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BANANA TISSUE CULTURE: CURRENT STATUS, EMERGING TECHNOLOGIES AND APPLICATIONS IN SUSTAINABLE CROP IMPROVEMENT

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ABSTRACT

Banana (*Musa* spp.) is an important fruit crop and staple food in tropical and subtropical regions. Conventional propagation through suckers is slow and often results in the spread of pests and diseases, making tissue culture an effective alternative for rapid multiplication of disease-free and genetically uniform planting materials. This review highlights recent advances in banana tissue culture, focusing on micropropagation, somatic embryogenesis, genetic transformation, and somoclonal variation. Key factors influencing successful micropropagation, including explant selection, culture establishment, shoot multiplication, rooting, and acclimatization, are discussed. The review also summarizes the role of somatic embryogenesis and genetic transformation in developing disease-resistant and climate-resilient banana cultivars, along with approaches to minimize somoclonal variation and maintain genetic fidelity. Emerging technologies such as Temporary Immersion Bioreactor Systems (TIBs), CRISPR/Cas genome editing, artificial intelligence, automation and nanotechnology are also highlighted for their potential to improve propagation efficiency and reduce production costs. Overall, banana tissue culture remains a key tool for sustainable crop improvement and large-scale production of quality planting materials, contributing to enhanced banana productivity and global food security.

Key words : Banana (*Musa* spp.), Tissue culture, Micropropagation, Somatic embryogenesis, Genetic transformation.

Introduction

Banana and plantain (*Musa* spp.; family Musaceae) are among the world's most important fruit crop, that are native to Southeast Asia and are now extensively cultivated across tropical and subtropical regions worldwide (Kothawade *et al.*, 2019). Globally, bananas are predominantly produced by small-scale farmers and nearly 87% of total production are used for local consumption as a food security crop rather than international trade. They provide a staple food for millions of people, particularly in Africa and southeast Asia (Al-Amin *et al.*, 2009; Asten *et al.*, 2012).

Conventionally, bananas are propagated vegetatively through suckers arising from the mother plant. Though widely practiced for centuries, sucker-mediated propagation method possesses major challenges including- (1) systemic transmission of pathogens, particularly viruses, bacteria, fungi, and nematodes, from infected mother plants to subsequent generations, (2) low multiplication rate that limit rapid production of planting materials for large-scale cultivation, (3) bulky nature of suckers complicate handling, long-distance transport and storage, which further hinders efficient distribution of planting material and adds up the production costs. Collectively, these constraints affect the quality of planting

material and further reduces banana productivity below actual potential per hectare (Kelta *et al.*, 2018).

Plant tissue culture (PTC) technique also has great potential as an efficient alternative for vegetative propagation of economically important species, especially for those that are difficult to propagate by conventional methods like seeds or cuttings (Muhammad, 2007). Among the various tissue culture techniques, micropropagation, also referred to as *in vitro* propagation, is the most widely adopted method for large-scale production of genetically uniform, true-to-type, and disease-free planting materials. It involves the aseptic culture of small sections (i.e. explants) of tissues and organs including shoot tips, apical or axillary meristems, nodal segments, or other vegetative tissues, in closed vessels on chemically standardized nutrient media supplemented with appropriate plant growth regulators. The cultures are maintained under the controlled environmental conditions with optimum light intensity, temperature, relative humidity, and photoperiod to facilitate organogenesis/embryogenesis, plant regeneration and acclimatization (Loberant *et al.*, 2010). Micropropagation of plants is a useful technique for large-scale propagation of food crops, medicinal and ornamental plants, tree species and other economically important plants (Rout *et al.*, 2000; Rout *et al.*, 2006).

Micropropagation involves four major steps: (1) selection of suitable explants, (2) establishment of aseptic cultures (3) shoot multiplication through axillary bud proliferation and (4) root induction and acclimatization (hardening) of regenerated plantlets. The different techniques of culturing plant tissues may offer certain advantages over traditional methods of propagation. Growing plants *in vitro* in a controlled environment with in-depth knowledge of the culture conditions and the nature of the plant material, ensures effective clonal propagation of genetically superior genotypes of economically important plants. Furthermore, the nutritional, hormonal, and environmental conditions can be precisely regulated to ensure reproducible plant regeneration and ensures uniformity among regenerated plants (Iliev *et al.*, 2010). The actual production of TC plants was 350 million in total installed capacity of 500 million (Shukla, 2017). Thus, the history of commercial tissue culture in India is a story of 'rise and fall, and rise again' as quoted by Prakash (2006).

This review summarizes recent advances in banana (*Musa* spp.) tissue culture, with emphasis on micropropagation, somatic embryogenesis, genetic transformation and somaclonal variation. It also highlights emerging technologies, including genome editing,

temporary immersion bioreactors, artificial intelligence, and precision tissue culture. It also discusses current challenges and future prospects for developing disease-resistant, climate-resilient, and genetically stable banana cultivars for sustainable production.

Micropropagation of Banana

Explant selection : Successful banana micropropagation starts with the selection of appropriate explant material, as it directly influences clonal genetic fidelity, shoot multiplication rate, regeneration efficiency and disease-free planting material. The explants are obtained from healthy, virus free banana mother plants maintained under field or greenhouse conditions. The sword suckers bearing meristems are preferred source of explants because exhibit greater physiological vigor than water suckers. The pseudo-stems at the basal regions of the suckers, which contain meristems, are widely utilized as explants. Other explants include the stem tip, axillary bud tip, immature inflorescences, rhizome buds, and root tip due to high mitotic activity of meristematic tissues and their capacity to concentrate or synthesize essential growth regulators such as auxins and cytokinins (Suman *et al.*, 2017).

Explant sterilization : Microbial contamination remains a principal constraint that severely limit the efficiency of banana micropropagation. Microbes compete with cultured plant tissues for nutrients, and certain microbial species produce phytotoxins that lead to culture mortality, tissue necrosis, and diminished shoot proliferation and roots (Kane *et al.*, 2003). For example, the fungus *Aspergillus niger* and *Aspergillus flavus* have been documented to produce oxalate and aflatoxin toxins, respectively, which are lethal to plant cultures (Obuekwe *et al.*, 1989). The sub-culture process is a significant source of contamination, introducing around 5-15% of pollutants with each sub-culture (Leifert *et al.*, 2001). The primary source of microbial contamination is inadequate sterilization of explants, growth media, instruments and the hands of operators (Omamor *et al.*, 2007). *Pseudomonas syringae*, *Bacillus licheniformis*, *Bacillus subtilis*, *Cornebacterium* sp., and *Erwinia* spp. are identified as the primary bacterial contaminants in plant tissue cultures (Odutayo *et al.*, 2004). The predominant fungal pollutants commonly identified in plant tissue cultures include *Alternaria tenuis*, *Aspergillus niger*, *Aspergillus fumigatus* and *Fusarium culmorum* (Odutayo *et al.*, 2004; Odutayo *et al.*, 2007). Effective contamination management begins with careful selection of healthy explants followed by rigorous surface sterilization. Plant materials intended for *in vitro* propagation are subjected to surface sterilization utilizing

