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REVIEW ARTICLE

Artificial intelligence and tissue culture: Transforming rice regeneration systems

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ABSTRACT

The enhancement of rice through genetic means is important to solving food security concerns due primarily to its status as the main source of nutrition for more than half of the people living in the world today. Plant tissue culture has been used for many decades for regenerating and transforming rice; however, the method has had issues due to limitations such as plant genotype dependency, poor media compositions, and high variability in plant responses that regenerate through tissue culture. These limitations have been documented by previous studies which have stated that there is a need for improved methods of accurately regenerating crops. Recently, artificial intelligence (AI) has been incorporated into plant biotechnology as a new technology with the ability to assist scientists in developing data-based solutions to improve complex biological systems, such as crop regeneration. This mini review will focus on the application of AI to enhance the regeneration of rice via tissue culture and discuss how the optimisation of culture conditions, the use of predictive models, automating monitoring and smart systems will all result in increased rates of crop regeneration and increased levels of predictability with experimentation. AI will fundamentally change the field of rice biotechnology by increasing reproducibility, and accelerating the improvement of crops enhanced through genetic engineering.

KEY WORDS

Culture condition optimization; Predictive modeling; Genetic engineering; Crop regeneration; Artificial intelligence (AI); Rice tissue culture

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Introduction

Globally, rice (Oryza sativa L.) is one of the most important staple crops. Over half of the world's population (mainly in Asia and parts of Africa) derives its major source of calories from this crop [1]. The socio-economic importance and nutritional value of rice position it at the heart of global food security and agricultural sustainability. Rice production is under pressure from increasing population, climate change, and decreasing arable land; therefore, increasing the productivity and resilience of rice will be a top priority for scientists [2]. Although conventional breeding methods are beneficial for increasing productivity, they are often slow and cannot effectively address complex traits, such as stress tolerance, disease resistance, and yield stability [3]. As a result, plant tissue culture and other forms of biotechnological intervention are increasingly being used as critical means by which scientists can rapidly improve crops.

The revolution of rice biotechnology by plant tissue culture techniques allows for controlled production via in vitro regeneration; genetic transformation; rapid production of elite genotypes [4]. Techniques such as the induction of callus, somatic embryogenesis, organogenesis, etc., are used commonly for the production of transgenic or improved varieties of rice. These methods can assist in the introduction of desirable traits such as tolerance to abiotic pressures (e.g., drought, salinity) and resistance to biotic pressures (e.g., pests, disease). Also, tissue culture is important for the production of doubled haploids, germplasm conservation, and mutation breeding. However, there are numerous technical and biological challenges associated with the application of tissue culture in rice production that results in inefficiencies and lack of reproducibility [5].

Conventional rice tissue culture systems are very dependent on genotype; each rice genotype responds differently to in vitro culture, and thus each genotype has varying levels of callus formation and plant regeneration through tissue culture techniques. Because of this genotypic response variation, to achieve optimum callus formation and plant regeneration, it will be necessary to extensively optimize the culture media for each rice genotype by testing many variations of the media (e.g., plant growth regulators, carbon sources, and micro nutrients). Trial and error is a common method of optimizing a given rice genotype for tissue culture and is an extremely time-consuming and labor intensive process and often results in suboptimal callus production and/or regeneration. In addition, other issues, such as somaclonal variation, contamination, and low plant regeneration efficiency, further complicate rice tissue culture [6]. Finally, there are no consistently used "standard" protocols, and biological systems are complex, making it difficult to reliably obtain consistent results and thus limiting the use of tissue culture-based technology for use in large-scale rice improvement breeding programs.

In recent times, digitisation in farming has created many opportunities to solve the problems faced by farmers [7]. Technology has advanced rapidly and, as a result, AI is one area

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that will significantly affect agriculture and biotechnology methods in the years to come [8]. The different types of computer techniques for AI include; machine learning, deep learning, artificial neural networks, and computer vision. These allow computers to learn about datasets themselves, detect trends within them and create predictions based upon them that require very little input or participation from humans [9].

