Sustainable Banana and Plantain Cultivation: The Role of Micropropagation and Macropropagation in Genetic Conservation and Crop Production

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Abstract: In the face of climate change, food security crops like bananas and plantains are essential in tropical regions, because they are vital for food security and economic stability, but they face significant challenges from pests, diseases, and climate change, threatening their sustainability. In response to these challenges, micropropagation and macropropagation have emerged as promising techniques for improving banana and plantain production. One of the key challenges facing the expansion of banana and plantain farming is the insufficient supply of healthy propagules. Farmers typically rely on the natural regeneration of suckers for planting material due to their easy availability. However, despite their accessibility, sucker production in the field is a slow process that yields limited quantities of planting material, which are often contaminated with soil borne pathogens such as nematodes. Micropropagation involves the rapid multiplication of plant material under aseptic conditions, providing disease free planting material and conserving genetic resources. Macropropagation, which induces plantlets from banana corms, is faster and more cost effective. This review examines the role of these techniques in enhancing crop yields, conserving genetic resources, and promoting sustainable agriculture, we discusses benefits, challenges, and future directions, highlighting the potential of micropropagation and macropropagation to support resilient and sustainable banana and plantain production systems. Ultimately, the adoption of these techniques could play a crucial role in addressing the pressing challenges faced by banana and plantain farmers, thereby supporting food security and economic stability in regions dependent on these crops.

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Introduction

Banana and plantain (*Musa* spp. L) are perennial crops that thrive in humid tropical and subtropical climates. Bananas and plantains rank as the fourth most important food crop, with the majority of production and consumption occurring within tropical and subtropical regions. Bananas and plantains thrive mainly between latitudes 20ºN and 20ºS, where tropical climates prevail. Optimal growth and flowering occur at temperatures ranging from 22 ºC to 31 ºC, accompanied by evenly distributed annual rainfall of 2000–2500 mm (Robinson and Saúco, 2010). The crop is cultivated in over 120 countries, yielding approximately 104 million tons annually, with roughly one third of production distributed across each continent. From 2010 to 2020, global banana production grew by 9.96%, reaching 119 million tons. Bananas ranked as the fourth most harvested crop worldwide, following rice, wheat, and maize. They are among the most widely consumed and affordable fruits globally. In 2014, India was the leading producer, contributing about 29% of the world's total banana production, followed by China, Philippines, Brazil, and Ecuador (Panigrahi *et al.,* 2021), and in 2024 in many Asian and African nations, plantain and banana rank as the second most widely produced fruits after citrus (Al-Dairi *et al.,* 2023), contributing approximately 16% to global fruit production. Globally, the leading banana exporters include Ecuador (6.81 million tons) and the Philippines (2.38 million tons), among others. (FAO, 2024)

Banana and plantain serves as major sources of calories and income for millions of people. These crops are highly valued not only for their nutritional content but also for their socio economic contributions to rural livelihoods. Banana and plantain are naturally well known for their soft texture, pleasant aroma, and the convenience of being easy to peel and eat. The plant can grow to a height of 6–8 meters, with its leaves arranged in a spiral pattern, it can be eaten fresh or processed into a variety of products on both small and industrial scales, such as chips, dried fruit,ice cream, smoothies, and flour (Debabandya *et al.,* 2010; Al-Dairi *et al.,* 2023). These crops play a vital role in contributing to food security and serve as a significant source of export income for several countries.(Siddiq *et al.,* 2020). Bananas and plantains supply more than 25% of the carbohydrate requirements for over 70 million people in Africa and beyond (Udomkun *et al.,* 2021), they are a rich source of essential minerals, including iron, sodium, potassium, copper, magnesium, and calcium, as well as vitamins such as vitamin C, niacin, thiamine, and folic acid. In addition to their high nutritional content, they contain numerous beneficial bioactive compounds. Research has shown that they provide phenolics, volatile compounds, phytosterols, carotenoids, flavonoids, biogenic amines, and dietary fiber, all of which contribute to human health and well being (Mengstu *et al.,* 2021: Nitamani *et al.,* 2023).