either a sodium hypochlorite solution at concentrations of 0.3-1.0% (m/v) for 15-30 minutes or an aqueous mercuric chloride solution at 0.1-1.0% (m/v) for 8 minutes (Meghwal *et al.*, 2000; Maina *et al.*, 2010). This surface sterilization often eradicates most epiphytic pollutants, excluding endophytic ones (Habiba *et al.*, 2007). The administration of systemic fungicides such benomyl (benlate®) prior to the collection of plant materials also mitigates microbial contamination in plant *in vitro* cultures (Mngomba *et al.*, 2007).

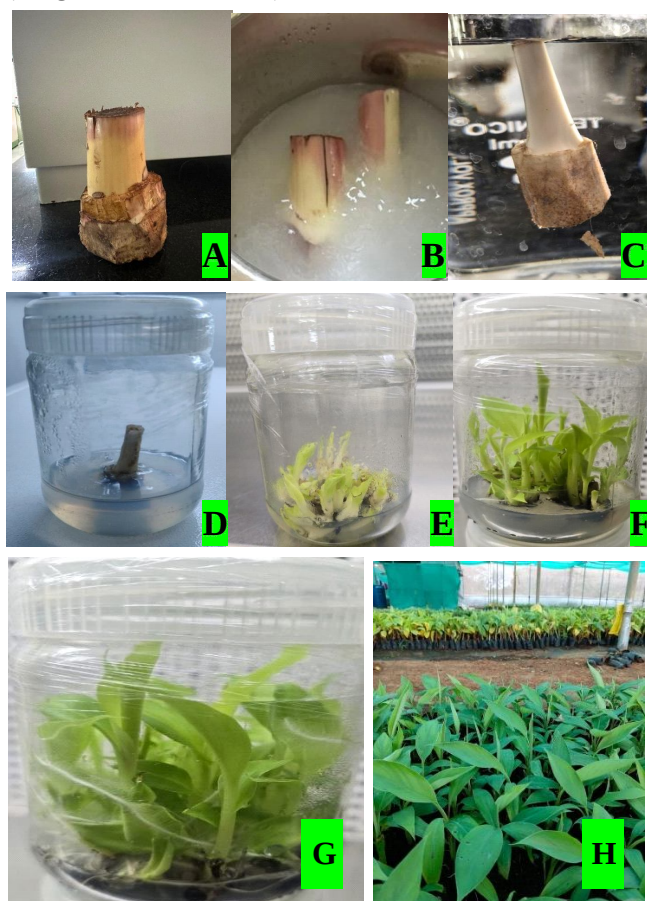


Fig. 1 : Stages of banana (*Musa* spp.) micropropagation. (A) Selection of healthy sword sucker as explant source; (B) Fungicide treatment (Bavistin); (C) antioxidant treatment (Citric acid + Ascorbic acid) to minimize phenolic oxidation; (D) culture initiation under aseptic conditions; (E) shoot induction and proliferation; (F) shoot multiplication through successive subcultures; (G) *in vitro* root induction; and (H) acclimatization (hardening) of regenerated plantlets under *ex vitro* conditions.

***In vitro* Environmental conditions**

Environmental factors including light quality, photoperiod, temperature, relative humidity, gaseous exchange, and culture vessel characteristics significantly alter cellular differentiation and organogenesis in banana micropropagation (Morini *et al.*, 2000).

Light quality is not only a energy source but also a developmental signal that modulates shoot elongation, chlorophyll biosynthesis, and photosynthetic competence. Tissue culture procedures frequently entail significant dissection and stress-induced damage to tissues, potentially resulting in physiological alterations in plants that influence the efficacy of the response (Leon *et al.*, 2001).

Culture initiation : Shoot cultures of banana are usually initiated from any plant portion containing a shoot meristem, such as the parental pseudostem, tiny suckers, peepers and lateral buds (Vuylsteke *et al.*, 1989). Also, the tip of the inflorescence and axillary flower buds (Cronauer *et al.*, 1985) are good explants for the commencement of tissue culture. In general, explant material should be selected from preferably mature individuals, whose reaction to environmental influences is known; and whose quality features, which are under the control of genotypic and environmental impacts, have been determined (Strosse *et al.*, 2004).

The most popular explant used for quick *in vitro* multiplication of banana is shoot tips of young suckers 40–100 cm high. From the selected sucker, a cube of tissue of roughly 1–2 cm³ including the apical meristem, is removed. The size of the explant should be compatible with the goal. A significantly bigger explant (3-10 mm) is preferable for rapid multiplication though it is more prone to blackening and contamination. Meristem-tip culture is the method of choice when virus or bacterium eradication is desired. The explant is then trimmed down to a small size (0.5–1 mm in length) leaving a dome of meristematic tissue with one or two leaf primordia. The drawback of meristem cultures however is that they can lead to a higher mortality rate and slower initial growth (Strosse *et al.*, 2004).

At this step the explant is surface sterilized and put to the nutritional medium (Suman *et al.*, 2019). Surface sterilization of explant in chemical solutions is a critical step to eliminate pollutants with minimum damage to plant cells (Hussain *et al.*, 2007). The most used disinfectants are sodium hypochlorite (Tilkat *et al.*, 2009), calcium hypochlorite (Garcia *et al.*, 1999), ethanol (Singh *et al.*, 2009) and mercuric chloride (Hussain *et al.*, 2007).

Murashige and Skoog (Murashige *et al.*, 1962) reported that MS-based medium is widely utilized for micropropagation of banana. The explant is then inserted immediately into culture medium favouring proliferation. Usually 30 g/l sucrose carbon source supplementation is provided (Kumar *et al.*, 2024).

The media is supplemented with varying types of

cytokinin and auxins in specific combination to induce production of shoot and root respectively (Chukwu *et al.*, 2025). Commonly used cytokinins for shoot proliferation and axillary bud development in the media are Benzyl Amino purine (BAP), Zeatin, thiadiazuron (TDZ), kinetin and meta-topolin (N6-(3-hydroxybenzyladenine) (MT)) (Cavallaro *et al.*, 2022). Also, numerous types of auxins generally incorporated to the medium for root development including indole acetic acid (IAA) and Naphthalene acetic acid (NAA) (Elmongy *et al.*, 2018). Cultures are grown in growth chamber either in light or dark settings depending on the mode of propagation (Suman *et al.*, 2019).

