International Journal of Environment and Climate Change

Volume 13, Issue 11, Page 4396-4407, 2023; Article no.IJECC.109721
ISSN: 2581-8627
(Past name: British Journal of Environment & Climate Change, Past ISSN: 2231–4784)

Advancement in Tissue Culture Techniques for Fruit Crops

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/IJECC/2023/v13i113620

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/109721

Review Article

Received: 26/09/2023
Accepted: 01/12/2023
Published: 05/12/2023

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ABSTRACT

Tissue culture is a highly promising approach that enables the efficient propagation of many plants from tiny fragments of the parent plant within a relatively brief timeframe and confined area. Tissue culture, a contemporary approach, is primarily employed for the efficient and extensive replication of many commercially significant plant species, such as the date palm. Utilizing the tissue culture technique presents a potential approach for generating a substantial quantity of genetically homogeneous palm plants that resemble other plants and yield typical fruit within four years from initial planting. Furthermore, this technique allows to produce date palm plants devoid of diseases, exhibiting an exceptionally high survival rate of nearly 100% when compared to the traditional vegetative propagation of shoots, owing to the robustness of their root system. The process of surface sterilization holds significant importance in the production of explants for in vitro studies, as it effectively addresses the issue of bacterial and fungal contamination originating from field sources, which might vary considerably across different fruit plant species. The efficacy of tissue culture techniques for date palm acclimatization in vitro is contingent upon the observation of leaf count prior to transplantation in the greenhouse. Hence, the primary objective of this study was to investigate the determinants that govern the tissue culture of fruit trees. India is known for being the native land of various fruit crops that are both significant and minor in terms of their importance. These crops include Indian gooseberry (*Emblica officinalis* Gaertn.), Karonda (*Carissa carandas* L.), Bael (*Aegle marmelos* Corr.), Jamun (*Syzygium cuminii* L.), and jackfruit (*Artocarpus heterophyllus* L.), etc. These fruits possess considerable nutritional, medicinal, and therapeutic value, making them highly valuable in commercial sectors such as medicine, food, and cosmetics. The limited availability of suitable planting materials imposes constraints on the commercial production process for these crops. Using plant tissue culture techniques holds promise in substantially augmenting the number of novel cultivars or genotypes inside fruit crops. The primary aim of this review study is to consolidate and synthesize the extant body of knowledge about the tissue culture techniques employed in cultivating various fruit crops.

Keywords: Tissue culture; In vitro; Somaclonal variation; Embryo rescue; Molecular marker.

1. INTRODUCTION

Fruits hold significant significance in human existence owing to their consumable, therapeutic, and cultural worth. Global fruit production has reached a substantial level of 896.45 million tons. This notable output is mostly attributed to five key fruit crops: bananas and plantains, watermelons, grapes, oranges, and apples [20,21]. Significant output has been observed in bananas and plantains, which are both classified as fruits. As primary suppliers of essential nutrients and secondary metabolites, fruits play a crucial role in the human diet and possess significant nutritional and therapeutic attributes [4,5,8,12]. In contemporary times, several fruits have emerged as functional foods due to their capacity to offer antioxidants and therapeutic phytochemicals, as evidenced by the research [47]. The demand for fresh fruits and fruit-based goods remains consistent, leading to increased momentum in fruit production across various fruit species. As a result, breeders are placing greater emphasis on achieving higher productivity levels. Post-harvest losses are a significant challenge in obtaining increased output and long-term economic benefits [28,29,31]. These losses are mostly attributed to the perishable nature of the produce, accelerated fruit ripening, and the deterioration of nutritional quality. Furthermore, other issues necessitate ongoing breeding efforts, including an extended juvenile phase, diminished fruit quality, increased seed quantities, and rootstock/scion incompatibility. Within this framework, the utilization of traditional breeding techniques has substantially impacted the advancement of novel and enhanced cultivars regarding fruit quality, aroma, antioxidants, yield, and nutritional characteristics [61]. Nevertheless, given the current challenges posed by climate change and the need for nutritional security, there is a growing need for extensive research efforts and innovative breeding strategies focused on enhancing several traits connected to fruit crops. These qualities include tolerance to biotic and abiotic stresses and an increase in nutritional quality. Several tropical fruits, such as banana, citrus, avocado, dragon fruit, papaya, mango, and guava, have recently garnered increasing interest in applying integrated omics methods [47].