The banana plant is valued not only for its delicious fruit but also for its production of textile grade fiber (Mohammed and Shymaa, 2021). Beyond their use as food, bananas and plantains generate large quantities of waste such as peels and other by products that can be repurposed for energy production, biofertilizers, biomethane, and biodegradable packaging materials (Bangar *et al.*, 2023). These by products, are often major contributors to environmental pollution, and can become valuable resources when repurposed into useful products for both food and non food industries. Their utilization not only significantly reduces pollution but also plays an important role in promoting a circular economy. Sap extracted from the banana pseudostem was used to develop a biofertilizer for onions for reducing the dependence on chemical fertilizers and also for increasing yield (Abro *et al.*, 2023). Enhancing bananas through traditional breeding methods is challenging due to their long generation cycles, differing ploidy levels, the sterility of most edible varieties, and limited genetic diversity. Nevertheless, several improved hybrids have been developed that combine resistance to black Sigatoka with desirable agronomic traits (Pillay *et al.*, 2024). Some banana cultivars require over a year to reach maturity, making the breeding process significantly longer compared to annual crops. As a result, breeders now focus much of their efforts on generating progeny from crosses rather than on their evaluation (Tripathi *et al.*, 2007).

Despite their importance, banana and plantain production faces multiple challenges, including pests and diseases (Banana Bunchy, Panama disease, Top Virus), low genetic diversity, and climate related stresses such as drought and flooding. (Viljoen, 2010). Additionally, both excessive and insufficient soil moisture significantly contribute to global crop yield losses (Idahosa *et al.,* 2010). The conventional propagation of banana and plantain using suckers is slow, often results in low multiplication rates, and can spread pathogens, and enhancing bananas through traditional breeding methods is challenging due to their long generation cycles, differing ploidy levels, the sterility of most edible varieties, and limited genetic diversity. Nevertheless, several improved hybrids have been developed that combine resistance to black Sigatoka with desirable agronomic traits (Pillay *et al.,* 2024). Some banana cultivars require over a year to reach maturity, making the breeding process significantly longer compared to annual crops. As a result, breeders now focus much of their efforts on generating progeny from crosses rather than on their evaluation (Tripathi *et al.,* 2007). These limitations underscore the urgent need for alternative propagation methods that support sustainable production and genetic conservation. Micropropagation and macropropagation are two complementary techniques that address these challenges (Njukwe *et al.,* 2013). Micropropagation, a tissue culture based method, allows for the rapid, large scale production of disease free planting material. Macropropagation, a more traditional technique involving corm treatment to stimulate sucker production, is cost effective and suitable for on farm use. Both methods have shown promise in improving the availability of clean planting material, enhancing genetic conservation efforts, and increasing productivity in smallholder systems. The main objective of his review explores the roles of micropropagation and macropropagation in sustainable banana and plantain cultivation and their advantages, limitations, and contributions to genetic conservation and production efficiency, aiming to guide researchers, extension agents, and policymakers in promoting sustainable and resilient banana and plaintain based systems.

Importance of Banana and Plantain in Food Security and Livelihoods

Bananas and plantains are essential components of food systems in many developing countries. They provide carbohydrates, vitamins (particularly vitamin A and C), and minerals such as potassium and magnesium (Oyeyinka and Afolayan, 2019). In addition to being a vital food source, these crops generate income for farmers through local markets and export chains. For instance, bananas are among the most traded fruits globally, with significant export volumes from Latin America and Africa (Van der Waal, 2010). In rural communities, banana and plantain cultivation supports household food security and provides year round harvests, offering economic resilience in times of seasonal food shortages (Adi, 2024). The relatively short growth cycle and adaptability to diverse agroecological zones make them particularly valuable for smallholder farmers. However, their productivity is often constrained by biotic and abiotic stresses, which can severely limit yields and affect livelihoods.

Locally, both banana and plantain markets contribute to employment in farming, transportation, processing, and retail sectors. Value added products such as banana chips, flour, and beverages further enhance their economic importance and create opportunities for small scale agribusinesses and rural development (Tripathi *et al.,* 2019).

