شهید باهنر کرمان
شاپا چاپی: ۶۷۰۵-۲۲۲۸ شاپا الکترونیکی: ۶۵۰۰-۲۲۲۸

پیشبرد تاب‌آوری اقلیم‌محور محصولات کشاورزی از طریق زیست‌فناوری گیاهی برای کشاورزی پایدار

وی. رامش کومار

*نویسنده مسئول: دانشیار، گروه زیست‌فناوری، مؤسسه علوم و فناوری ساتیاباما، چنای، تامیل نادو، هند. ایمیل: rameshkumar.biotech@sathyabama.ac.in

سوبه‌پرادا داش

دانشیار، گروه زراعت، دانشکده علوم کشاورزی، دانشگاه شکشا 'او' انوشاندان، بوبانسوار، اودیشا، هند. ایمیل: subhapradadash@soa.ac.in

رانگاناتهاسوامی مادیهالی کِنچاپا

دانشیار، گروه مهندسی مکانیک، دانشکده مهندسی و فناوری، دانشگاه جِین، منطقه راما نگارا، کارناتاکا، هند. ایمیل: mk.ranganatha@jainuniversity.ac.in

کانچان آواشتی

دانشیار، گروه علوم، دانشگاه فناوری اطلاعات ماهارشی، لکهنو، اوتار پرادش، هند. ایمیل: kanchan.awasthi@muit.in

تاکویر سینگ

مرکز تأثیر و نتایج پژوهش، دانشگاه چیتکارا، راجپورا، پنجاب، هند. ایمیل: takveer.singh.orp@chitkara.edu.in

لوویش دینگرا

مرکز پژوهش و توسعه چیتکارا، دانشگاه چیتکارا، هیماچال پرادش، هند. ایمیل: lovish.dhingra.orp@chitkara.edu.in

اومِش دایواگنا

استاد، ISME، دانشگاه اطلس اسکیل‌تک، بمبئی، هند. ایمیل: umesh.daivagna@atlasuniversity.edu.in :

تاریخ دریافت: ۱۴۰۴/۰۶/۲۹ تاریخ دریافت فایل اصلاح شده نهایی: ۱۴۰۴/۰۹/۱۴ تاریخ پذیرش: ۱۴۰۴/۰۹/۱۵

چکیده

هدف: این مقاله درباره چگونگی استفاده از زیست‌فناوری نوین گیاهی برای افزایش تاب‌آوری محصولات در برابر تغییرات اقلیمی و فشارهای محیطی بحث می‌کند. تمرکز آن بر ایجاد مدل‌های پایدار برای افزایش بهره‌وری کشاورزی و امنیت غذایی از طریق یکپارچه‌سازی داده‌های ژنتیکی، مولکولی و زراعی است. با توجه به محدودیت روش‌های سنتی اصلاح نباتات در بهبود مقاومت و پایداری عملکرد محصولات، این مرور نشان می‌دهد چگونه می‌توان از زیست‌فناوری برای ارتقای تاب‌آوری محصولات در برابر تغییرات اقلیمی استفاده کرد.

مواد و روش‌ها: روش‌شناسی این مطالعه بر پایه یک مرور سیستماتیک و تحلیل ترکیبی مقالات داوری‌شده منتشرشده بین سال‌های ۲۰۱۵ تا ۲۰۲۵ است. اطلاعات از پایگاه‌های علمی معتبر شامل Scopus، Web of Science و PubMed گردآوری شد. این مرور شامل یافته‌های آزمایش‌های اخیر در ویرایش ژنومیCRISPR/Cas9) ، (TALENs، تحقیقات محصولات تراریخت و مدل‌های یکپارچه مولکولی است. تغییرات ژنی که سبب افزایش تحمل تنش‌های زیستی و غیرزیستی، پایداری عملکرد و بهره‌وری غذایی شده‌اند مقایسه و تحلیل شدند.

نتایج: نتایج نشان می‌دهند که پیشرفت‌های زیست‌فناورانه به‌شکل قابل توجهی انعطاف‌پذیری و عملکرد محصولات کشاورزی را بهبود داده‌اند. ابزارهای ویرایش ژنوم، به‌ویژه CRISPR/Cas9، امکان ایجاد تغییرات دقیق در ژن‌های مرتبط با تنش‌های بیماری‌زا را فراهم کرده‌اند و این امر موجب افزایش تحمل به خشکی، گرما و آفات در محصولات اساسی مانند برنج، ذرت و سویا شده است. همچنین، رویکرد ترکیبی اومیکس-هوش مصنوعی در مدل‌سازی محصولات، توسعه مدل‌های پیش‌بینی‌کننده بهره‌وری پایدار و استفاده بهینه از منابع را بهبود بخشیده است. هم‌افزایی نوآوری‌های زیست‌فناورانه با روش‌های کشاورزی پایدار مانند آبیاری دقیق و بهبود میکروبیوم خاک نیز به کاهش اثرات زیست‌محیطی کمک کرده است.

نتیجه‌گیری: این مقاله نشان می‌دهد که چگونه زیست‌فناوری می‌تواند آینده کشاورزی را متحول کرده و مسیری پایدار، اخلاقی و فراگیر برای تولیدات کشاورزی فراهم سازد. برای دستیابی به اهداف امنیت غذایی جهانی بدون آسیب به یکپارچگی اکوسیستم، سرمایه‌گذاری بیشتر در ویرایش دقیق ژن، مدل‌سازی بیوانفورماتیکی و فناوری‌های مبتنی بر پایداری ضروری است.

کلمات کلیدی: پایداری اقلیم‌محور، تاب‌آوری، کشاورزی، زیست‌فناوری گیاهی

نوع مقاله: مروری

استناد: وی. رامش کومار، سوبه‌پرادا داش، رانگاناتهاسوامی مادیهالی کِنچاپا، کانچان آواشتی، تاکویر سینگ، لوویش دینگرا، اومِش دایواگنا (۱۴۰۵) پیشبرد تاب‌آوری اقلیم‌محور محصولات کشاورزی از طریق زیست‌فناوری گیاهی برای کشاورزی پایدار. *مجله بیوتکنولوژی کشاورزی*، ۱۸(۱)، ۳۶۳-۳۸۰.

Publisher: Shahid Bahonar University of Kerman & Iranian Biotechnology Society.