Today's world has a great deal of research performed on using AI for optimising experimental outcomes and predicting how plants will behave under certain circumstances and streamlining and automating complicated procedures in plant biotechnology [10]. AI has become increasingly viable as a way to deal with this multifactorial issue in plant tissue culture systems.
AI is quickly becoming an emerging tool in plant tissue culture due to its demonstrated ability to increase efficiency and accuracy based on many studies completed to date [11]. The use of machine learning algorithms to evaluate the large datasets produced from tissue culture studies enables researchers to identify the optimal growth regulator/environmental attribute combinations. Artificial neural networks, for example, have been effective in predicting the rates of callus formation and shoot regeneration based on input variables such as hormone volume and explant type [12]. Computer vision technologies have also been used to monitor in vitro cultures and provide real-time detection of contamination as well as accurate determination of growth stages [13]. These types of advancements reduce the need for human observation while increasing the repeatability and scalability of these types of processes.

Although there has been much progress in the field of artificial intelligence and its potential for rice tissue culture, the use of AI technology for this area is still relatively uncharted territory [14]. To date, the vast majority of studies conducted on this subject have centred on model plants or other high-value horticultural crops with little to no attention being paid to staple cereal crops, such as rice. Further, the vast majority of previous research has not addressed the integration of AI technologies into traditional tissue culture protocols [15]. Therefore, additional research must be performed in order to determine how AI may be effectively used to solve these unique issues associated with rice germplasm regeneration. More specifically, there is a need for improved models for predicting results, better quality datasets, and more user-friendly interfaces that will enable researchers and practitioners to apply AI technologies in various locations [16].

The primary hypothesis of this review is that the integration of AI with plant tissue culture can considerably enhance the efficiency, accuracy, and reproducibility of rice regeneration systems [17]. By leveraging data-driven approaches, it is possible to minimize experimental variability, optimize culture conditions, and accelerate the development of advanced rice varieties. The potential benefits of such integration extend beyond increased productivity, encompassing reduced costs, improved resource utilization, and enhanced scalability of biotechnological interventions. Furthermore, AI-driven automation can facilitate high-throughput screening and real-time decision-making, thereby transforming conventional laboratory practices into more advanced and intelligent systems [5].

In this context, the present mini review aims to explore the role of Artificial Intelligence in transforming rice tissue culture and regeneration systems [8]. It seeks to synthesize recent advancements, identify key challenges, and highlight future opportunities for integrating AI into plant biotechnology. By examining the intersection of computational intelligence and biological systems, this review provides insights into how emerging technologies can address longstanding limitations in rice tissue culture [12]. Ultimately, understanding and harnessing the potential of AI in this domain could contribute significantly to sustainable crop improvement and global food security.

Overview of Rice Tissue Culture Systems

Conventional techniques

Plant tissue culture in rice (Oryza sativa L.) is a well-established platform for genetic improvement, regeneration, and large-scale propagation. The success of these systems relies on plant cells' ability to exhibit totipotency under controlled in vitro conditions [13]. Among the various approaches, callus induction, shoot regeneration, and somatic embryogenesis are the most widely employed techniques.

Callus induction

Callus induction is the initial and critical step in rice tissue culture, involving the dedifferentiation of explant tissues such as mature embryos, immature embryos, seeds, or leaf bases into an unorganized mass of cells [18]. This process is typically induced using auxin-rich media, particularly with 2,4-dichlorophenoxyacetic acid (2,4-D). The quality and type of callus formed embryogenic or non-embryogenic—significantly influence subsequent regeneration efficiency [19]. Embryogenic calli are compact, nodular, and capable of regenerating into whole plants, whereas non-embryogenic calli are often friable and less competent. Factors such as explant type, genotype, medium composition, and culture conditions (light, temperature, and pH) play crucial roles in determining the success of callus induction.

