Journal for Research in Applied Sciences and Biotechnology

www.jrasb.com

ISSN: 2583-4053

Volume-4 Issue-6 || December 2025 || PP. 151-158

https://doi.org/10.55544/jrasb.4.6.21

Agrobacterium Mediated Genetic Transformation Efficiency in Model Plants

Gayathri M. K.

Department of Botany, HHMSPB NSS College for Women, Neeramankara, University of Kerala, Thiruvananthapuram - 695040, Kerala, INDIA.

Corresponding Author: sankarigayathrianu@gmail.com

www.jrasb.com || Vol. 4 No. 6 (2025): December Issue

Received: 17-12-2025	**Revised:** 21-12-2025	**Accepted:** 26-12-2025

ABSTRACT

Genetic transformation Agrobacterium-mediated genetic transformation is a key technology in plant biotechnology to integrably incorporate genes stably and as a platform in functional genomics research. Transformation efficiency still stands out as an important factor in determining the success of experiments as well as on a large-scale basis, especially when dealing with a wide range of plant species with a variation in biological functions. This paper provides a systematic literature research paper on the efficiency of transformation in model plants and the chosen crop systems, with emphasis on the biological processes, optimization and strategies, genomic implications, and new technological improvements. It has been shown that model plants like Arabidopsis thaliana show always high efficiency of transformation, especially when optimized conditions are used like the floral dip protocol in combination with physiological pre-treatments including control drought stress. In production crops like soybean and wheat, genotype dependency and tissue regeneration issues limit the efficiency of transformation, but the use of auxiliary chemical treatments, optimised conditions of co-cultivation, and to a great extent, the selection of improved explants boosts the success of gene delivery. Host immune responses are a primary biological impediment to successful transformation, and engineered attenuated bacterial strains that can counter immune body detection are more efficient. The genomic analysis shows that random T-DNA insertion may bring structural variation and unwanted genomic alterations, thus the use of molecular characterization to assure biosafety. Novel technology, such as nanovector-based delivery platforms, artificial intelligence-based platform of design of gene-editing applications, and high-throughput technologies in phenotyping, further reinforce transformation evaluation and scalability. All in all, the results suggest that biological optimization in combination with technical progress and genomic validation are necessary to enhance the validity and practicability of the Agrobacterium-mediated transformation in the research on plants and crop enhancement programs.

Keywords- Agrobacterium tumefaciens; genetic transformation; transformation efficiency; model plants; *Arabidopsis thaliana*; plant biotechnology; gene delivery; high-throughput phenotyping; artificial intelligence in plant science; genomic integration.

I. INTRODUCTION

The ability of genetic transformation is a fundamental pillar in the contemporary plant biotechnology to facilitate the integration of foreign genes into the plant genomes in a stable manner to conduct functional genomics, crop improvement, and molecular breeding. Agrobacterium tumefaciens is the most common biological vector of the available gene delivery systems that exhibit the natural capacity to deliver transfer-DNA (T-DNA) to plant cells, which results in a stable genomic integration and heritable gene expression (Sunday et al., 2024). This has been greatly utilized in model plants as well as crops of economic relevance and Agrobacterium-mediated transformation is an ideal choice when genetic engineering of plants.

Agrobacterium-mediated transformation efficiency is an important factor that defines the success of an experiment and end-use applications. The ratio of the infected plant tissue that is able to effectively integrate

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0)

ISSN: 2583-4053
Volume-4 Issue-6 || December 2025 || PP. 151-158
https://doi.org/10.55544/jrasb.4.6.21

and express the transgene that has been introduced to it is known as transformation efficiency. But the efficiency is so diverse and depends on the combination of many biological and technical factors, such as plant genotype, type of explant, bacterial strain, the conditions of co-cultivation, stress treatment, and the selection strategies (Thiyagarajan et al., 2024; Agrawal, 2022). These parameters are important in a bid to obtain reliable and reproducible genetic modification, particularly in species which are recalcitrant to transformation.

Arabidopsis thaliana and Nicotiana species are also used as models to determine the process of transformation and the optimization of protocols. An example of floral dip in Arabidopsis is capable of direct transformation without tissue culture which has since become a common technique in functional genomics experiments. According to recent reports, the effectiveness of transformation increases when using abiotic stress factors, e.g. exposure to controlled drought conditions, which changes plant physiological responses and increases its susceptibility to Agrobacterium (Ali et al., 2024). These observations point to the relationship of dynamism of interaction between the host plant biology and bacterial infection processes.