In the present context, several breeding techniques, including polyploidy, in vitro culture, mutagenesis, somaclonal variation, molecular markers, transgenics, and genome editing, are recognized as significant instruments for enhancing traits. Polyploidy in crop plants is frequently linked to an augmentation in cell size, commonly called the gigas effect. This phenomenon has been effectively utilized in ornamental species [10]. The phenomenon of polyploidy has been found to have a notable impact on increased heterozygosity, the emergence of new genotypes, and enhanced vigour [53]. Polyploid plants frequently exhibit unique biochemical, physiological, morphological, and ecological characteristics that facilitate environmental adaptation [41,65]. Multiple instances of polyploid fruit species have been documented in scientific literature, showcasing their advantageous characteristics such as enhanced quality [67] larger fruit size [69], improved disease resistance in Actinidia sp. [68], increased productivity [44], as well as augmented biomass, fruit and flower size, pigment content, and secondary metabolite production [64]. The utilization of induced mutations has been vital in advancing favourable mutants, which have been approved for cultivation as novel crop types worldwide [52,56]. Several noteworthy examples encompass rice, barley, cotton, groundnut, legumes, ornamentals, rapeseed, and Japanese pear. The field of biotechnological research in fruit crops, namely focusing on bananas, strawberries, papaya, pineapple, apples, citrus, and grapes, has seen significant advancements compared to other perennial fruit trees. Research in the field of plant cell and tissue culture has made significant contributions toward the establishment of methodologies for the efficient propagation of superior clones on a wide scale and the production of planting material free from viral contamination. Furthermore, this research has yielded valuable insights into the phenomenon of somaclonal variation, the process of somatic embryogenesis, and the techniques involved in genetic transformation.

Tissue culture is a highly prevalent method utilized for expeditious asexual multiplication in vitro. This technique demonstrates efficiency in terms of time and area use, resulting in increased productivity and producing pathogen-free and superior propagules. Additionally, it enables the secure and controlled transportation of germplasm between countries. When traditional approaches prove insufficient in meeting the demand for propagation material, this technology can generate a vast number of evenly flowering and producing plants. Micropropagation technology plays a crucial role in the efficient and large-scale multiplication of vegetatively propagated plant species, ensuring the preservation of their genetic integrity, quick propagation, and maintenance of their unique characteristics. The global expansion of this technology has been substantial. Various fundamental techniques of tissue culture, including anther/microspore culture, somaclonal variation, embryo culture, and somatic hybridization, are currently being utilized to harness valuable genetic diversity to achieve gradual enhancements in commercial cultivar.

2. TISSUE CULTURE TECHNIQUES IN FRUIT CROPS

The utilization of plant cell and tissue culture techniques has substantially impacted various aspects, including the propagation of economically valuable fruit species, preservation of genetic resources, synthesis of bioactive substances, and manipulation of desirable features through genetic modification. The commercial cultivation of various fruit species has been made feasible by implementing improved techniques for in vitro multiplication. This has been successfully achieved in peach, apple, cherry, apricot, citrus spp., mango, banana, and date palm. Tissue culture technologies have made significant contributions to various aspects of plant growth, including the establishment of techniques to produce plants free from viral infections, the efficient propagation of superior clones, the induction of somatic embryogenesis, the generation of somaclonal variation, the creation of transgenic plants, and the preservation of genetic resources. When dealing with vegetative propagated plants, the utilization of multicellular meristems is a common practice for doing in vitro mutagenesis [66]. Nevertheless, the presence of chimeras and the potential for phenotypic instability pose constraints in this approach.

3. MICROPROPAGATION

Micropropagation has become a viable method for propagating nearly all fruit crops. Using meristem culture has facilitated the production of virus-free planting material in several horticultural crops. Notably, strawberry is one of the initial fruit crops in which micropropagation technology has been established as a standardized practice.