Shoot multiplication

Shoot multiplication is the central phase of banana micropropagation, that aims to augment the quantity of propagules by multiplying them through successive subcultures until the target number of plants is achieved (Saini *et al.*, 2002). The multiplication medium comprised MS salts and vitamins supplemented with 5.0 mg/l BAP. Subculturing was performed every four weeks, with the removal of black tissues preceding the process. The discoloration of the explant may result from the release of phenolic chemicals (Muhammad *et al.*, 2004).

The multiplication rate is contingent upon both cytokinin concentration and genotype. Typically, cultivars with just A genomes generate 2–4 new shoots, while those possessing one or two B genomes yield a cluster of numerous shoots and buds during each cultural cycle (Strosse *et al.*, 2004).

A maximum of 10,000 plantlets from a single sucker within eight months has been documented (Singh *et al.*, 2013). New axillary and adventitious shoots may emerge straight from the shoot-tip explant approximately 6–12 weeks following the commencement of culture, contingent upon the original size of the explant. Clusters may be segregated, pruned, and subcultured at intervals of 4 to 6 weeks (Strosse *et al.*, 2004).

Variations in the multiplication rates of various Musa spp. genotypes have been documented (Abdullah *et al.*, 1997; Vuylsteke, 1998). This study revealed variability in the multiplication rate across explants of the same genotype. Despite being of the same genotype, the variations in growth rate may be attributed to the physiological responses of distinct rhizomes (Muhammad *et al.*, 2004).

Rooting phase

The robust rooting of *in-vitro* cultivated plantlets was noted on MS medium supplemented with 1.5 mg/l IBA.

who achieved 5.5 roots per plantlet on MS media augmented with 1.5 mg/l IBA (Gubbuk and Pekmezci, 2004; Molla M *et al.*, 2006). MS medium augmented with 1.0 mg L⁻¹ IBA yielded the greatest number of roots (7.0 roots per shoot) in banana cultivar ‘Anupom’, with IBA demonstrating superiority over NAA and IAA for root induction (Rahman *et al.*, 2005). Root development in banana plantlets with IBA and IAA treatments demonstrates that auxin concentration markedly affects rooting efficacy and the subsequent establishment of plantlets (Al-Amin *et al.*, 2009).

IBA markedly improves rooting percentages in all substrates at an optimal dose of 1.0 mg L⁻¹. Rooting diminishes at elevated concentrations (2.0 and 4.5 mg L⁻¹), exhibiting a dose-dependent relationship. The data from our investigation clearly indicates that rooting is incremental in comparison to other banana micropropagation protocols. (Deo *et al.*, 2019). The superior and resilient rooting in soil-rite indicates that its aeration and texture promote root development more effectively than dense agar or glass bead-liquid systems.

Acclimatization (Hardening)

The survival and adaptation of plantlets under *ex vitro* condition is influenced by a lot of elements directly or indirectly (Pospisilova *et al.*, 1999). The most significant part of hardening is the initial root establishment in the potting mixture which produces less loss to the plants from desiccation (Vasane *et al.*, 2006).

The medium of choice of most nurserymen is coir pith because of its texture and physical and chemical qualities (Savithri *et al.*, 1993). Vermicompost is known to improve the root ramification and deliver macro and micro nutrients to the plants (Sharma *et al.*, 1999). It has been found in ‘Williams’ and ‘Grande Naine’ that higher proportion (>50%) of heavier inorganic media may result in compaction of media, waterlogging and root dieback following over watering and hence, should be avoided (Robinson *et al.*, 2009). In cultivar ‘Grande Naine’, the plantlets maintained for secondary hardening in soil alone as a media showed poor growth and inclusion of substrates like coir pith combined with soil showed considerable root development possibly due to the porous nature of the medium (Vasane *et al.*, 2006).

On transfer of micro shoots to *ex vitro* settings high mortality is seen since the cultivated plants had non functional stomata, weak root system and poorly developed cuticle (Mathur *et al.*, 2008). Because *in vitro* created plantlets are not easy to acclimatize to *in vivo* condition. The most critical step in the micro-propagation of banana is acclimatization (hardening) (Vasane *et al.*,

2006).

Somatic Embryogenesis

Somatic embryogenesis (SE) is an *in vitro* technique for plant regeneration and it is extensively utilized as a significant biotechnological instrument for continuous clonal proliferation (Park *et al.*, 1998). It is a process via which somatic cells or tissues differentiate into embryos. Somatic embryos can develop into whole plants without the necessity of sexual fertilization, unlike zygotic embryos. Somatic embryogenesis can be triggered either directly from explants or indirectly through the formation of a mass of disorganized cells known as callus (Suman and Kumar, 2016). The embryonic callus exhibited a high germination rate of somatic embryos when cultivated solely on abscisic acid (ABA). Somatic embryogenesis serves not only as a method for bulk proliferation of plants but is also considered a significant instrument for genetic alteration. The method can also be employed to cultivate plants that are resilient to diverse stressors (Bouquet and Terregosa, 2003) and to incorporate genes through genetic transformation (Maynard *et al.*, 2003).

Direct Somatic embryogenesis

Direct somatic embryogenesis is the process in which somatic embryos are produced directly from explant tissues without passing through an intermediate callus stage. This method is considered highly desirable because it minimizes genetic variation and enables the regeneration of genetically uniform plants (Escalant and Teisson, 1989). In banana (*Musa* spp.), direct embryo formation has been achieved using explants such as immature male flower buds, shoot apices, scalps and meristematic tissues that possess high embryogenic potential (Suman and Kumar, 2016). The efficiency of this process is influenced by several factors, including the banana genotype, physiological condition of the explant, and the composition of the culture medium (Strosse *et al.*, 2004).

For embryo induction, sterilized explants are cultured on Murashige and Skoog (MS) medium enriched with auxins, particularly 2,4-dichlorophenoxyacetic acid (2,4-D) or picloram, which stimulate embryogenic cell differentiation (Murashige and Skoog, 1962; Suman and Kumar, 2016). Under these conditions, epidermal and sub-epidermal cells become embryogenically competent and divide continuously to form somatic embryos directly on the explant surface. The developing embryos subsequently progress through the globular, heart-shaped, torpedo and cotyledonary stages before regenerating into complete plantlets under suitable *in vitro* conditions (Park *et al.*, 1998).