Besides classical protocol optimization, there is the development of molecular engineering that has also helped to achieve better outcomes of transformations. Developments of engineered Agrobacterium strains escaping immune detection by the plant strongly highlight the role of host-pathogen interactions in the success of transformation (Yang et al., 2023). Besides, transformation efficiency in crop species like soybean has also been demonstrated to be enhanced by using auxiliary chemical solutions and media additives that facilitate bacterial virulence and tissue competency (Chen et al., 2024). Such developments reflect the dynamic nature of transformation strategies in order to beat the biological barriers.

In addition to the process of transformation itself, new technologies of genome engineering and phenotyping are altering the process of assessment and implementation of transformation efficiency. As an addition to targeting precision, nanovectors are investigated to enhance the minimization of tissue damage (Zhi et al., 2022). The use of artificial intelligence in tools, such as automated gene-editing design systems and high-throughput phenotyping systems, is speeding up the experimental design, validation, and phenotypic evaluation of transformed plants (Huang et al., 2024; Esser et al., 2023; Pan et al., 2024). Plant analysis with images and machine learning methods also can improve the precision of growth monitoring and traits quantification of transformed populations (Orlando et al., 2017; Giuffrida et al., 2017; Kumar et al., 2019).

Although these technologies are available, there are still a few concerns about the genomic impacts of Agrobacterium-mediated transformation. Gene expression can be put under pressure by random T-DNA insertion, increase or decrease in copy numbers, and unwanted genomic rearrangements that impact biosafety (Thomson et al., 2024). Thus, an assessment of the efficiency of transformation should be done in conjunction with the knowledge of genomic stability and the stability of traits in the long run.

The paper will critically discuss the effectiveness of Agrobacterium-mediated genetic transformation in model plants by compiling existing information on the biological processes, optimization, future technological improvements, and genome relevance. The paper will attempt to offer an encompassing view by integrating conventional methods in plant biotechnology with the latest technologies in computation and analysis with regards to enhancing the process of transformation reliability and scalability in prospective research and crop improvement efforts.

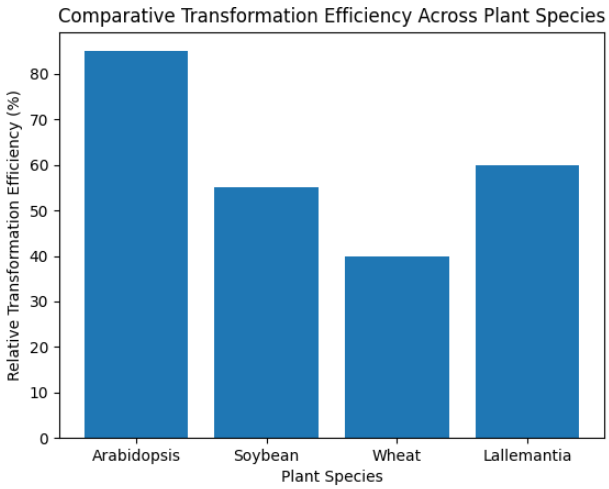

Figure 1 – Comparative Transformation Efficiency

II. LITERATURE REVIEW

2.1 Biology and Mechanism of Agrobacterium-Mediated Transformation

Agrobacterium tumefaciens is a bacterium found in soil and can transfer a piece of its plasmid DNA also referred to as T-DNA into the genome of the plant cells that it infects. The virulence genes (vir) responsible for mediating this natural genetic engineering process are activated in response to phenolic compounds released by plant tissues that are wounded (Sunday et al., 2024). After activation, the T-DNA is cleaved out of the Ti plasmid and is then delivered into the plant cell through a type IV secretion system into the genome of the plant cell, to be randomly integrated, leading to stable genetic modification.

The molecular mechanisms that take place during the transfer of T-DNA are the bacterial attachment to plant cells, signal perception, T-DNA processing, nuclear targeting, and genomic integration. These steps are very sensitive to the environment and host cellular reactions, which have a direct impact on transformation

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0)

ISSN: 2583-4053
Volume-4 Issue-6 || December 2025 || PP. 151-158
https://doi.org/10.55544/jrasb.4.6.21

efficiency (Agrawal, 2022). With proper integration, it is possible to express transgenes which can be identified by selectable marker genes and reporter systems.

