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DEVELOPMENT OF PLANT TISSUE CULTURE AND INDOOR FARMING SYSTEMS IN CONTROLLED ENVIRONMENTAL CONDITIONS USING LIGHT-EMITTING DIODES (LEDs) FOR THE PRODUCTION OF HIGH-VALUE CROPS

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Abstract

The plant tissue culture system makes it possible to produce plants in a controlled environment under sterile conditions in large quantities and at a constant and faster rate. Light is one of the most important variables that can affect the growth and development of plant tissue culture, influencing photosynthesis, morphogenesis and physiological processes. Light-emitting diodes (LEDs) are useful in this scenario as they allow the irradiation of a narrow spectrum of light that meets the requirements of plants for their growth and development. Different LED-generated spectra with uniform intensity are used in plant tissue culture to enhance plant growth, development and proliferation. In a vertical farming system, LEDs can be used as energy-efficient light sources to produce high-quality products with high nutritional value. Commercially viable growing systems for high-value vegetables such as premium lettuces, herbs, microgreens, edible flowers and strawberry plants have been developed. The continuous acquisition of new concepts and knowledge in photobiology and plant morphogenesis, complemented by the rapid development of LED technology, will make the application of solid-state lighting more remunerative.

Key words: *Indoor Farming, Light-emitting diodes, Plant Tissue Culture, Secondary Metabolites.*

INTRODUCTION

Plant tissue culture (PTC) is a fundamental science from the field of plant biotechnology that contributes to the understanding of plant growth and development at the cellular level (Sudheer et al., 2022; Nautiyal et al., 2024; Raj et al., 2025). Plant tissue culture is defined as an *in vitro* method for growing or manipulating plant cells, tissues, organs or whole plantlets under sterile and controlled environmental conditions such as temperature, light and humidity on a culture medium. This method is based on totipotency (each living plant cell has the genetic potential to regenerate into a whole plant) and plasticity (the ability of cells to change their developmental pathway in response to external stimuli) (Bidabadi and Jain, 2020). PTC was first proposed in 1902 by the German botanist Gottlieb Haberlandt, who is widely regarded as the father of plant tissue culture (Gaikwad et al., 2017). He cultured palisade tissue in Knop's solution with sucrose and observed cell growth. In 1904, Hanning successfully cultured excised crucifer embryos on a mineral sugar medium, a technique that was later further developed by Overbeck in 1941. An important milestone was reached in 1972 when Carlson et al. created the first somatic hybrid by fusing protoplasts of *Nicotiana glauca* Graham (Solanaceae) and *N. langsdorffii* Weinm. (Evans and Flick, 1983). Tissue culture was first used by the orchid industry for mass propagation in the 1950s.

PTC overcomes the limitations of conventional propagation, especially for species with limited or unprofitable seed production, by providing a platform for the rapid clonal propagation of elite genotypes and the production of genetically uniform stocks (Smith and Drew, 2000). Any plant organ, such as roots, stems, buds, apical meristems, cotyledon nodes, leaves, anthers or ovaries, can be used for culture. Meristem tip culture provides pathogen-free planting material, which is crucial for vegetatively propagated plants such as banana and potato (Krishna et al., 2022). The technique also supports *in vitro* conservation and cryopreservation protocols, protecting the germplasm of rare or endangered taxa. In addition, totipotent regeneration systems are essential for modern biotechnology, as they serve as a regenerative backbone for genetic transformation, genome editing and the production of double haploids, which together accelerate breeding cycles and trait introgression (Altman, 2003).

Some of the applications of PTC are summarised in Table 1. From a sustainability perspective, closed, aseptic culture systems require significantly lower inputs of land, water and agrochemicals than field propagation (El-Sherif, 2018). The agronomic impact is illustrated in Bihar, India, where the use of tissue culture-derived, virus-indexed banana plantlets increased yields from ~20 t ha^{-1} in 2004-2005 to ~45 t ha^{-1} in 2022-2023 (Kumar et al., 2024). However, there are various challenges associated with *in vitro* cultivations (Ramlal et al., 2024; Bishnoi et al., 2025) and there is a need to include PTC in modern research due to its wide application and need (Negi et al., 2024). Light and physical conditions (temperature, relative humidity) are very important for the proper growth and development of plants, as they regulate the basic processes (Cavallaro et al., 2022). Incandescent lamps (IL), fluorescent tubes (FL), high-pressure sodium lamps (HP-Na) and metal halide lamps (MH) used to be common; however, these are being replaced by more efficient and promising technologies (Cavallaro et al., 2022). Light-emitting diodes (LEDs) are an emerging tool with promising benefits for *in vitro* cultures, especially for plant improvement and secondary metabolite production (Livadariu et al., 2023; Sena et al., 2024). Maintaining controlled environmental conditions is also crucial for the continuous supply of healthy and good biomass of crops. Therefore, given the prevailing irregularities in climatic changes and the loss of agricultural land, alternative approaches should be utilised.

This article provides an overview of the importance of plant tissue culture, the importance of light, including light-emitting diodes, and vertical rearing in the mass propagation of tissue-cultured plants.