Shoot regeneration

After the callus has been formed, the cells of the callus must re-differentiate into new shoot structures [20]. This change from an auxin dominated culture medium to a cytokinin based medium must occur (usually with BAP or kinetin) for shoot regeneration to occur. The physiological state of the callus and the culture environment will significantly affect the capability of shoot regeneration; thus, it is important to have optimal shoot regeneration protocols established because this is one of the key bottlenecks to achieving complete plants from tissue culture systems. Shoot regeneration may occur via direct organogenesis from the callus or via an indirect pathway through the formation of an intermediate structure [21]. Low shoot induction rates will greatly limit the overall success of tissue culture systems.

Somatic embryogenesis

Somatic embryogenesis is an alternate regeneration pathway in which somatic cells develop into embryo-like structures that can give rise to complete plants [22]. This process mimics zygotic embryogenesis and is particularly valuable for large-scale propagation and genetic transformation studies. In rice, somatic embryos are typically induced from embryogenic calli under specific hormonal and environmental conditions [22]. These embryos pass through distinct developmental stages—globular, scutellar, and coleoptilar—before germinating into plantlets. Somatic embryogenesis offers advantages such as higher multiplication rates and uniformity; however, its efficiency is often limited by genotype and culture conditions [23].

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Challenges

Despite the significant advancements in rice tissue culture, several challenges continue to limit its efficiency, reproducibility, and scalability [24].

Genotype specificity

The genotype dependency of rice tissue culture is a substantial constraint. Varietal differences in response to in vitro conditions introduce inconsistencies in the induction of callus, establishment of embryogenic cultures, and regeneration. In particular, indica varieties resist callus induction and regeneration with greater difficulty than japonica varieties [25]. Therefore, developing specific protocols for each variety adds complexity and length to the period of optimization.

Contamination

Microbial contamination has been a common problem in all types of tissue culture systems from bacteria, fungi and even already present contaminants to the explants themselves [26]. Microbial contamination has a significant effect on both the culture's viability and the outcome of the experiment making it hard to repeat the experiment in the same way. In order to keep sterile conditions, one must use strict sterilization methods, maintain a controlled environment, and continually monitor the tissue cultures, which requires a lot of money and time.

Contamination

A further major limitation is what has been referred to as low and variable rates of regeneration when generating new plantlets from callus tissue. Although callus induction may occur easily, the successful conversion of callus to healthy, mature plantlets continues to be difficult [20]. Many different factors influence callus conversion rate such as callus quality, sub-culturing durations, and hormone imbalances, which can greatly influence the capability to regenerate plants. Such limitations have limited the practical use of tissue culture for producing new crops for breeding and transformation programs.

Hormonal Imbalance

The tissue culture success rate is closely related to the right combination of auxins and cytokinins in plant growth regulators [27]. This amounts to a precise level of each hormone in tissue culture, where even slight changes (in concentrations) in either hormone can lead to a dramatic change in development responses. For example, if there is an increased level of auxin relative to cytokinin, tissues may exhibit abnormal growth, decreased regrowth, or too much callus without differentiation or normal tissue formation [21-24]. Determining the right hormonal ratios is often difficult because of how the growth regulators' complex interactions are influenced by genotype response variability.

Artificial Intelligence in Plant Tissue Culture

AI techniques used

Plant tissue culture has benefitted significantly from the capabilities that Artificial Intelligence (AI) now provides [28]. Machine Learning (ML) is another example of a superior method to optimize complex biological systems via data-driven decisions, where analysis of experimental datasets allows for pattern recognition and predictions of callus induction or regeneration efficiency and similar biological outcomes. At the next level, Deep Learning (DL) allows for the implementation of multi-layered models that are capable of processing higher dimensions of data, particularly images, to assess the performance of in vitro cultures [14-16]. With artificial neural networks (ANNs) acting as mathematical models of the functioning of biological neural networks, ANNs are a widely used tool in providing models for demonstrating non-linear dependencies between culture variables (e.g., hormones) and growth response(s). Additionally, computer vision techniques provide ways to automate the monitoring of in vitro cultures through analysis of their visual data, reducing the need for manual visual inspection and increasing accuracy.