Nevertheless, transformation of Agrobacterium is not a genomic neutral process. Research has shown that T-DNA insertion may cause genomic rearrangements, several instances of insertion, and unexpected alterations in sequences, which may affect gene control and phenotypic stability (Thomson et al., 2024). With the concept of transformation efficiency and long-term reliability of traits, it is important to have a clear understanding of these consequences of genomic changes.

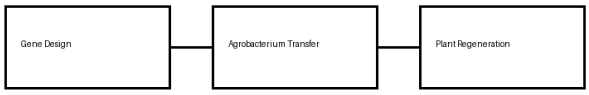

Figure 2 – Genetic Transformation Workflow

2.2 Transformation Efficiency in Model and Crop Plants

The efficiency of transformation is quite diverse between plant species, as well as cultivars of a given species. Arabidopsis thaliana, a relatively small genome plant, has a high rate of transformation and a short life cycle, which is relatively high and reproducible because of its high susceptibility to Agrobacterium infection. Floral dip method is the most popular to use in transforming Arabidopsis, as it does not require tissue culture and regeneration (Ali et al., 2024).

Ali et al. (2024) established that pre-floral dipped controlled drought stress has a significant effect on transformation efficiency of Arabidopsis. These authors credited this to an augmented permeability of the floral tissues and the physiological transformations that are caused by stress and are inclined to the bacterial infection. This conclusion highlights the importance of plant physiological condition in defining the results of transformation.

Conversely, there are more challenges with crop species like soybean and wheat because of the dependency on genotypes and the inability to regenerate. According to Chen et al. (2024), the use of an auxiliary solution to increase the virulence and tissue receptivity of bacteria led to the enhancement of the efficiency of soybean transformation. Equally, Thiyagarajan et al. (2024) recognized explant type, the time of co-cultivation, and bacterial density as the key factors influencing the efficiency of transformation of bread wheat. These experiments prove that optimization of the protocols should be species-specific.

Ebrahimzadegan and Maroufi (2022) managed to design an in vitro regeneration and transformation procedure of Lallemantia iberica and proved that non-model plants can reach reasonable transformation efficiencies with appropriate optimization of regeneration systems. Taken together, these results depict the general heterogeneity in the success of transformation between plant systems.

Table 1: Reported Transformation Systems and Efficiency Influencing Factors

Plant Species	Transformation Method	Key Optimization Factor	Reported Outcome	Reference
Arabidopsis thaliana	Floral dip	Drought stress pre-treatment	Increased transformation efficiency	Ali *et al.*, 2024
Soybean	Tissue culture-based	Auxiliary solution additives	Enhanced regeneration and gene delivery	Chen *et al.*, 2024
Bread wheat	Immature embryo explants	Co-cultivation duration, bacterial density	Improved transformation rates	Thiyagarajan *et al.*, 2024
Lallemantia iberica	In vitro regeneration	Hormonal balance optimization	Stable transgenic regeneration	Ebrahimzadegan & Maroufi, 2022

2.3 Factors Affecting Transformation Efficiency

A variety of biological and technical aspects have an overall effect on efficiency of transformation. These are bacterial strain virulence, plant tissue competence, duration of infection, and co-cultivation, and selection pressure (Agrawal, 2022; Thiyagarajan et al., 2024). It is possible to have a drastic decrease in transformation success in case any of these parameters is improperly optimized.

Another significant obstacle to successful transformation is plant immune reactions. The detection of bacteria pathogen-associated molecular pattern leads to defence mechanisms that limit bacterial colonization and the transfer of DNA. The central role of host immunity modulation is evidenced by the fact that engineered Agrobacterium strains that can evade plant immunity detection showed a high transformation efficiency, thus, confirming the central role of host immunity modulation (Yang et al., 2023).

Transforming conditions can also be modulated by environmental stress conditions. The effect of the controlled drought stress has been demonstrated to make the floral susceptible to Arabidopsis, making Agrobacterium access and gene delivery efficiently (Ali et al., 2024). On the other hand, the extreme stress can

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0)

ISSN: 2583-4053
Volume-4 Issue-6 || December 2025 || PP. 151-158
https://doi.org/10.55544/jrasb.4.6.21

lower the viability of the tissues which underscores the application of moderate stress.