Plants reproduced by in vitro techniques exhibit enhanced uniformity, a greater propensity for runner production, improved field survival rates, and a 24% increase in fruit yield compared to plants propagated through traditional methods. Plant tissue culture offers significant opportunities for the micropropagation of several fruit and horticultural crops, including strawberries, papaya, banana, grapes, pineapple, Citrus, tomato, cucumber, and watermelon. Tissue-based shoot tip culture techniques have significantly contributed to the micropropagation industry in commercial crops like bananas. These techniques have facilitated high-volume in vitro multiplication and the production of superior planting material. Over the past ten years, researchers have successfully achieved mass propagation using somatic embryogenesis and embryogenic cell suspension (ECS) techniques [51]. These findings indicate that these methods have promise for the micropropagation sector. The maintenance of genetic homogeneity in clonally propagated plant populations has emerged as a significant challenge for the micropropagation business, as the occurrence of genetic variation in the offspring of these plants is considered undesirable [49]. One prominent illustration can be seen in the case of bananas, where off-types originating from tissue-cultivated plantlets varied from 6 to 38% in Cavendish cultivars [50]. Nevertheless, older reports have indicated that this percentage could reach as high as 90% [58]. From a business perspective, any variation, especially genetic variation, is seen as detrimental and of little value in micropropagation for commercial purposes. This is because such variations can result in a loss of genetic integrity. In recent decades, genetic variants have been noticeable in vitro cultivated tissues, including undifferentiated cells, isolated protoplasts, and calli tissue [33]. The commercial propagation of bananas is achieved by utilizing tissue culture techniques. The future of the banana business in the country is contingent upon effective management and control of Banana Bunchy Top Virus (BBTV) illness. The optimal solution is using in vitro technology to produce disease-free banana plants to replace fields that have been afflicted. Several fruit crops utilize sexual propagation methods. Certain species exhibit dioecy, wherein male and female flowers are borne on separate individuals.

From a commercial perspective, there is a preference to produce female plants, as these are the ones that give fruits. This objective may be achieved exclusively through the utilization of tissue culture techniques. The process involves grafting a minute shoot tip that has been carefully removed from a superior mother tree onto a rootstock seedling that has been previously decapitated. This rootstock seedling has been cultivated in a sterile environment to ensure optimal conditions for growth. The initial endeavor in Citrus was undertaken, which was subsequently improved upon by Embryo rescue refers to a technique employed in plant breeding and biotechnology that involves rescuing and cultivating embryos from sexually incompatible embryos. Embryo rescue is a distinct domain wherein plant breeders possess the capacity to salvage their hybridizations that would otherwise undergo abortion. Using cultured embryos at appropriate phases of development can effectively address challenges associated with post-zygotic incompatibility. This technique holds great significance in cultivating horticultural species characterized by their hardiness and extended tolerance. The utilization of ovule culture in grape cultivation facilitates the advancement of hybrid cultivars.

4. SOMACLONAL VARIATION

Somaclonal variation is a valuable mechanism for generating novel plant genotypes in breeding. Recent advancements in tissue culture techniques have significantly expanded this phenomenon's potential applications in viticulture. The field of tissue culture techniques has witnessed significant progress, enabling the regeneration of diverse horticultural species by in vitro methods. Micropropagation protocols, designed for large-scale multiplication, have been developed for various crops, facilitating their commercial cultivation. Plant tissue culture can potentially induce genetic variability, specifically somaclonal variants, through gene mutation or alterations in epigenetic markings. Conspicuous somaclonal variation is a disadvantage for both in vitro cloning and germplasm preservation. Somaclonal variation has emerged as a valuable tool for breeders in horticultural crops, particularly those challenging to breed or possessing limited genetic diversity. This phenomenon offers a means to introduce genetic variability quickly and efficiently without needing advanced technological interventions. Somaclonal variants confer advantageous attributes in generating diversity and enhancing resilience to environmental pressures. The phrase "somaclonal variation" was coined by Larkin and Scowcroft to describe the occurrence