A major benefit of direct somatic embryogenesis is that the absence of a callus phase substantially lowers the risk of somaclonal variation, thereby preserving the genetic stability of regenerated plants (Escalant and Teisson, 1989). Since embryos arise directly from organized tissues, plant regeneration is relatively rapid and produces true-to-type clones suitable for commercial propagation. However, the success of this technique varies among banana cultivars because the embryogenic response is strongly influenced by genotype. Therefore, selecting an appropriate explant and optimizing the concentration of plant growth regulators are crucial for obtaining efficient embryo induction and regeneration (Strosse *et al.*, 2004).

Indirect Somatic Embryogenesis

Indirect somatic embryogenesis is a regeneration pathway in which somatic embryos develop through an intermediate callus phase before differentiating into complete plants. This approach is the most commonly employed method for banana regeneration because of its high efficiency and suitability for large-scale propagation and genetic transformation (Strosse *et al.*, 2004). Explants including immature male flowers, immature zygotic embryos, shoot tips and meristematic tissues are cultured on Murashige and Skoog (MS) medium supplemented with elevated concentrations of auxins, especially 2,4-D, to stimulate the formation of embryogenic callus (Murashige and Skoog, 1962; Dhed'a *et al.*, 1991). The resulting friable callus contains actively dividing undifferentiated cells capable of producing somatic embryos.

Following successive subcultures, the embryogenic callus is transferred to liquid medium to establish embryogenic cell suspensions (ECS), which provide an efficient source of regenerable cells for banana biotechnology (Strosse *et al.*, 2004). When these cultures are moved to regeneration media containing lower auxin levels and appropriate cytokinins, embryogenic cells differentiate into somatic embryos. These embryos subsequently develop through the globular, heart-shaped, torpedo and cotyledonary stages before germinating into healthy plantlets with well-developed shoots and roots (Park *et al.*, 1998).

Indirect somatic embryogenesis offers several advantages, including high multiplication rates, synchronized embryo development, efficient plant regeneration and the production of embryogenic cell suspensions suitable for genetic engineering applications (Tripathi *et al.*, 2019). These cell suspensions are widely used for *Agrobacterium*-mediated transformation, particle

bombardment, mutation breeding and CRISPR/Cas-based genome editing because of their excellent regenerative ability (Khanna *et al.*, 2004). However, maintaining embryogenic cultures for extended periods may result in somaclonal variation, chromosomal alterations and epigenetic modifications, making regular evaluation of genetic stability necessary (Cote *et al.*, 2001).

Applications in Banana improvement

Somatic embryogenesis has emerged as a fundamental technique in banana improvement programmes because it combines rapid clonal multiplication with modern biotechnological approaches (Tripathi *et al.*, 2019). One of its primary applications is the large-scale production of healthy, disease-free and genetically uniform plantlets, which contribute to better crop establishment, enhanced yield and stable performance (Strosse *et al.*, 2004). In addition, embryogenic cultures serve as highly responsive tissues for plant regeneration, making them ideal targets for genetic transformation studies to develop disease resistance such as Fusarium wilt Tropical Race 4 (TR4), Black Sigatoka, Banana Xanthomonas Wilt and Banana Bunchy Top Virus using both *Agrobacterium*-mediated transformation and particle bombardment techniques (Tripathi *et al.*, 2019).

Furthermore, genes associated with tolerance to drought and salinity, insect resistance, delayed fruit ripening, enhanced nutritional composition and extended shelf life have been incorporated into elite banana cultivars, thereby improving both productivity and fruit quality (Paul *et al.*, 2017).

Apart from genetic transformation, somatic embryogenesis is extensively applied in mutation breeding, germplasm conservation, cryopreservation of embryogenic cultures, synthetic seed production and functional genomics research (Park *et al.*, 1998). The establishment of embryogenic cell suspensions (ECS) has also accelerated the development of genome editing technologies, particularly CRISPR/Cas9, allowing precise modification of endogenous genes without introducing foreign DNA (Ntui *et al.*, 2020). The integration of somatic embryogenesis with genomics, transcriptomics, molecular markers and advanced breeding strategies has created new opportunities for developing biotic and abiotic stress resistance and nutritionally improved banana cultivars. Consequently, somatic embryogenesis continues to be one of the most reliable and efficient regeneration systems supporting sustainable banana production and future crop improvement efforts (Tripathi *et al.*, 2019; Dale *et al.*, 2017).

Genetic Transformation in Banana

Genetic transformation is the key component of plant cell tissue culture, facilitating the transfer of genes with desirable traits into host plants, ultimately resulting in the recovery of transgenic plants (Hinchey *et al.*, 1994). Genetic transformation in plants can be accomplished using either vector-mediated (indirect gene transfer) or vector less (direct gene transfer) methods (Sasson, 1993). Among vector-dependent gene transfer methods, *Agrobacterium*-mediated genetic transformation is the most prevalent for the expression of exogenous genes in plant cells. Genetic transformation by root explants has effectively facilitated the incorporation of agronomic features in plants (Franklin and Lakshmi, 2003).

Genetic transformation has become an important biotechnological approach for the genetic improvement of banana because conventional breeding is limited by factors such as polyploidy, sterility, prolonged generation time and poor seed production. Through genetic engineering, desirable genes can be introduced accurately into superior banana cultivars without affecting their valuable agronomic traits. This technology has been widely applied to enhance resistance against diseases, insect pests and environmental stresses while simultaneously improving fruit quality and nutritional characteristics (Tripathi *et al.*, 2010).

Advances in transformation techniques have greatly contributed to functional genomics research in banana. These methods allow the incorporation of genes responsible for disease resistance, stress adaptation, delayed fruit ripening, nutritional enhancement and increased productivity into commercially important cultivars. Furthermore, recent developments in genome editing technologies, particularly CRISPR/Cas9, have enabled targeted modification of endogenous genes with greater precision and without the need to introduce foreign DNA (Dale *et al.*, 2017).

The process of genetic transformation generally consists of four major stages: preparation of suitable explants, delivery of foreign DNA into plant cells, identification of transformed cells using selectable marker genes and regeneration of complete plants through tissue culture techniques. Embryogenic cell suspensions, immature male flowers, meristematic tissues and multiple shoot cultures are widely preferred as explants because of their excellent regeneration potential (Strosse *et al.*, 2004).

Although, transformation efficiency differs among banana genotypes, continuous improvements in tissue culture methods, transformation protocols, and selection

systems have considerably increased the success of transgenic plant production. These developments have facilitated the generation of banana varieties with improved resistance to destructive diseases such as Fusarium wilt Tropical Race 4 and Banana Xanthomonas Wilt (Tripathi *et al.*, 2019).