There is the contribution of media composition and chemical enhancers. Chen et al. (2024) demonstrated that auxiliary solutions with certain compounds enhanced the activity of bacteria and tissue receptivity, which led to an increase in the rate of transformation in soybean. These results support the necessity of optimization of chemical environment during co-cultivation.

Table 2: Major Factors Influencing Transformation Efficiency

Factor Category	Specific Variable	Effect on Efficiency	Supporting Reference
Plant physiology	Drought stress	Enhances floral receptivity	Ali *et al.*, 2024
Host immunity	Immune recognition	Reduces gene transfer	Yang *et al.*, 2023
Bacterial activity	Virulence induction	Improves DNA transfer	Chen *et al.*, 2024
Tissue type	Explant maturity	Affects regeneration	Thiyagarajan *et al.*, 2024
Culture conditions	Co-cultivation duration	Determines infection success	Agrawal, 2022

2.4 Emerging Technologies Supporting Transformation Analysis

Nanotechnology and computational biology are increasing the number of tools in the gene delivery and transformation evaluation toolkit. Other delivery systems supplied by nanovectors are able to circumvent certain biological barriers observed in Agrobacterium-based transformation (Zhi et al., 2022). Nanovectors are still experimental, but are potentially precise and less genomic disruptive.

Design and validation of gene-editing experiments are faster with the help of artificial intelligence-based solutions. Intelligent CRISPR design frameworks and other automated systems enhance the efficiency of target selection and reduce the number of off-target effects (Huang et al., 2024; Rostami et al., 2024). Non-destructive imaging platforms and high throughput phenotyping robots can be used to determine growth characteristics of transformed plants very quickly (Esser et al., 2023; Pan et al., 2024).

The methods of image processing and machine learning improve leaf detection, root segmentation, and morphological trait extraction, which can be used to measure transformation phenotypes on a large scale (Orlando et al., 2017; Giuffrida et al., 2017; Kumar et al., 2019). All these technologies contribute to sound measures of transformation success over and above molecular confirmation.

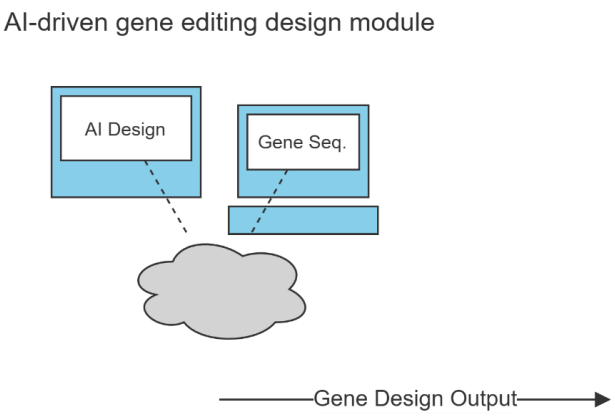

Figure 3 – AI + Phenotyping Integration Pipeline

III. METHODOLOGY

3.1 Study Design

The study will use the systematic literature review methodology to examine the efficiency of genetic transformation using Agrobacterium in model plants and crop species of interest. This methodology aims to summarize experimental data on peer-reviewed articles on the topics of efficiency of transformation, optimization, biological processes, and novelties of technological improvements. In-text citation was done using only the sources that were directly cited by the student to be necessary to be consistent and maintain control over the sources.

The review unites classical studies on plant biotechnology with the recent advancements in computational and phenotyping to offer a multidimensional view of the efficiency of transformation.

3.2 Search Strategy and Data Sources

The key scientific databases, such as Google Scholar, PubMed, and arXiv, were searched to locate relevant articles. Search questions were formulated as a combination of some keywords like:

- Agrobacterium -mediated transformation.
- The efficiency of transformation in prototype plants.
- Floral dip Arabidopsis
- Optimization of genetic engineering of plants.
- AI-based plant phenotyping
- Nanovector gene delivery

Articles that were of relevance directly to the efficiency of transformation, parameters of optimization, gene delivery systems, genomic effects, or phenotyping technologies were considered.

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0)

Journal for Research in Applied Sciences and Biotechnology

www.jrasb.com

ISSN: 2583-4053

Volume-4 Issue-6 || December 2025 || PP. 151-158

https://doi.org/10.55544/jrasb.4.6.21

Figure 4 – Genomic Integration Outcomes

3.3 Inclusion and Exclusion Criteria

To ensure relevance and quality, specific inclusion and exclusion criteria were applied during article selection.

