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Plant tissue culture for sustainable agriculture

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Sustainable agriculture is being impacted by global climate change and population growth, particularly in developing countries, where small-scale farmers have historically managed a number of planting materials. As a result, farmers cultivating food and staple crops like yams, taro, plantains, etc., are unable to consume their harvests, even while facing hunger and poverty due to insufficient planting materials. They must reserve substantial portions of their harvested crops to use as planting materials for the next planting season, while uncertain if any biotic and abiotic factors might affect their agricultural yields. Plant tissue culture, as a novel biotechnological approach in agriculture, has the potential to address farmers' concerns about having access to year-round planting materials. Once effectively implemented, it can enable them to utilize their harvested food crops for both consumption and income generation, which can contribute to improving their livelihoods. Furthermore, plant tissue culture emerges as a promising technique for improving crop varieties and increasing production efficiency by generating disease-free plants with desirable traits. Despite the high prices and microbial contamination, plant tissue culture has the potential to enhance food security and reduce poverty rates among smallholder farmers. Ultimately, it is a crucial resource for improving life quality in developing countries and promoting agricultural sustainability.

INTRODUCTION

Global climate change and the rising world population's impact on sustainable agriculture

For centuries, peasants and small farmers in the developing countries have managed, selected, enhanced, multiplied, stored, and exchanged planting materials. These practices produce biodiverse, ecologically resilient plants that are capable of adapting to both abiotic and biotic stresses (Da Vià 2012; Altieri *et al.,* 2012). Smallholder farmers are now compelled to adapt their farming practices as a result of the impact of global climate change on agricultural productivity (Abebaw, 2025; Cohn *et al.,* 2017; Makuvaro *et al.,* 2018). Recent research underlines that the existing high-yield global agriculture system, which is dependent on high yields, is unable to provide food security and the preservation of biodiversity for agricultural sustainability. Although high yields are necessary for ensuring food security of a growing population, they often deplete soil health, biodiversity, and crop varieties. Additionally, economic factors, including the rising input costs and low product prices, hinder farmers' capacity to implement sustainable agriculture and preserve planting material diversity (Pretty, 2018).

Plant tissue culture as an effective alternative for crop improvement

Plant tissue culture, becoming an essential state-of-the-art technique in modern agriculture, horticulture, and biotechnology, plays a crucial role in overcoming the new global climate challenges. Crop improvement through tissue culture involves using plant biotechnology to develop novel and improved plant varieties by generating genetic diversity (Giller *et al.,* 2021). It facilitates the mass propagation of disease-free plants and enhances traits such as stress tolerance and disease resistance (Kumar *et al.,* 2025; Sehgal and Khan, 2020). The techniques include cell culture-derived soma clonal variants, haploid production via anthers or microspore cultures for rapid homozygous plant creation, genetic transformation to introduce foreign genes, and gene editing with CRISPR-Cas9 for precise genetic modifications as new essential tools for crop improvement. They speed up breeding cycles and introduce desired traits that conventional breeding may find challenging to achieve (Khezri *et al.,* 2024; Quiroz *et al.,* 2025; Manchanda *et al.,* 2024; Wijerathna-Yapa *et al.,* 2022). For vegetatively propagated crops like bananas and plantains, conventional propagation relies heavily on suckers, which are prone to pest and disease transmission. Tissue culture provides a clean and scalable alternative (Hemanthakumar and Preetha, 2023; Drenth, 2021). Additionally, plant tissue culture allows rapid, efficient and disease-free genetically uniform plants (clones) with desirable traits, from a single parent plant.