Agrobacterium-mediated Transformation

Among the various gene transfer techniques available, *Agrobacterium*-mediated transformation is the most commonly employed indirect method for banana because it provides efficient DNA transfer, stable integration of foreign genes and generally results in fewer transgene copies. The soil bacterium *Agrobacterium tumefaciens* naturally transfers a segment of transfer DNA (T-DNA) into plant cells and this natural mechanism has been modified by scientists to introduce beneficial genes rather than disease-inducing genes (Gelvin, 2003).

Embryogenic cell suspensions are regarded as the most suitable explants for *Agrobacterium*-mediated transformation owing to their high regenerative capacity and transformation efficiency. Nevertheless, other explants, including multiple shoot cultures, meristematic tissues, immature male flowers, and scalps, have also been successfully utilized. During the transformation process, explants are co-cultivated with *Agrobacterium* carrying a binary vector that contains the target gene, promoter and selectable marker gene. Following co-cultivation, transformed tissues are selected using antibiotics such as kanamycin or hygromycin, while antibiotics like cefotaxime or timentin are applied to eliminate residual bacterial cells (Khanna *et al.*, 2004).

This transformation system has enabled the successful introduction of numerous beneficial genes into banana. Resistance genes such as Hrap and Pflp have been incorporated to improve resistance against Banana Xanthomonas Wilt, while antimicrobial peptides and antifungal genes have enhanced protection against Fusarium wilt. Likewise, genes associated with abiotic stress tolerance and nutritional enhancement have also been effectively transferred through this method (Tripathi *et al.*, 2019).

The major strengths of *Agrobacterium*-mediated transformation include stable integration of foreign DNA, low transgene copy number, minimal gene rearrangement, high reproducibility and relatively low operational cost. However, the technique still faces challenges such as genotype-dependent responses, variable transformation efficiency among cultivars and the lengthy period required for plant regeneration.

Direct Gene Transfer methods

Direct gene transfer methods enable the introduction of foreign DNA into plant cells without the use of biological vectors such as *Agrobacterium*. These techniques are especially valuable for banana genotypes that respond poorly to bacterial transformation or when several genes must be transferred simultaneously.

Particle bombardment, also referred to as the biolistic method, is the most widely adopted direct transformation technique in banana. In this procedure, microscopic gold or tungsten particles coated with plasmid DNA are propelled at high speed into plant tissues using a gene gun. After entering the cells, the DNA separates from the particles and becomes randomly integrated into the plant genome (Sanford, 1990).

Other direct DNA delivery techniques include electroporation, polyethylene glycol (PEG)-mediated transformation of protoplasts, silicon carbide whisker-mediated transformation and microinjection. Electroporation uses electrical pulses to temporarily increase cell membrane permeability, thereby facilitating DNA uptake. Similarly, PEG-mediated transformation promotes DNA entry into isolated protoplasts by altering membrane permeability, although efficient regeneration of banana plants from transformed protoplasts remains technically demanding.

Particle bombardment has been extensively employed for transferring genes associated with disease resistance, insect resistance, abiotic stress tolerance and metabolic engineering. A major advantage of this technique is that it is applicable to a wide range of banana genotypes and does not depend on bacterial infection. However, it often results in multiple transgene insertions, complex integration patterns, DNA rearrangements and a higher probability of gene silencing compared with *Agrobacterium*-mediated transformation (Birch, 1997).

Despite these drawbacks, continuous refinement of bombardment parameters, tissue culture protocols and regeneration techniques has considerably improved transformation efficiency and the successful recovery of transgenic banana plants.

Applications in Banana improvement

Genetic transformation has significantly broadened the scope of banana improvement by overcoming many of the limitations associated with conventional breeding. One of its most important applications is the development of disease-resistant cultivars. Transgenic bananas expressing defense-related genes have shown improved resistance to Fusarium wilt, Black Sigatoka, Banana

Bunchy Top Virus, and Banana Xanthomonas Wilt, thereby minimizing crop losses and reducing dependence on chemical pesticides (Tripathi *et al.*, 2019).

Genetic engineering has also contributed to the production of insect-resistant banana cultivars through the incorporation of insecticidal and defense-related genes. In addition, genes responsible for drought tolerance, salinity tolerance, oxidative stress resistance, and temperature adaptation have improved the ability of banana plants to withstand adverse environmental conditions.

Another important application is nutritional improvement through biofortification. Genetic transformation has been employed to increase the levels of provitamin A, iron, zinc and other essential micronutrients in banana fruits, thereby enhancing their nutritional quality and helping to combat micronutrient deficiencies in developing countries. Manipulation of genes involved in ethylene biosynthesis has also delayed fruit ripening, extending shelf life, minimizing post-harvest losses and improving the market value of banana fruits (Paul *et al.*, 2017).

The emergence of genome editing technologies, particularly CRISPR/Cas9, has further revolutionized banana improvement by allowing precise modification of endogenous genes without the introduction of foreign DNA. Compared with conventional transgenic approaches, genome editing provides greater accuracy while reducing regulatory concerns, making it a promising strategy for developing disease-resistant, climate-resilient and nutritionally enriched banana cultivars (Ntui *et al.*, 2020).

Overall, genetic transformation has become an integral component of modern banana improvement programmes. By combining advances in molecular biology, genomics and plant tissue culture, this technology has accelerated the development of superior banana cultivars capable of addressing future agricultural challenges, improving productivity and strengthening global food security.

Somaclonal variation

Somaclonal variation (SV) refers to the variability generated during *in vitro* propagation (Cote *et al.*, 2001). SV can be classified as either somatically or meiotically stable occurrences (Peredo *et al.*, 2006). The meiotically stable variation is referred to as 'mutation' (Wang *et al.*, 2012). Nonetheless, not all structural variation (SV) is meiotically transmissible, particularly the reversible epigenetic SV (Oono 1985), leading to the adoption of

the term 'variation' in this context (Cote *et al.*, 2001).

Shoot-tip culture maintains genetic stability more effectively than callus or cell suspension cultures; yet, somaclonal variation is prevalent in plants regenerated from banana shoot-tip cultures (Strosse *et al.*, 2004). The occurrence of somaclonal variation in the plantain subgroup (*Musa* spp. AAB group) has been thoroughly investigated (Vuylsteke *et al.*, 1991). The occurrence of somaclonal variation is significantly affected by the genetic stability of each cultivar, with its frequency heightened by culture-induced variables. No data suggests that growth regulators often employed in tissue culture directly influence the rate of variation; however, research indicates a positive correlation between somaclonal variation and generation number (Strosse *et al.*, 2004). In 'Williams' (AAA) *in vitro* plants, dwarfism and leaf-off types accounted for 3.7% and 0.7% respectively after one subculture cycle, increasing to 6.1% and 1.9% respectively after five cycles (Reuveni *et al.*, 1990).