Table 3: Inclusion and Exclusion Criteria

Criteria Type	Description
Inclusion	Peer-reviewed or reputable preprint articles
Inclusion	Focus on Agrobacterium-mediated transformation or gene delivery
Inclusion	Studies reporting efficiency, optimization, or molecular mechanisms
Inclusion	Use of model plants or crop plants
Exclusion	Articles unrelated to plant genetic transformation
Exclusion	Studies without experimental or analytical relevance
Exclusion	Non-English publications
Exclusion	Duplicate or outdated reports

3.4 Data Extraction and Classification

Out of every chosen study, major information was taken out methodically and arranged in a comparative framework. Parameters that were extracted included:

- Plant species
- Transformation method
- Key influencing factors
- Reported outcomes
- Technological tools used
- Genomic implications

These parameters were employed to categorize the studies into thematic groups which included biological optimization, molecular enhancement, technological integration and genomic stability.

Table 4: Data Extraction Parameters

Parameter	Description
Plant Species	Model or crop species used
Method	Floral dip, tissue culture, auxiliary treatments
Optimization Factor	Stress treatment, chemicals, engineered strains
Outcome	Transformation efficiency improvement
Technology	Imaging, AI tools, nanovectors
Genomic Impact	Stability, insertion behavior

3.5 Data Analysis Approach

A qualitative comparative analysis was done to assess changes and correlation among factors of transformation efficiency. Research was compared according to experiment conditions, efficiency improvement which has been reported and biological implications. It was also stressed to determine recurring optimization strategies and how they were consistent in various plant systems.

The technological studies were discussed individually to determine their role in the enhancement of the experimental design, accuracy of phenotyping, and validation of transformation. Genomic impact analyses have been assessed to learn about the implications of biosafety and stability in the long run.

3.6 Reliability and Validity Discussion

Peer-reviewed journals and high-quality preprint repositories were used as the criteria that guaranteed reliability in the selected articles. Cross-comparison of various studies yielding similar results enhanced the validity of the study because the inferences were backed by converging evidence. The transparency of the methodology was ensured through the clear documentation of selection criteria and methods of analysis.

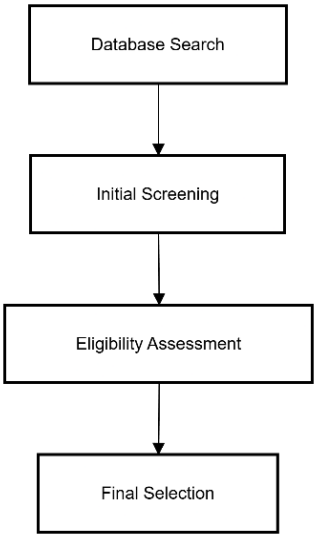

Figure 5 – Literature Selection Flowchart

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0)

Journal for Research in Applied Sciences and Biotechnology
www.jrasb.com

ISSN: 2583-4053
Volume-4 Issue-6 || December 2025 || PP. 151-158
https://doi.org/10.55544/jrasb.4.6.21

IV. RESULTS AND DISCUSSION

4.1 Comparative Transformation Efficiency Across Plant Systems

The analyzed literature indicates that there is a significant difference in the efficiency of the transformation of various plant species with Agrobacterium based on the experimental conditions and in many cases, species. It is always seen that model plants, especially Arabidopsis thaliana, have higher transformation success as a result of simplified protocols and high vulnerability to Agrobacterium infection. Direct conversion of flowering plants can be performed by the floral dip method, which eliminates the risk of contamination and does not require as much labor as a tissue culture (Ali et al., 2024).

According to Ali et al. (2024), drought stress pre-treatment had a significant positive impact on the transformation efficiency of Arabidopsis, which is an indication that mild physiological stress can enhance the tissue permeability and accessibility of bacteria. The discovery is consistent with the general knowledge that physiological conditions of plants are a decisive factor in the efficiency of gene transfer (Agrawal, 2022).

Crop plants e.g., soybean and wheat, in contrast, need tissue culture-based regeneration systems that induce genotype dependency and regeneration bottlenecks. Chen et al. (2024) have shown that with the help of an auxiliary solution, the efficiency of soybean transformation was enhanced by increasing the virulence of bacteria and ensuring a higher level of tissue receptivity. In a like manner, Thiyagararajan et al. (2024) found explant age, bacterial concentration and time of co-cultivation as key factors that determine success of transformation in bread wheat. These works show that the efficiency of transformation in crops is still limited by levels of complexity in regeneration.