of variation resulting from the cultivation of cells or tissues. Somaclonal variants have become increasingly prevalent, and they now serve as a novel means of creating genetic diversity to acquire desirable features. The phenomenon of somaclonal variation holds significant potential in the context of fruit crops, mainly due to their predominant method of vegetative propagation and other breeding challenges, like limited genetic diversity and an extended period of immaturity. Somaclonal variation in conjunction with in vitro selection has been employed as an in vitro methodology to screen desirable traits. The resulting soma clones, enhanced through this process, have found application in breeding fruit crops [62, 45]. The application of selection pressure during in vitro selection, along with accurate identification of somaclonal variation, holds the potential for introducing desirable traits, such as resistance to Phytophthora, herbicide tolerance, and heat tolerance, into strawberry breeding programs [71].

Somatic embryogenesis, temporary immersion, and plant cell cultures exhibit considerable promise for fruit trees' in vitro propagation and genetic modification, including mango, banana, pistachio, apple, papaya, coffee, and date palm. Somatic embryogenesis presents several advantages in comparison to organogenesis. These advantages encompass its notable rates of multiplication, the potential for scaling up through the utilization of bioreactors, and the ability to supply artificial seeds. Furthermore, somatic embryogenesis serves as a viable gene transfer target highlighted [15]. Successfully constructed somatic embryogenic systems in bananas, which have proven to be effective in facilitating high-frequency and large-scale propagation systems and in the creation of mutants by in vitro mutagenesis. Embryogenic cell cultures offer several advantages, including acquiring non-chimeric offspring and efficiently separating chimeric sectors [51]. This system has become a standard practice in numerous prospective applications, such as developing artificial seeds, mutants, transgenic plants, and genome-edited plants [62, 25].

5. FACTORS AFFECTING TISSUE CULTURE OF FRUIT CROPS

Effect of mother plant on tissue culture: The impact of explant type, genotype, and age on shoot regeneration in *Pyrus communism*. The researchers found that the most significant number of shoots and optimal shoot regeneration occurred when leaf sections were cultured on a Murashige and Skoog (MS) medium supplemented with 6.0 mg L^{-1} benzyl adenine (BA) and 0.1 mg L^{-1} naphthaleneacetic acid (NAA) [63]. The issue of phenolic exudation and contamination in guava c.v. "Banaras" was shown to be absent when utilizing somatic embryo-produced young and aseptic plantlets as the source of explants [45]. Shoot tips from three different fig cultivars, namely Aboudi, Gizy, and Sultany, cultivated plantlets. These shoot tips were cultured individually on Murashige and Skoog (MS) medium, supplemented with 0.5 mg L^{-1} 6-Benzylaminopurine [38]. The addition of this growth regulator was found to enhance the development of explants while simultaneously mitigating issues such as necrosis and browning. Simultaneously the successful development of shoot tips of pear rootstock was achieved through cultivation on MS media, compared to using one-nodal cutting [17]. Shoot tips derived from young suckers in banana plants were effectively cultivated on an MS media during the establishing phase [59]. It was discovered that leaf disc explants from two peach rootstocks exhibited good development when cultivated on a medium containing Murashige and Skoog (MS) nutrients [9]. In a study, it was demonstrated that the shoot tip, when utilized as the explant, proved to be an effective method for the micropropagation of banana plants [60]. A study found that nodal segments were more effective than leaf and root segments of citrus trees for inducing callus [54]. Simultaneously, utilizing somatic embryo-produced young and aseptic plantlets as explants source proved effective in micropropagation of the guava cultivar "Banarasi" [46]. An in vitro study was conducted on papaya (*Carica papaya* L.) using five sources of explants (Shoot tip, nodule stem, internode segment, young leaf, and petiole) for shoot proliferation. It was found that all explants formed calli when grown on MS medium + 1 mg L^{-1} BA + 0.5 mg L^{-1} NAA four weeks after culturing. When re-culturing callus on the same components of the nutrient medium, it led to indirect shoot regeneration from callus induced from the shoot tips and nodule stem only.