Somaclonal variation is the occurrence of genetic and phenotypic differences among plants regenerated through *in vitro* culture techniques. The concept was introduced to describe both heritable and non-heritable changes that arise during plant tissue culture (Cote *et al.*, 2001). In banana (*Musa* spp.), the production of genetically uniform planting materials is the primary objective of commercial micropropagation. However, prolonged exposure of tissues to *in vitro* conditions, repeated subculturing, regeneration through callus or cell suspension cultures and the continuous use of plant growth regulators may induce genetic, chromosomal or epigenetic alterations, leading to the development of off-type plants (Strosse *et al.*, 2004). These variations are commonly expressed as changes in plant height, leaf morphology, flowering behaviour, bunch characteristics, fruit quality, yield and disease resistance (Kaepler *et al.*, 2000). Although somaclonal variation is considered undesirable in large-scale clonal propagation, it has also been recognized as an important source of novel genetic variability that can be exploited for mutation breeding and crop improvement programmes (Cote *et al.*, 2001; Wang and Wang, 2012).

According to Strosse *et al.* (2004), shoot-tip-derived banana plants generally exhibit greater genetic stability than those regenerated through callus cultures because organized meristematic tissues undergo fewer genetic alterations during cell division. Nevertheless, the frequency of somaclonal variation increases with successive subculture cycles and differs among cultivars. Reuveni and Israeli (1989) reported that in the banana cultivar

'Williams', the occurrence of dwarf and abnormal leaf phenotypes increased considerably after repeated subculturing, indicating that prolonged *in vitro* maintenance enhances genetic instability.

Causes of Somaclonal variation

Somaclonal variation is caused by several biological and culture-related factors that influence the genetic stability of cultured tissues. One of the major causes is the prolonged maintenance of explants under tissue culture conditions, particularly through repeated subculturing, which increases the accumulation of spontaneous genetic changes over time (Strosse *et al.*, 2004). Regeneration through callus cultures or embryogenic cell suspensions presents a greater risk of variation because these systems involve rapid and unorganized cell division, thereby increasing the possibility of chromosomal rearrangements, gene mutations and epigenetic alterations (Cote *et al.*, 2001).

The composition of the culture medium also contributes significantly to the induction of variation. High concentrations of auxins, particularly 2,4-dichlorophenoxyacetic acid (2,4-D), stimulate dedifferentiation and callus formation but may indirectly promote genomic instability during prolonged culture (Strosse *et al.*, 2004). Kaeppler *et al.* (2000) reported that long-term tissue cultures frequently exhibit chromosomal abnormalities such as polyploidy, aneuploidy, deletions, duplications, and translocations. In addition, Lambe *et al.* (1997) demonstrated that epigenetic mechanisms, including DNA methylation and histone modifications, can alter gene expression without changing the DNA sequence, resulting in reversible phenotypic variations.

Oxidative stress generated under artificial culture conditions is another important factor responsible for DNA damage and mutation accumulation (Wang and Wang, 2012). Furthermore, the response to tissue culture is highly genotype-dependent, with different banana cultivars exhibiting varying degrees of genetic stability under identical culture conditions (Peredo *et al.*, 2006). Therefore, the frequency of somaclonal variation depends on the interaction between genotype, regeneration pathway, duration of culture and environmental conditions maintained during *in vitro* propagation (Strosse *et al.*, 2004).

Detection methods

The identification of somaclonal variation is essential to ensure the genetic fidelity of tissue culture-derived banana plants. Morphological evaluation remains the most basic approach and involves examining regenerated plants

for differences in plant height, pseudostem colour, leaf morphology, flowering behaviour, bunch architecture, and fruit quality (Strosse *et al.*, 2004). Although, this method is economical and straightforward, it detects variation only after plants have reached maturity under field conditions.

Cytological techniques are widely employed to identify chromosomal abnormalities, including alterations in chromosome number, structural rearrangements, and ploidy levels. Flow cytometry has become a valuable tool for rapidly estimating nuclear DNA content and detecting polyploid or aneuploid regenerants (Kaeppler *et al.*, 2000).

Molecular marker systems provide a more reliable assessment of genetic fidelity because they detect DNA-level changes before phenotypic abnormalities become apparent. Marker techniques such as Random Amplified Polymorphic DNA (RAPD), Inter Simple Sequence Repeat (ISSR), Amplified Fragment Length Polymorphism (AFLP), Simple Sequence Repeat (SSR), Sequence Characterized Amplified Region (SCAR) and Single Nucleotide Polymorphism (SNP) analyses have been successfully used to evaluate genetic stability in banana micropropagation (Peredo *et al.*, 2006). These molecular markers facilitate the early identification of off-type plants while ensuring clonal uniformity.

Recent advances in molecular biology have also enabled the detection of epigenetic variation through methylation-sensitive molecular markers, methylation-specific PCR and whole-genome bisulfite sequencing. Moreover, next-generation sequencing (NGS), comparative genomics and transcriptome analyses have significantly improved the accuracy of detecting both genetic and epigenetic alterations associated with somaclonal variation (Kaeppler *et al.*, 2000; Wang and Wang, 2012).

Strategies to Minimize Somaclonal variation

Maintaining genetic fidelity is a primary objective of commercial banana micropropagation. Several approaches have been developed to minimize the occurrence of somaclonal variation during banana micropropagation. Escalant and Teisson (1989) reported that direct regeneration systems, particularly shoot-tip culture and direct somatic embryogenesis, maintain greater genetic stability than indirect regeneration through callus cultures because organized meristematic tissues undergo fewer genetic changes. Similarly, Strosse *et al.* (2004) recommended the use of meristematic explants rather than callus-derived tissues for commercial propagation.

Restricting the number of subculture cycles is another effective strategy because prolonged *in vitro* maintenance promotes the accumulation of mutations (Reuveni and Israeli, 1989). Commercial tissue culture laboratories therefore limit the duration of multiplication cycles to preserve clonal fidelity. Optimizing the concentration of plant growth regulators, particularly by avoiding prolonged exposure to high concentrations of 2,4-D, also reduces the probability of genetic instability (Strosse *et al.*, 2004). Likewise, minimizing oxidative stress, nutrient imbalance, and extended culture periods contributes to maintaining genetic stability.

Routine genetic fidelity testing using RAPD, ISSR, SSR and AFLP markers should be incorporated into quality control programmes before the commercial distribution of tissue culture-derived banana plants (Peredo *et al.*, 2006), further suggested that cryopreservation of embryogenic cultures can effectively preserve genetic integrity by reducing the need for repeated subculturing. In addition, the use of healthy mother plants, carefully selected explants and standardized tissue culture protocols collectively ensures the production of disease-free, genetically uniform and true-to-type banana planting materials with minimal somaclonal variation (Strosse *et al.*, 2004; Kaeppler *et al.*, 2000).