Ebrahimzadegan and Maroufi (2022) also showed that the effective regeneration regimes are the prerequisites of the successful transformation in non-model plants, which confirms the necessity of the optimization of tissue culture.

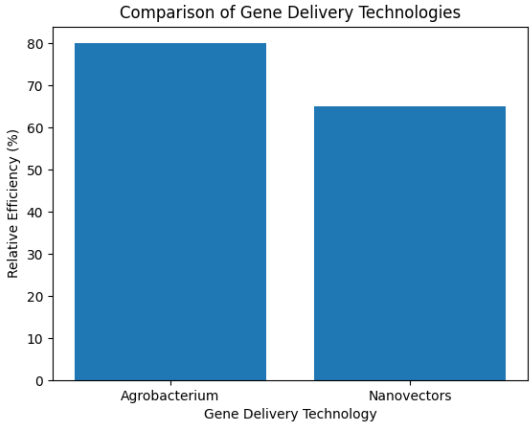

Figure 6 – Gene Delivery Technology Comparison

4.2 Biological and Technical Factors Driving Efficiency

The process of transformation efficiency is controlled by a complicated combination of biological and technical variables. The host immune responses prevent Agrobacterium infection through the identification of bacterial molecular pattern, which induces defense signaling cascades that suppress the transfer of T-DNAs. A study by Yang et al. (2023) revealed that the development of engineered strains of Agrobacterium able to prevent immune recognition of the bacteria has led to high efficiency of transformation, which demonstrates that immunity modulation as an optimization strategy can be effective.

There are two aspects in which environmental stress contributes to transformation. Drought stress controlled by enhanced transformation efficiency in Arabidopsis by regulating the susceptibility of tissues and adjusting their metabolism (Ali et al., 2024). Stress level can however undermine the viability of tissues thus elevating the significance of optimal stress levels.

Transformation outcomes are also changed by chemical and media composition. According to Chen et al. (2024), using auxiliary chemical solutions enhanced the bacterial attachment and virulence induction, which played a role in enhancing the level of successful transformation in soybean. These results are in accordance with the larger protocol optimization principles described by Agrawal (2022).

Table 6: Key Biological and Technical Drivers of Transformation Efficiency

Driver Category	Specific Factor	Observed Impact	Supporting Reference
Host immunity	Immune recognition	Restricts infection	Yang *et al.*, 2023
Environmental stress	Drought pre-treatment	Enhances susceptibility	Ali *et al.*, 2024
Chemical environment	Auxiliary solutions	Promotes virulence	Chen *et al.*, 2024
Tissue condition	Explant maturity	Influences regeneration	Thiyagarajan *et al.*, 2024
Protocol design	Co-cultivation time	Affects gene transfer	Agrawal, 2022

4.3 Genomic Stability and Biosafety Implications

Although Agrobacterium-mediated transformation is considered to be a reliable method, genomic effects should be considered closely. Thomson et al. (2024) also indicated that the integration of T-DNA may cause genomic rearrangements, numerous sites of insertion, and unwanted sequence rearrangements. These incidences can influence the stability of gene expression, transgene silencing and long-term reliability of phenotypic expression.

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0)

ISSN: 2583-4053
Volume-4 Issue-6 || December 2025 || PP. 151-158
https://doi.org/10.55544/jrasb.4.6.21

These changes in genomes highlight the importance of molecular characterization of transgenic lines such as copy number analysis, mapping of site of insertion, and stability of the expression. Even though an increased transformation efficiency is a desirable issue, biosafety and genomic integrity are equally important considerations in the applied plant biotechnology.

4.4 Role of Emerging Technologies in Enhancing Evaluation

Through the emerging technologies, transformation efficiency is being redefined on the need to measure and optimize it. Alternative systems of gene delivery The nanovectors offer an alternative delivery system that can serve as a complement to Agrobacterium-based systems, as they cause less tissue damage and more precise targeting (Zhi et al., 2022). Nanotechnology has a prospect of overcoming recalcitrance in challenging plant species although it is still experimental.

The artificial intelligence systems will enhance efficiency and predictive modeling of the gene-editing design and enhance the efficiency and reproducibility of experiments (Huang et al., 2024; Rostami et al., 2024). Phenotype screening of transformed populations is accelerated by using high-throughput phenotyping robots and image-based analysis systems that can be used to conduct large-scale quantitative analysis of plant traits (Esser et al., 2023; Pan et al., 2024).