The article by Chowhan S *et al.*, examined the effects of planting on the development and production of five modern rice varieties with the objective of identifying appropriate cultivars to use in late T [15]. Boro seasons in 2000 and 2001. The experimental cultivars were BR23, BRRI dhan33, BRRI dhan37, BRRI dhan38 and BRRI dhan39. Results showed that transplanting during the month of August was very risky because of the tidal water pressure which often led to loss of crops. The early September transplantation was the most suitable one to produce more grains. In particular, BR23, BRRI dhan37, and BRRI dhan38 were transplantable to the fourth week of September with yields of about 3 t ha -1 in the southern, tidal, non-salty areas of Bangladesh.

Applications in plant science

Rapid advancements in artificial intelligence (AI) technologies will expand the applications for tissue culture of plant tissue. Growth prediction models allow researchers to make predictions on the expected regenerative success of a culture based on various variables, eliminating the numerous trials needed to determine the results of tissue culture. With the aid of computer vision and deep learning algorithms, real-time monitoring of culture occurrence foreshadowing contaminations, callus types, and containing the current growth state during development can now be performed by utilizing image analysis [21]. AI-based optimizations for culture conditions assist in the determination of the best combinations of nutrients, plant growth regulators, and environmental factors, providing reproducibility and enhancement of the efficiency of tissue culture. All these applications indicate that AI has the potential to modify the current processes within plant tissue culture, creating a much more accurate, scalable, and automated system.

Integration of Artificial Intelligence in Rice Regeneration Systems

Optimization of culture media

Optimizing culture media is essential for successfully regenerating rice; therefore, the application of Artificial Intelligence (AI) is an excellent method to improve this [28]. AI can use models, such as machine learning and artificial neural networks, to analyze multiple complex datasets and create predictions of the best combinations of plant growth regulators, including auxins and cytokinins. AI can identify exact ratios of hormones for different genotypes while reducing the need for empirical trial-and-error experiments. Nutritional optimization is possible by modeling how macro- and micronutrients interact with carbon sources and other respect to their environmental conditions [22]. The predictive ability of these models makes it possible to create customized media formulations that improve callus formation, increase the efficiency of rice regeneration, and reduce costs and the use of resources.

Callus induction and shoot regeneration

Using AI to build predictive models has a considerable impact on achieving improvements in both callus induction and shoot regeneration methods. By analyzing past experimental results using AI algorithms, researchers have the capability to predict the likelihood of a successful callus forming and a resulting

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shoot being formed under set conditions based on their previous success rate [18]. This will allow them to choose the best conditions to use before starting their experiment, which should reduce the number of experimental attempts they will need to make. In addition to what was mentioned above, AI models can identify which parameters such as explant types, genotypes, and duration of time in culture affect how efficiently regenerating occurs. Therefore, incorporating AI into the rice tissue culture system creates outcomes that are more reliable and reproducible.

Image-based monitoring

Image-based monitoring, enabled by computer vision and deep learning, has transformed the way in vitro cultures are observed and managed. AI systems can automatically detect contamination at early stages by analyzing visual patterns, thereby preventing culture loss and improving laboratory efficiency [5,17]. In addition, these systems can classify callus types and identify different growth stages with high accuracy. Real-time monitoring reduces the need for manual inspection, enhances precision, and supports data collection for further model refinement.

Automation and robotics

Smart tissue culture systems, which combine AI with automation and robotics, have been developed to facilitate automated culture processing (such as media preparation, subculturing and environmental control). AI-powered high-throughput screening platforms allow for the simultaneous assessment of multiple treatment conditions and therefore can greatly speed up experimental workflows [13]. These developments will lead to more scalable systems, insuring greater consistency and reproducibility, and will provide the foundation for next-generation rice regeneration systems.