Recent advances in Banana micropropagation

Over the last few decades, banana (*Musa* spp.) tissue culture has progressed considerably from a simple method of clonal propagation to an advanced biotechnological tool supporting crop improvement, germplasm conservation, disease management and genetic engineering. Traditional micropropagation techniques have made it possible to produce large quantities of disease-free and genetically uniform planting materials. Despite these achievements, limitations such as high production costs, contamination, somaclonal variation, low multiplication efficiency and the extensive labour required have prompted researchers to develop more efficient and sustainable tissue culture technologies (Strosse *et al.*, 2004).

Recent innovations have substantially improved the effectiveness and commercial applicability of banana micropropagation. Modern approaches, including Temporary Immersion Bioreactor Systems (TIBs), Light-Emitting Diode (LED) lighting, photoautotrophic micropropagation, nanotechnology-assisted tissue culture, artificial intelligence (AI)-based automation and CRISPR/Cas genome-editing technology, have enhanced the overall efficiency of propagation systems. These technologies

contribute to higher multiplication rates, lower production expenses, improved rooting and acclimatization, reduced contamination and the development of banana cultivars with enhanced resistance to diseases and environmental stresses (Tripathi *et al.*, 2019; Ntui *et al.*, 2020).

The integration of biotechnology with digital and engineering innovations has further modernized banana tissue culture by enabling automated monitoring of culture conditions, image-based growth analysis and predictive modelling of plant development. Such technological progress is expected to improve production efficiency, maintain genetic uniformity and reduce operational costs, thereby strengthening the commercial banana tissue culture industry (Kodym and Zapata-Arias, 2001).

Temporary Immersion Bioreactor Systems (TIBs)

Temporary Immersion Bioreactor Systems (TIBs) have emerged as one of the most important innovations in plant tissue culture for the large-scale propagation of banana. Unlike conventional culture methods that use agar-solidified media, TIBs expose explants to liquid nutrient medium only for short, programmed intervals, followed by complete drainage and aeration. This intermittent immersion strategy ensures adequate nutrient uptake while avoiding prolonged contact with the liquid medium, thereby minimizing physiological disorders such as hyperhydricity and tissue vitrification (Etienne and Berthouly, 2002).

They reported that temporary immersion culture enhances nutrient absorption, improves oxygen availability and promotes efficient gas exchange, leading to vigorous shoot proliferation and healthier plant growth. Because the explants remain immersed only for limited periods, excess water accumulation within the tissues is prevented, allowing the development of morphologically normal and physiologically healthy plantlets.

Among the different temporary immersion systems developed for plant propagation, the RITA (Recipient for Automated Temporary Immersion) bioreactor is one of the most extensively adopted for banana tissue culture. The system consists of separate compartments for nutrient medium and plant material. Through controlled air pressure, the liquid medium is periodically transferred to immerse the explants and subsequently drained back into the reservoir. This automated process minimizes manual intervention, decreases the possibility of contamination and ensures uniform exposure of explants to nutrients (Teisson and Alvard, 1999).

Numerous investigations have demonstrated that TIBs produce significantly higher multiplication rates than

conventional agar-based culture systems. Alvard *et al.* (1993) observed that temporary immersion increased shoot multiplication by approximately three times while simultaneously reducing labour input and production costs. Likewise, Escalona *et al.* (1999) found that banana plantlets cultured in temporary immersion systems exhibited greater shoot biomass, improved leaf expansion, higher chlorophyll content, and superior rooting performance compared with those grown on semi-solid media.

An additional benefit of temporary immersion technology is its ability to minimize hyperhydricity, a common physiological disorder characterized by watery, fragile and malformed tissues resulting from continuous exposure to liquid medium. The alternating cycles of immersion and aeration maintain proper oxygen supply around the explants, thereby promoting normal tissue differentiation and improving overall plant quality (Etienne and Berthouly, 2002).

The periodic immersion of explants also improves nutrient availability by ensuring direct contact between plant tissues and the liquid culture medium. Consequently, mineral nutrients, vitamins, carbohydrates and plant growth regulators are absorbed more efficiently than in agar-solidified media, where nutrient diffusion is relatively slow. This improved nutrient uptake enhances shoot vigour, promotes stronger root development, increases leaf area and ultimately improves acclimatization success after transfer to greenhouse conditions (Georgiev *et al.*, 2014).

From an economic perspective, Temporary Immersion Bioreactor Systems offer substantial advantages for commercial tissue culture laboratories. The elimination of agar from the culture medium significantly reduces media preparation costs because agar is one of the most expensive components of conventional tissue culture media. Furthermore, automation reduces the labour required for medium preparation, explant transfer and routine subculturing, thereby improving production efficiency (Georgiev *et al.*, 2014).

Automation represents another key feature of TIB technology. Modern bioreactors are equipped with programmable control systems capable of regulating immersion duration, immersion frequency, aeration cycles, temperature and nutrient supply. Such automation improves the consistency and reproducibility of tissue culture operations while facilitating the large-scale commercial production of banana plantlets (Teisson and Alvard, 1999).

Temporary immersion systems have also been

successfully incorporated into somatic embryogenesis protocols. Strosse *et al.* (2004) reported that embryogenic cell suspensions maintained in TIBs produced synchronized embryo development, improved embryo maturation and higher regeneration frequencies than conventional shake-flask cultures. These advantages are particularly valuable in genetic transformation and genome-editing studies, where large numbers of regenerable embryos are essential.

More recently, TIB technology has been integrated with advanced sensor-based monitoring systems capable of continuously measuring dissolved oxygen concentration, nutrient utilization, pH and biomass accumulation. Such real-time monitoring enables precise regulation of culture conditions, improves multiplication efficiency and minimizes physiological stress experienced by cultured tissues (Georgiev *et al.*, 2014).

Overall, Temporary Immersion Bioreactor Systems have significantly improved commercial banana micropropagation by increasing multiplication efficiency, lowering production costs, reducing contamination and hyperhydricity, enhancing rooting and acclimatization and enabling automated large-scale propagation. As research continues to refine these systems, TIB technology is expected to become a standard platform for industrial-scale banana tissue culture in the coming years.

Future Perspectives

Banana (*Musa* spp.) tissue culture has become an indispensable component of modern banana improvement programmes because of its role in rapid multiplication, germplasm conservation, disease-free planting material production and genetic transformation. Although significant progress has been achieved in micropropagation techniques over the past few decades, several challenges such as high production costs, contamination, somaclonal variation, limited automation and genotype-dependent responses continue to restrict the large-scale commercial adoption of tissue culture technology (Strosse *et al.*, 2004). Future research is increasingly focused on developing sustainable, cost-effective and precision-based tissue culture systems that integrate advanced biotechnological tools with digital technologies.