Table 1. Areas of application of plant tissue culture

Areas of application	Tissue culture	Typical outcome/benefit	References
Micro-propagation	Multiplication via nodal, shoot-tip, or somatic embryo culture	Uniform, true-to-type plants (oil-palm, banana, ornamental foliage)	Butt et al., 2015
Virus elimination	Meristem culture + thermotherapy/chemotherapy	Clean stock of potatoes, sweet potatoes, and cassava	Naik and Buckseth, 2018
Haploid & doubled-haploid production	Anther/ovule or microspore culture	Completely homozygous lines in one generation for cereals, rapeseed	Niazian and Shariatpanahi, 2020; Ramlal et al., 2023
Somaclonal variation/*in vitro* mutagenesis	Callus culture followed by variant screening	Novel traits such as low-caffeine coffee, dwarf ornamentals, grapevine, sugarcane	Bairu et al., 2011
Genetic transformation & genome editing	*Agrobacterium*-mediated or biolistic gene delivery followed by regeneration	Transgenic/herbicide-tolerant or CRISPR-edited crops	Altpeter et al., 2016
Protoplast fusion	Fusion of somatic protoplasts, regeneration of hybrids	Interspecific hybrids (e.g., tomato × potato “pomato”)	Karp et al., 1987
Secondary-metabolite production	Cell-suspension or hairy-root cultures in bioreactors	Constant supply of paclitaxel (Taxus), shikonin (Lithospermum)	Dörnenburg and Knorr, 1995
Conservation & seed-sector back-ups	Slow-growth storage, cryopreservation	Long-term safekeeping of coconut, yam, and *Musa* germplasm	Rajasekharan and Sahijram, 2015

Areas of application	Tissue culture	Typical outcome/benefit	References
Physiology & stress studies	Controlled *in vitro* assays	Rapid screening for salt- or drought-tolerant lines or embryogenesis-related studies	Sahu et al., 2023; Nautiyal et al., 2024
Cryopreservation	Orchid preservation in liquid nitrogen for long-term storage	Long-term preservation of germplasm using liquid nitrogen	James Antony et al., 2019
Suspension cultures	Biomass increase of certain cells for the production and enhancement of secondary metabolites	Secondary metabolite production	Lim et al., 2025

LIGHT-EMITTING DIODE (LED) TECHNOLOGY IN PLANT TISSUE CULTURE

Light, both quantity and quality as well as photoperiod, are the most important factors influencing the light-induced responses in plants responsible for growth and development under artificial culture conditions. Illumination is essential for the induction of photosynthesis and photomorphogenic responses in a controlled environment (Batista et al., 2018; Murthy et al., 2024). Artificial light sources have long been used in PTCs and growth rooms, including FL, such as cold cathode fluorescent lamps (Ding et al., 2010), high pressure sodium lamps (HP-Na) and plasma lamps were used for comparison of cucumber production by Guo et al. (2016), MHL and IL light by Dutta Gupta and Jatothu, (2013). However, they were replaced by LED technology due to several disadvantages, which include the generation of more heat, energy consumption and differences in absorption spectra that hinder plant growth under *in vitro* conditions (Xu et al., 2016).

On the other hand, the use of LED technology in PTC is advantageous in terms of longevity, space saving, lower heat dissipation and no use of mercury (Shukla et al., 2017; Batista et al., 2018; Ying et al., 2020; Gnasekaran et al., 2021). LEDs have been proposed as a primary light source for space-based plant research chambers and as a potential replacement light source for plant growth and development in vitro to achieve the success of commercial LED lighting (Bello-Bello et al., 2017; Barceló-Muñoz et al., 2022). So far, many plants have been tested under LED, for example Momordica cochinchinensis, *Ficus carica* var. 'Black Jack', *Zingiber officinale* var. rubrum Theilade, *Hylocereus costaricensis*, *Cucumis metuliferus* and white strawberry (Lim et al, 2020; Gnasekaran et al, 2021; Parab et al, 2021; Winson et al, 2021; Lai et al, 2022; Pang et al, 2023a, 2023b), the spectra produced by LEDs will have uniform intensity and quality, which is a better source for plant growth and development. Developing an ideal lighting system with optimal light intensity, best lighting position and lighting times while saving energy is the most important goal in this field.

INDOOR VERTICAL FARMING

One of the global threats at present is global warming and the associated climate change. Greenhouse gas emissions such as carbon dioxide (CO_2), which is released when fossil fuels are burned, and other gases such as nitrous oxide, methane and chlorofluorocarbons contribute to global warming. As a result, the temperature and precipitation in the Earth's atmosphere are disturbed, which is exacerbated by anthropogenic activities (Malhi et al., 2021). This in turn affects agriculture and its production, leading to lower yields, higher prices and reduced food availability, which in turn leads to food insecurity. This is exacerbated by the unprecedented increase in population at an alarming rate and the loss of agricultural land to urbanisation.

It will therefore become even more difficult in the coming years to find suitable land for agriculture to meet the growing demand for food (Arora, 2019). Therefore, alternatives should be explored to maximise yield in a sustainable and promising way. Controlled environment farming systems, such as vertical farming (VF) and indoor farming, have the potential to increase production in the most sustainable way possible without compromising yield and quality (Avendaño-Abarca et al., 2022). VF can be defined as a multi-tiered production system where yield is a function of area. Sharathkumar et al (2020): "A multi-tiered indoor crop production system in which all growth factors such as light, temperature, humidity, CO_2 concentration, water and nutrients are precisely controlled to produce high quantities of high-quality fresh produce throughout the year, completely independent of sunlight and other outdoor conditions". Depending on the needs and requirements, VFs have different facilities such as plant factories with artificial lighting, container farms, in-store farms and equipment farms (Butturini and Marcelis, 2020). Avendaño-Abarca et al. (2022) have shown that vertical indoor farming increases strawberry production in conjunction with LED technology, especially with green and red LEDs.

CONCLUSIONS

The field of plant tissue culture plays an important role in the maintenance of germplasm and mass propagation. LED technology also offers immense potential for plants grown *in vitro*. These technological approaches, including LEDs and indoor vertical farming, are therefore recommended to explore further possibilities and ways to maximise yield.

Author contributions

S. Subramaniam conceived the study and supervision. Ay. Ramlal and S. Subramaniam were involved in editing and revisions. Both authors have read and approved the final manuscript.

Data availability statement

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Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publishing

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Competing interests

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