Case Studies and Recent Advancements

The increasing adoption of artificial intelligence (AI) within rice tissue culture systems supports the significant strides that have been made in utilizing AI to model the in vitro responses of rice tissue. Many studies conducted over the last 5-7 years have engaged machine learning and artificial neural networks to model and optimise responses in vitro. AI predictive models have been used to determine the best dose of plant growth regulators to induce callus or regenerate shoots resulting in much higher success rates relative to traditional empirical approaches [28]. There are also studies where ANN models were able to predict regeneration outcomes with a higher accuracy than traditional statistical methods therefore will allow for more targeted experimentation.

In comparative studies, AI-assisted cultures have been shown to be more efficient and consistent than traditional tissue culture techniques. Whereas traditional tissue culture methods rely on numerous iterations to achieve success through trial and error, AI-based systems are able to use past data to forecast optimal conditions in order to limit the number of experiments needed.

The most recent studies of tissue cultures have demonstrated how computer vision and deep learning can also be employed for the automated classification of embryogenic and non-embryogenic callus, resulting in more accurate selections and minimizing human bias.

Additional studies also show the use of high-throughput screening platforms integrated with AI capabilities that evaluate many different variables simultaneously (such as genotype, hormone combinations, and environmental conditions) [29].

Collectively, these findings demonstrate how AI improves both the efficiency of tissue culture regeneration and the overall tissue culture workflow for rice production by making the tissue culture processes easier to implement and duplicate at a large scale.

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Advantages of AI in Rice Tissue Culture

The integration of Artificial Intelligence into rice tissue culture offers several significant advantages over traditional methodologies.

Increased efficiency

AI enables rapid optimization of culture conditions by analyzing large datasets and identifying optimal parameters, thereby enhancing regeneration success rates and reducing experimental iterations.

Reduced cost and time

By minimizing trial-and-error experimentation, AI significantly lowers resource consumption, including reagents, labor, and time. This is particularly beneficial for large-scale research and commercial applications.

Precision and reproducibility

AI-driven models provide precise predictions and standardized protocols, reducing variability associated with manual techniques. This leads to more consistent and reproducible outcomes across different experiments and laboratories.

Data-driven decision making

AI facilitates informed decision-making by leveraging data analytics and predictive modeling. Researchers can make evidence-based adjustments to culture conditions, improving overall experimental design and success.

Table 1. AI advantages in rice tissue culture (2018–2023 data)

Advantage	Study / Year	Type of AI Used	Key Quantitative Findings	Implication for Rice Tissue Culture
Increased Efficiency	Aasim et al., 2022	ML (Random Forest, ANN, XGBoost)	Prediction accuracy up to 98–100% (F1 score)	Highly efficient optimization of culture conditions; reduces failed experiments
	Hesami et al., 2019–2021 (reviewed in 2022 study)	ANN models	Imssproved prediction of regeneration & growth parameters	Faster identification of optimal media and hormone combinations
	Malabadi et al., 2023	ML + RSM		Minimizes trial-and-error, lowering reagent and labor costs
Reduced Cost & Time	Malabadi et al., 2023			
	Nikita et al., 2023	AI bioreactors	Improved reproducibility and success rates of organogenesis	Cost-effective large-scale rice micropropagation
	Ali & Aasim, 2024 (based on 2023 data trends)	ML + predictive modeling		Standardized protocols for consistent rice regeneration

Precision & Reproducibility	Murthy et al., 2024 (experimental data 2023 base)	AI-controlled bioreactors	~30% increase in metabolite production	Demonstrates reproducible and optimized culture conditions
Data-Driven Decision Making	Williamson et al., 2023	AI data analytics	AI enables large-scale biological data interpretation	Supports evidence-based optimization of tissue culture systems
	Özcan et al., 2023	ML modeling	Identification of key influencing factors automatically	Helps refine experimental design and improve success rates

Limitations and Challenges

Although AI has the ability to significantly change how rice tissue cultures are done there are still numerous limits that prohibit it from becoming widely accepted. One of the major challenges in developing AI models is the unavailability of large amounts of quality data to properly train the model that produces good predictive models [30].

Tissue Culture experiments are usually done using very small sample sizes or the data generated is highly variable and does not follow a standard protocol, as well as there is a lot of variability among laboratories, thus making the data used to train the models not reliable and unable to be generalized.