Plant tissue culture stages

The plant tissue culture involves several critical stages: explant selection/collection and sterilization (Stage 0), culture initiation/establishment (Stage 1), shoot multiplication under optimized growth hormones (Stage 2), root induction (Stage 3), and ultimately hardening in a controlled chamber and acclimatization in a greenhouse (Stage 4) (Phillips and Garda, 2019, Rinaldi *et al.,* 2012). Aseptic conditions with optimized and effective protocols are required throughout the different stages to ensure high survival rates and genetic fidelity. Stage ‘0’ involves selecting and sterilizing an explant, such as leaves, stems, roots, flowers, nodes, seeds, or meristematic tissue, to eliminate surface contaminants. This process includes washing explants with detergent and ethanol and rinsing with sterile water. In stage ‘1’, sterile growth media including macro and micronutrients, growth regulators, and a gelling agent such as agar and gelrite are prepared. This media is sterilized using autoclaving, and explants are inoculated onto the sterilized medium within a laminar flow hood in a sterile environment. Stage ‘2’ allows explants to multiply into several plantlets. Subculturing is often required to transfer the developing plantlets to fresh nutrient-rich media for continued growth. Stage ‘3’ begins when plantlets develop shoots, and adjustments to the growth medium are made to promote root development. This usually involves changing the plant growth hormones. In stage ‘4’, rooted and healthy plantlets are gradually hardened and transferred to a greenhouse or soil environment (Stage 4). This hardening-off process helps the plants adapt to the new temperature, humidity, and light conditions before being planted in the fields. All these stages facilitate the development of disease-free plantlets, lessening the dependence on chemical pesticides, and aid in the preservation of threatened plant species, thereby enhancing food security and promoting environmental sustainability (Sirangi, 2025; Ragavendran and Natarajan, 2017).

Challenges in plant tissue culture

Several challenges are encountered in plant tissue culture. Among them are maintaining sterility, managing phenol exudation, and hyper-hydricity. The major hurdle is contamination from bacteria and fungi, particularly in large-scale production. Other significant hurdles encompass the recalcitrance of certain plant species to tissue culture and the complexity of acclimatizing some plantlets from laboratory to natural conditions (Natarajan *et al.,* 2025, Permadi *et al.,* 2023). Moreover, soma clonal variation may also compromise the plant uniformity and affect yields and fruit quality. The infrastructure and equipment cost, media, and labor can also be prohibitively expensive (Abebaw *et al.,* 2021). Addressing those technical challenges requires ongoing technical training, standardization of protocols, and integration of a cost-effective production system.

Accessible crop production systems: Plant tissue as a key to facilitate planting materials supply to farmers

Notwithstanding the various challenges associated with its methodologies, plant tissue culture offers farmers the opportunity to get pathogen-free and vigorous plants capable of significantly improved yields for rapid and large-scale production, ensuring uniformity in growth and maturity (Manchanda *et al.,* 2024, Husen, 2024). In areas where major staple crops (e.g., banana, plantain, yams, potato, cassava, etc.) are difficult to propagate conventionally or from traditional sucker-derived plants, tissue culture enables large-scale availability of planting materials for farming use year-round, breaking the seasonal constraints faced by farmers (El-Sherif, 2018). It will be of great interest to supply farmers with a considerable number of planting materials, even for species that have high demand. This approach allows farmers to increase their stock of desired plant varieties without relying on their planting materials or traditional propagation methods. Additionally, tissue culture can be used for the conservation of endangered plant varieties through cryopreservation for future use or reintroduction into the agricultural field.

The importance of plant tissue for farmers’ subsistence and poverty alleviation

The deployment of large-scale tissue culture has the potential to alleviate poverty by increasing productivity and improving the income of the smallholder farmers. Plant tissue culture eliminates seasonal dependency (Year-round production), ensuring a steady supply of planting materials throughout the year. This emerging technology of tissue culture provides an effective way to maintain a stable and profitable farming industry, particularly in developing countries. With tissue culture, small farmers are no longer scared when consuming their harvested crops, as they can still receive a supply of new, high-quality plant materials for future planting, knowing that tissue culture offers a sustainable way to regenerate and maintain elite plant genetics. A Single explant from a healthy mother plant can be cloned into thousands, and plant tissue culture, as season-independent, can ensure farmers with a steady supply of disease-free planting material year-round to fulfill their needs. With the possibility of doubling the yields compared to traditional systems, plant tissue is of great interest to enhance food security and household income (Opabode, 2017). For example, by reducing reliance on suckers and vegetative propagation, farmers minimize the spread of devastating diseases such as Banana Bunchy Top Virus (BBTV) and Fusarium wilt, which threaten global production. From a developmental perspective, tissue culture technology aligns with global agricultural transformation goals by fostering sustainable intensification, poverty reduction, and climate resilience. Partnerships with small industries and supportive government policies are very crucial to scale production in agriculture and ensure accessibility for smallholders.

Conclusion

Tissue culture is not merely a laboratory tool but a strategic driver of agricultural development, enabling food system stability, improved nutrition, and enhanced farmer livelihoods. Integrating genomics, transcriptomics, and metabolomics into plant tissue culture could improve regeneration and conservation protocols and allow for the extraction and analysis of beneficial plant-derived compounds for industrial use.

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