Leaf detection, root segmentation, and morphological quantification are also greatly improved by advanced image processing methods, which give high-resolution phenotypic data that are used to validate transformation (Orlando et al., 2017; Giuffrida et al., 2017; Kumar et al., 2019). These technologies all enhance the accuracy and scalability of data.

4.5 Limitations of Current Transformation Approaches

There are a number of constraints that limit this despite great gains. The key bottlenecks are genotype dependency, complexity of a tissue culture and fluctuating immune responses. Moreover, new technologies like AI platforms and nanovectors are very expensive to implement infrastructure-wise and technically, which cannot be accessible to smaller laboratories.

Moreover, transformation efficiency cannot be reported using standardized measures, which makes cross-studies comparative. The problematic areas that need to be addressed in future studies are consistent assessment systems and optimization measures that can be automated.

V. CONCLUSION AND FUTURE PERSPECTIVES

Genetic transformation through Agrobacterium is at the root of plant biotechnology as it is simple, economical and produces stable transgenic lines. This review has summarized the existing information about transformation efficiency in model plants and chosen crop species, the focus being on the biological processes, optimization approaches, genomic considerations, and new technological improvements, which all contribute to the transformation outcomes.

Arabidopsis thaliana exemplar plants have been shown to show high levels of transformation efficiency that are maximized by specific protocols like floral dip method and when physiological pre-treatments are used. Seriously, the significance of host physiological manipulation in gene delivery procedures has been reported by the controlled drought stress that has been proven to increase tissue vulnerability and transformation success. There is a more variation in the transformation efficiency in crop plants such as soybean and wheat, as these are genotype dependent, unable to regenerate, and have tissue culture limitations. Nonetheless, the use of auxiliary chemical conditions, optimizing the co-culture, and perfecting the strategies of the explant selection have shown quantifiable enhancements in the outcomes of the transplantations.

The success of transformation largely depends on the host-pathogen interactions. Plant immune system is a significant resistant factor towards Agrobacterium infection, lowering the efficiency of genes transferring. The creation of engineered bacterial strains that would be able to alleviate immune responses is an avenue that holds promise with regard to enhancing the reliability of transformation in various plant species. However, this increased efficiency should be offset against biosafety because there is a possibility of random T-DNA integration causing genomic rearrangements, undesirable mutations, and instability of transgenes. Extensive molecular characterization of transgenic lines thus continues to be critical in the provision of genetic integrity and stability of traits in the long term.

The world of the plant genetic research is quickly changing due to the technological achievements. Another approach that could be used to supplement the Agrobacterium-mediated delivery systems is the use of nanovector-based delivery systems with the ability to target cells and cause less cellular damage. Computer-controlled apparatus of automated gene-editing design and predictive models facilitates experimental procedures whereas high-throughput phenotyping methods provide a chance to perform broad-scale quantitative evaluation of plant characteristics. Image analytics also aid increased accuracy and effectiveness of phenotypic assessment, and help to screen transformed populations quickly. Collectively, the innovations enhance the quality of data, reproducibility, and scalability of transformation research.

Notwithstanding these developments, there are a number of constraints. The protocols of transformation are very species- as well as genotype-specific and there is no standardized benchmarking on reporting transformation efficiency. The demands of the state-of-the-art phenotyping and computational systems can restrict access based on resource-constrained labs.

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0)

ISSN: 2583-4053
Volume-4 Issue-6 || December 2025 || PP. 151-158
https://doi.org/10.55544/jrasb.4.6.21

Secondly, ecological and regulatory aspects of genetically modified plants in the long run still remain a factor in the adoption of technology.

The following research directions are advisable in the future: the creation of universally flexible transformation procedures, better approaches to bacterial engineering to increase their compatibility with different plants, and the incorporation of AI-based optimization software to design new experiments and predict their results. The reporting on transformation efficiency through the use of standardized metrics will enhance the cross-study comparability and reproducibility. Moreover, integrating Agrobacterium-based systems with the emerging nanotechnologies and new precision genome editing systems will open up new possibilities to functional genomics acceleration and sustainable crop enhancement.

Finally, improving the effectiveness of Agrobacterium meditated transformation must be done in a multidisciplinary manner including biological optimization, molecular engineering, computational intelligence and biosafety assessment. Further innovation in this area will enhance consistency, expandability as well as the societal effects of the plant genetic engineering-based technologies.