Recent developments in molecular biology, genome editing, artificial intelligence, nanotechnology, sensor-based monitoring and automation have opened new opportunities for improving banana tissue culture. Combining tissue culture with modern biotechnology will accelerate the development of climate-resilient, disease-resistant and nutritionally improved banana cultivars (Tripathi *et al.*,

2019). Integrating genome editing technologies with efficient regeneration systems will revolutionize banana improvement by enabling precise modification of economically important traits while maintaining elite cultivar characteristics (Ntui *et al.*, 2020).

The future of banana tissue culture is expected to rely on multidisciplinary approaches that combine plant biotechnology, engineering, computational biology and data science. Such integrated technologies will improve propagation efficiency, reduce production costs, enhance genetic fidelity and facilitate large-scale commercial production of high-quality banana planting materials (Georgiev *et al.*, 2014).

Sustainable Tissue Culture Systems

The development of sustainable tissue culture systems has become a major priority for ensuring environmentally friendly and economically viable banana propagation. Conventional micropropagation relies heavily on agar, synthetic plant growth regulators, disposable plastic culture vessels and energy-intensive growth rooms, all of which increase production costs and generate environmental waste (Kodym and Zapata-Arias, 2001).

Future tissue culture systems are expected to incorporate eco-friendly alternatives that reduce resource consumption while maintaining propagation efficiency. Temporary Immersion Bioreactor Systems (TIBs) significantly reduce the requirement for agar, improve nutrient utilization and decrease labour costs, thereby contributing to sustainable commercial micropropagation. The replacement of fluorescent lamps with energy-efficient LED lighting systems reduces electricity consumption while improving shoot growth and rooting performance (Georgiev *et al.*, 2014).

Researchers are also investigating biodegradable culture containers, recyclable laboratory materials and natural gelling agents to minimize plastic waste generated during tissue culture operations. The utilization of renewable energy sources such as solar-powered growth chambers and climate-controlled greenhouses may further reduce operational costs and environmental impacts (Kodym and Zapata-Arias, 2001).

The optimization of nutrient media through precision nutrient management. Reducing the unnecessary use of expensive chemicals and plant growth regulators while maintaining high multiplication efficiency can significantly lower production costs. Furthermore, improving acclimatization techniques will reduce plant mortality and increase the overall efficiency of commercial banana propagation systems (Strosse *et al.*, 2004).

Integration of Biotechnology

The integration of advanced biotechnological tools with tissue culture has greatly expanded the possibilities for banana improvement. Tissue culture now serves not only as a propagation technique but also as an essential platform for molecular breeding, genetic transformation, genome editing, conservation and functional genomics (Tripathi *et al.*, 2019).

The efficient regeneration systems developed through tissue culture are indispensable for producing genetically transformed banana plants resistant to Fusarium wilt Tropical Race 4 (TR4) (Dale *et al.*, 2017). Combining tissue culture with marker-assisted selection, genomic sequencing and genetic engineering accelerates the development of improved banana cultivars possessing enhanced disease resistance, drought tolerance, nutritional quality and yield potential (Tripathi *et al.*, 2019).

The integration of omics technologies, including genomics, transcriptomics, proteomics, metabolomics and phenomics is expected to provide a comprehensive understanding of gene function during banana growth and development. Such information will facilitate the identification of candidate genes controlling important agronomic traits and improve the efficiency of tissue culture-based breeding programmes. Cryopreservation combined with molecular characterization will strengthen global germplasm conservation efforts by ensuring the long-term preservation of banana genetic resources while maintaining genetic integrity (Panis *et al.*, 2020).

Precision Tissue Culture

Precision tissue culture is an emerging concept that integrates automation, artificial intelligence, robotics and sensor-based monitoring to improve the consistency and efficiency of plant micropropagation. Unlike conventional tissue culture methods, precision systems continuously monitor environmental and physiological parameters to optimize plant growth under controlled conditions (Georgiev *et al.*, 2014).

Artificial intelligence algorithms can analyse thousands of images of cultured plantlets to monitor shoot multiplication, rooting, contamination and morphological abnormalities. Machine learning models are capable of predicting optimal culture conditions by analysing historical experimental data, thereby reducing trial and error experimentation and improving reproducibility (Hesami *et al.*, 2021).

Advanced sensors incorporated into modern bioreactors continuously measure parameters such as pH, temperature, dissolved oxygen concentration, relative

humidity, nutrient availability and carbon dioxide levels. Real-time monitoring allows immediate adjustment of culture conditions, improving multiplication efficiency while reducing physiological stress experienced by cultured tissues (Georgiev *et al.*, 2014).

Robotic systems are also expected to automate routine tissue culture operations including explant preparation, media dispensing, subculturing and plantlet transfer. Automation minimizes human error, reduces contamination and significantly lowers labour costs, making commercial banana micropropagation more efficient and economically competitive (Hesami *et al.*, 2021).

Future Research Priorities

Although substantial progress has been made in banana tissue culture, several research areas require further investigation to overcome current limitations and improve commercial applications. One important priority is the development of genotype-independent regeneration protocols that can be successfully applied to a wide range of banana cultivars, including recalcitrant genotypes (Strosse *et al.*, 2004).

The reduction of somaclonal variation through improved culture protocols, optimized plant growth regulator combinations and routine molecular screening for genetic fidelity. Further studies are also required to understand the molecular mechanisms underlying regeneration, embryogenesis and stress responses during tissue culture (Kaeppeler *et al.*, 2000).

Future investigations should explore the application of artificial intelligence, machine learning and big-data analytics for optimizing culture media, predicting regeneration efficiency and improving decision-making during commercial micropropagation. Similarly, integrating nanotechnology with tissue culture may enhance nutrient delivery, improve disease control and stimulate plant regeneration under controlled conditions (Hesami *et al.*, 2021).

Another important research priority involves improving CRISPR/Cas-mediated genome editing systems by increasing editing efficiency, minimizing off-target mutations and developing DNA-free genome editing approaches. Combining efficient regeneration systems with precise genome editing technologies will accelerate the production of improved banana cultivars possessing resistance to major diseases, enhanced tolerance to climate change and superior fruit quality (Ntui *et al.*, 2020).

Finally, international collaboration among research institutions, biotechnology industries and commercial tissue

culture laboratories will be essential for translating laboratory innovations into affordable technologies for farmers. Such collaborative efforts will strengthen food security, promote sustainable banana production and support the long-term conservation and genetic improvement of banana worldwide.

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