Another concern with using AI tools in tissue cultures to develop rice varieties is that the implementation of AI is very complex and requires a variety of different techniques from different fields of study, such as Plant Biotechnology, Data Science, and Computational Modeling, thus preventing researchers that may not have received training in the advanced analytical techniques from being able to use these tools.

Another constraint on the use of AI tools in rice tissue cultures is the high initial cost of the tools themselves, thus prohibiting many research laboratories in low-resource settings from being able to adopt these tools. The cost of building advanced computational infrastructures, imaging equipment, automation solutions, and proprietary software solutions is very high thus preventing many institutions from using these advanced technologies.

Additionally, integration issues in developing regions pose practical concerns. Limited access to digital infrastructure, inconsistent power supply, and lack of technical support can impede the seamless incorporation of AI-based systems into existing workflows. These challenges highlight the need for cost-effective, user-friendly, and scalable solutions to ensure broader applicability.

Future Perspectives

The fusion of Artificial Intelligence alongside cutting-edge biotechnology empowers additional advantages for the future of rice tissue culture. For example, AI integration with CRISPR genome editing provides AI assistance with target identification, designing the guides for genome editing, and using prediction models for genomic editing outcomes; thus, providing greater accuracy for possible improvements for crops [31].

Another key trend developing is the creation of smart laboratories (Lab 4.0), in which AI, Automation, and the rapidly expanding Internet of Things (IoT) technologies are combined to develop fully integrated, self-functioning laboratory systems capable of optimizing working conditions based on real-time information about the experiment being conducted. The efficiencies created from smart laboratory use will improve reproducibility and scalability.

The most important technology supporting future tissue culture practices will be AI Real Time Monitoring Systems (RTMS) using computer vision to monitor the growth and contamination status continuously of the in vitro culture and dynamically adjust all environmental parameters of the culture to provide optimal growth conditions [32].

Furthermore, the application of AI-driven tissue culture is likely to expand beyond rice to other cereal crops such as wheat, maize, and barley, facilitating broader agricultural advancements. Overall, these developments indicate that AI will be instrumental in shaping next-generation plant biotechnology and sustainable crop production.

Conclusion

This mini review highlights the transformative potential of Artificial Intelligence (AI) in enhancing rice tissue culture and regeneration systems. Conventional tissue culture techniques, including callus induction, shoot regeneration, and somatic embryogenesis, have played a vital role in rice improvement; however, their effectiveness is often constrained by genotype dependency, low regeneration efficiency, contamination risks, and the need for extensive trial-and-error optimization. These limitations have restricted the scalability and reproducibility of tissue culture-based approaches in rice biotechnology.

The integration of AI offers a paradigm shift by introducing data-driven, predictive, and automated solutions to these challenges. AI techniques such as machine learning, deep learning, artificial neural networks, and computer vision enable precise optimization of culture media, accurate prediction of regeneration outcomes, and real-time monitoring of in vitro cultures. By reducing experimental variability and minimizing manual intervention, AI significantly improves efficiency, consistency, and reproducibility in rice regeneration systems. Moreover, AI-driven automation and high-throughput screening platforms accelerate experimental workflows, making the process more cost-effective and scalable.

Importantly, AI addresses the core limitations of traditional tissue culture by enabling informed decision-making based on complex datasets, thereby reducing dependency on empirical methods. This advancement not only enhances the success rate of regeneration but also supports the development of standardized protocols adaptable across different genotypes and laboratory conditions.

Looking ahead, the integration of AI with emerging technologies such as genome editing, smart laboratories, and real-time monitoring systems holds immense promise for revolutionizing rice biotechnology. Such advancements can accelerate the development of high-yielding, stress-tolerant, and climate-resilient rice varieties. Overall, the convergence of AI and plant tissue culture represents a significant step toward sustainable agricultural innovation and global food security.

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Disclosure Statement

No potential conflict of interest was reported by the authors.

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