Effect of surface sterilization on tissue culture: The explants of banana plants underwent surface sterilization using a solution of 0.1% $HgCl_2$ containing tween 20 for 5 minutes. Following this, the explants were meticulously rinsed with sterile, deionized water [60]. It was shown that the survival rate of explants in pomegranate was significantly improved by

subjecting the shoot tip and nodal bud to a 20-minute treatment with sodium hypochlorite (NaOCl), commonly known as Clorox [57]. In a separate investigation about the in vitro propagation of mangoes, it was observed that the utilization of a mixture of 10% sodium hypochlorite (specifically, "Clorox" containing 5.25% sodium hypochlorite, NaOCl) and 0.05% mercuric chloride ($HgCl_2$) for dipping periods of 7 and 10 minutes resulted in the most favourable outcomes in terms of survival percentages and contamination levels. Furthermore, using a 10% sodium hypochlorite solution yielded favourable outcomes regarding surface sterilization, resulting in minimal visible contaminants on the rootstocks. The species referred to as Mariana (*Prunus mariana*) [7]. Furthermore, provided a comprehensive account of the successful surface sterilization of grape tissue (*Vitis vinifera*) by utilizing a 10% sodium hypochlorite solution combined with surfactant drops, with an exposure time of 10 minutes [55]. Immersing explants in a 15% sodium hypochlorite solution for 15 minutes proved an efficacious method for sterilizing grape rootstocks [16].

Effect of phenol exudation on tissue culture: The utilization of activated charcoal in the culture media resulted in the stimulation of initiation and proliferation of woody plants. However, it is essential to note that activated charcoal might have adverse effects, such as the adsorption of growth regulators and the reduction of the medium's pH [22]. Simultaneously, subjecting newly sprouted apple shoots to a prolonged period of darkness effectively diminishes the excretion of phenolic chemicals from those shoots. Conducted a study wherein they tried to develop pomegranate c.v. Mridula in vitro. They observed that using sterile wax on nodal segments reduced phenol exudation and led to a higher proportion of successful establishment of the explants [57]. Various techniques were employed in this study, including maintaining explants in a dark environment following culture. Additionally, antioxidants such as citric acid (100 mg L^{-1}) and ascorbic acid (150 mg L^{-1}) were introduced to the medium for 30 minutes. Furthermore, activated charcoal (3gL^{-1}) was incorporated into the media. Applying these treatments leads to a decrease in the production of phenolic compounds and the occurrence of browning in olive explants [1].

Effect of media strength and type on tissue culture: The study indicated that the medium with half MS strength exhibited the highest shoot number value [37]. Furthermore, the induction of shoot proliferation from nodal explants of grape rootstock was observed when cultured on a medium with half-strength Murashige and Skoog formulation [36]. The date palm exhibited the maximum survival rate (ranging from 70% to 86%) when subjected to a medium strength half medium following a pre-acclimatization stage of one month. In contrast, the survival rate was much lower (12% to 28%) when the date palm was directly transferred to the greenhouse [35]. It was observed that the most substantial enhancement in greening and explant growth per micro flower bud was observed when using full and one-half medium strength compared to one-quarter medium strength in the case of pear "Le Conte" flower buds [70]. Several parameters have been shown to influence the in vitro root production of date palm c.v. Boufeggous plantlets [40]. These factors include the use of solid or liquid medium before acclimatization. Using a liquid medium is considered more appropriate for the intermediate stage of plant growth (solid or semisolid media) before the transplantation of Barhee date palm plantlets into a greenhouse [24]. The survival rate of in vitro acclimatized date palm c.v. Barhee was found to be highest among plantlets cultivated on liquid Ms medium, compared to other medium conditions [72].

Effect of carbon source on tissue culture: In a study conducted on the effect of different concentrations of sucrose (10, 20, 30, 40, and 50 g L^{-1}) added to the MS medium with the aim of multiplication of papaya (*Carica papaya* L.) shoots. It was noted that the concentration of 30 gm L^{-1} sucrose was significantly superior to the rest of the sucrose concentrations in terms of the high response to shoot multiplication. It recorded the highest rate of number of branches, reaching 4.1. shoots per culture. The study demonstrated that adding 30 g L^{-1} sucrose to the growth medium yielded the most favourable outcome for shoot tip explants of papaya [32]. In a study it was demonstrated that a concentration of 30 g L^{-1} of sucrose, used as a carbon source, exhibited the most favourable outcomes for the in vitro rooting of banana (*Musa spp.*) cultivar Grand Naine plantlets [1]. Simultaneously, adding 30-60 g L^{-1} sucrose to the culture medium resulted in optimal explant development and shoot growth of date palms. Fructose, on the other hand, exhibited the highest dry weight values compared to other carbon sources such as glucose, sucrose, and maltose [6]. Including a medium strength treatment resulted in increased