REFERENCES

[1] Agrawal, S.E.R. (2022) 'A review: Agrobacterium-mediated gene transformation to increase plant productivity', *Journal of Phytopharm*, 11, pp. 111–117.

[2] Ali, I., Salah, K.B.H., Sher, H., Ali, H., Ullah, Z., Ali, A., Alam, N., Shah, S.A., Iqbal, J., Ilyas, M. and Al-Quwaie, D.A.H. (2024) 'Drought stress enhances the efficiency of floral dip method of Agrobacterium-mediated transformation in *Arabidopsis thaliana*', *Brazilian Journal of Biology*, 84, p. e259326.

[3] Chen, L., Wang, L., Zhang, L., Li, Y. and Han, S. (2024) 'Enhancing Agrobacterium-mediated soybean transformation efficiency with an auxiliary solution', *Crop Health*, 2(1), p. 17.

[4] Ebrahimzadegan, R. and Maroufi, A. (2022) 'In vitro regeneration and Agrobacterium-mediated genetic transformation of Dragon's Head plant (*Lallemantia iberica*)', *Scientific Reports*, 12(1), p. 1784.

[5] Esser, F., Rosu, R.A., Cornelißen, A., Klingbeil, L., Kuhlmann, H. and Behnke, S. (2023) 'Field robot for high-throughput and high-resolution 3D plant phenotyping'.

[6] Giuffrida, M.V., Scharr, H. and Tsaftaris, S.A. (2017) 'ARIGAN: Synthetic Arabidopsis plants using generative adversarial networks'.

[7] Huang, K., Qu, Y., Cousins, H., Johnson, W.A., Yin, D., Shah, M., Zhou, D., Altman, R., Wang, M. and Cong, L. (2024) 'CRISPR-GPT: An LLM agent for automated design of gene-editing experiments'.

[8] Khan, N., Lyon, O.A.S., Eramian, M. and McQuillan, I. (2020) 'A novel technique combining image processing, plant development properties, and the Hungarian algorithm to improve leaf detection in maize'.

[9] Kumar, S., Luo, W., Kantor, G. and Sycara, K. (2019) 'Active learning with Gaussian processes for high throughput phenotyping'.

[10] Orlando, J.I., Manterola, H.L., Ferrante, E. and Ariel, F. (2017) 'Arabidopsis roots segmentation based on morphological operations and CRFs'.

[11] Pan, Y., Hu, K., Liu, T., Chen, C. and Kang, H. (2024) 'Pheno-Robot: An auto-digital modelling system for in-situ phenotyping in the field'.

[12] Rostami, M., Ghariyazi, A., Dashti, H., Rohban, M.H. and Rabiee, H.R. (2024) 'CRISPR: Ensemble model'.

[13] Sunday, G., Nwaneri, G., Ugwu, C.M., Onyekachi, O.I., Ruth, C.C., Ebenebe, I.N., Nedum, C.H. and Oli, A.N. (2024) 'Agrobacterium tumefaciens: Biology and application in genetic engineering', *GSC Advanced Research and Reviews*, 20(1), pp. 389–398.

[14] Thiyagarajan, K., Noguera, L.M., Pacheco, M., Govindan, V. and Vikram, P. (2024) 'Factors influencing Agrobacterium-mediated genetic transformation efficiency in bread wheat (*Triticum aestivum* L.)', *Indian Journal of Genetics and Plant Breeding*, 84(1), pp. 63–72.

[15] Thomson, G., Dickinson, L. and Jacob, Y. (2024) 'Genomic consequences associated with Agrobacterium-mediated transformation of plants', *The Plant Journal*, 117(2), pp. 342–363.

[16] Wytock, T.P. and Motter, A.E. (2024) 'Cell reprogramming design by transfer learning of functional transcriptional networks', *arXiv*.

[17] Yang, F., Li, G., Felix, G., Albert, M. and Guo, M. (2023) 'Engineered Agrobacterium improves transformation by mitigating plant immunity detection', *New Phytologist*, 237(6), pp. 2493–2504.

[18] Zhi, H., Zhou, S., Pan, W., Shang, Y., Zeng, Z. and Zhang, H. (2022) 'The promising nanovectors for gene delivery in plant genome engineering', *International Journal of Molecular Sciences*, 23(15), p. 8501.

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0)