proliferation % and shoot quantity compared to the other treatments [70]. Sucrose concentrations ranging from 30-40 g L^{-1} as carbon sources yielded optimal outcomes in the micropropagation of banana plants [60].

Effect of light, temperature and pH on tissue culture: The factors that influence the growth and development of organisms include light availability, temperature conditions, and pH requirements. Culturing date palm plantlets of the Barhi cultivar in vitro typically involves subjecting them to a light intensity of 2000 lux. This is achieved by utilizing varying quantities of white cool fluorescent lamps, which provide 16 hours of light followed by 8 hours of darkness. This light intensity has been found to enhance several critical parameters under investigation, including root length, root number, shoot length, and greening, compared to alternative light intensities. It was shown that the shoot thickness of the cultures increased when exposed to a light intensity of 3000 lux [27]. Exposure of in vitro plantlets to elevated levels of light intensity (ranging from 4000-12000 lux) and temperature (ranging from 26-36 EC) can potentially result in leaf charring and plantlet wilting [11]. Furthermore, the optimal shoot thickness for in vitro root production of date palm cultivar Barhi was observed when the cultures were exposed to a light intensity of 3000 lux. Documented the number of roots, root length, number of leaves, and greening in the cultures under a light intensity of 2000 lux [72]. Furthermore, subjecting the explant to cold pretreatment at a temperature of 5 EC for three days resulted in the most favourable outcomes regarding the reactions exhibited by peach rootstocks. They minimized root initiation time while maximizing root length at a pH of 5.5 during the medium preparation for in vitro rooting of Banana plantlets, namely the Grand Naine cultivar [2].

Effect of plant hormones on tissue culture: Adding 3 mg L^{-1} BA and 0.5 mg L^{-1} NAA to the culture media resulted in a regeneration response of 71.89% from model segments in citrus plants. The highest rooting percentage (71%) was achieved in certain instances by cultivating callus produced from modal segments on Ms medium enriched with 0.5 mg L^{-1} NAA and 3 mg L^{-1} BA [54]. Adding 1.0 mg L^{-1} BA to the MS medium resulted in the most effective proliferation of almond plantlets of the Nonpareil cultivar. In another study, papaya shoots were multiplied in vitro from axillary bud explant by using different combinations of plant growth regulators. It was found that culturing the axillary buds of papaya plants in MS medium + 1 mg L^{-1} BA and 0.5 mg L^{-1} NAA led to a high shoot multiplication response (100%) and the highest shoot rate reached 4.7 shoots per culture [3]. It was found in a study that culturing the shoot tips of the *Citrus japonica Thumb*. plant in MS medium + 2 mg L^{-1} BA and 15 mg L^{-1} chitosan led to a high response to shoot proliferation and recorded the highest average number of shoots, reaching 5.2 shoots per explant. When the shoots produced from the multiplication were grown on MS medium + 2 mg L^{-1} NAA and 15 mg L^{-1} chitosan, it led to a high response to root induction [48]. Nodule stem explants of moringa (*Moringa oleifera* L.) plant that were grown in MS medium + 1 mg L^{-1} BA and 0.2 mg L^{-1} NAA recorded the highest response rate to shoot proliferation and the number of shoots reached 68.33% and 4.91 shoots, respectively [19]. The highest number of roots and longest root length/plantlets were seen when the concentration of indole acetic acid was 8.0 mg L^{-1} [30]. In a study conducted, it was observed that the addition of 1.0 and 1.5 mg L^{-1} of benzylaminopurine (BAP) in combination with 1.0 mg L^{-1} of indole-3-butyric acid (IBA) resulted in a survival rate of 96.7% for MM 106 apple plantlets and 93.3% for Anna apple plantlets [26]. Furthermore, adding 0.5 mg L^{-1} BAP to the MS medium stimulated shoot proliferation, with an average of 5.37 shoots per explant seen in a study conducted on a dwarfing cherry rootstock [34]. The findings of this study indicate that the addition of 2.22 mg L^{-1} BAP to the Olive medium resulted in the highest proliferation rates, with an average of 3.4 additional explants observed after 30 days. OM treated with 3 g L^{-1} IBA achieved a rooting rate of 85% in similar circumstances. Simultaneously, applying a high cytokinin concentration resulted in jojoba's most effective shoot proliferation [42].

6. SECONDARY METABOLITE PRODUCTION THROUGH TISSUE CULTURE

The term "secondary metabolite" pertains to a molecule synthesized by plants that is not essential for their primary growth and development [43]. Throughout history, humans have extensively utilized the derivatives of plant secondary metabolism to fulfill a diverse range of requirements [13]. The predominant application of these substances has historically been in medicine, initially by empirical methods and then, in the 19th century, through a more systematic

approach facilitated by the isolation of molecules [13]. Secondary metabolites are commonly identified by their intricate and varied chemical composition, often consisting of several chiral centers and labile bonds, which presents difficulties in their chemical production [43]. Hence, the extraction of biologically active compounds is predominantly derived from their natural sources. Nevertheless, due to the prevalence of wild plants as opposed to cultivated varieties, there is a potential hazard of over-utilization and a subsequent constraint in synthesizing these substances when sourcing from their native environments. The regulated cultivation of plant cells and tissues in a laboratory setting, known as in vitro culture, provides a robust technological framework for synthesizing plant-derived natural compounds. In vitro propagation, called micropropagation, involves cultivating plants or plant organs (often roots) or calluses in a controlled laboratory environment. This technique has been shown to yield plant material capable of creating secondary metabolites [39, 18]. Micropropagation has emerged as a financially profitable venture, offering significant benefits compared to traditional horticultural propagation methods. It enables the consistent production of a large quantity of genetically identical plants throughout the year, the creation of pathogen-free plant materials, and a notable increase in multiplication rates [14]. Using plant cell culture has emerged as a highly effective method for producing several valuable natural products. The array of economically significant products encompasses colours such as anthocyanins and betacyanins, anti-inflammatory drugs like berberine and rosmarinic acid, and anti-cancer compounds such as paclitaxel and podophyllotoxin [23].

7. CONCLUSION

The propagation of new plants by plant tissue culture (PTC) exhibits promising commercial potential across various plant categories, encompassing crops, fruits, vegetables, and ornamental species. Over 100 species in India have undergone reengineering through contemporary PTC methods. According to current estimates, India can generate about 350 million cultured plants annually. The utilization of PTC in plant biology offers potential solutions to various challenges encountered in experimental biology, particularly laborious when using traditional methods. PTC currently assumes a substantial role in preserving plant well-being, encompassing several aspects such as genetic engineering, breeding, and afforestation. The agriculture and horticulture industries have greatly benefited from its various advantages, including cultivating plants resistant to pests, diseases, and viruses. Creating plants that exhibit resistance to abiotic stressors and possess biofortified traits has significantly influenced the trajectory of contemporary agriculture and food production. The commercial cultivation of plants through PTC industries holds significant promise and potential, if production facilities can overcome many limitations, including the availability of advanced research resources, financial considerations, and effective marketing strategies. India possesses a range of agroclimatic zones and benefits from cost-effective labour availability. These advantageous conditions, along with the implementation of government initiatives, have the potential to facilitate India's sustained self-sufficiency in agricultural production. Moreover, digital technologies can bring about a transformative impact on the PTC (Plant Tissue Culture) market. The research and implementation of novel software for the purpose of monitoring plant growth, alongside the introduction of mobile applications designed to assist farmers and industrialists in various stages of the plant production process, ranging from the collecting of explants to the final sale of fully developed plants in the market. Considering these various considerations, it can be said that the Indian tissue culture business, despite its relatively late start, has the potential to have a significant impact on the global stage.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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