Challenges in Conventional Propagation and Production

Traditional sucker propagation, while widely practiced, is limited by low multiplication rates and a high risk of disease transmission (Tumuhimbise and Talengera, 2018). The practice often relies on selecting suckers from infected mother plants, contributing to the persistence and spread of pathogens in the field. Additionally, the slow rate of sucker development restricts the scalability of planting material, hindering the expansion of banana and plantain cultivation. Moreover, many banana cultivars are sterile or triploid, making sexual reproduction and seed based propagation unfeasible. This further limits genetic recombination and complicates breeding efforts. The genetic uniformity of widely grown cultivars, such as the Cavendish group, increases vulnerability to emerging diseases and environmental stresses, underscoring the need for propagation techniques that can maintain and diversify genetic resources. (Ortiz, 2013)

Banana and plantain production faces several challenges, particularly with conventional propagation and cultivation methods:

1. Limited Propagation Capacity: Traditional propagation relies on suckers (offshoots), which produce a limited number of planting materials. This slows down large scale cultivation and makes it difficult to meet growing demand or expand farms quickly. (Ntamwira *et al.,* 2017)
2. Pest and Disease Pressure: Conventional propagation often spreads pests and diseases like Panama disease (Fusarium wilt), Black Sigatoka, and Banana Bunchy Top Virus. Since the planting material is usually taken from infected parent plants, these diseases can rapidly spread and devastate entire plantations.
3. Low Genetic Diversity: Most commercial banana and plantain varieties are genetically similar and sterile, which limits natural breeding. This low genetic diversity makes the crops highly vulnerable to diseases and environmental stress, as there's little resistance variation within the population. (Manzo-Sánchez, 2017)
4. Labor Intensive Practices: Banana and plantain farming is labor intensive, particularly in land preparation, weeding, de suckering, and harvesting. This increases production costs, especially where mechanization is limited.
5. Climate Sensitivity: Conventional production is highly sensitive to climate variability. Drought, flooding, and extreme weather conditions can severely affect yields and plant health, particularly in regions without irrigation or adaptive farming practices.
6. Post Harvest Losses: High perishability and inadequate storage, transport, and processing infrastructure lead to significant post harvest losses. This reduces profits for farmers and limits the availability of bananas and plantains in distant markets. (Kainga and Sikpi, 2019)

Micropropagation: Technique, Benefits, and Limitations

Micropropagation involves the in vitro culture of explants (shoot tips or meristems) under sterile conditions to produce multiple plantlets (Hasnain *et al.,* 2022). The process typically includes stages such as initiation, multiplication, rooting, and acclimatization. One of the most significant advantages of micropropagation is its ability to generate large numbers of uniform, disease free plants within a relatively short time (Suman, 2017; Idowu *et al.,* 2009). Plant tissue culture is a powerful technique that contributes significantly to various fields (Gabr *et al.,* 2010) including asexual plant reproduction, and accelerated breeding of new crop varieties, artificial seed production, and preservation of plant genetic resources. This technique supports advancements in plant breeding, seed production, and conservation of plant genetic diversity. (Irini *et al.,* 2012)

Micropropagation is particularly valuable for plant species that are challenging or impossible to propagate using traditional methods like seeds or vegetative cuttings, helping to meet the demand for planting materials when conventional approaches fall short. Especially in banana and plantain

Technique: Micropropagation is a tissue culture technique used to rapidly multiply plants under sterile, laboratory conditions. It involves the following key steps:

1. Explant Selection: Small tissue samples (usually from the shoot tip or meristem) are taken from a healthy parent plant (Suman, 2017)
2. Sterilization: The explants are sterilized to eliminate bacteria, fungi, and viruses.
3. Culture Initiation: Explants are placed in nutrient rich media containing plant hormones (like cytokinins and auxins) to promote cell

division and shoot formation.

4. Multiplication: The newly formed shoots are repeatedly subcultured to multiply into hundreds or thousands of identical plantlets.
5. Rooting and Acclimatization: Shoots are induced to form roots, then gradually adapted to external environmental conditions before being planted in soil.(Misra and Misra, 2012).

Benefits

1. Mass Production: Enables rapid production of large numbers of uniform, high quality planting materials in a short time. (Danida, 2002)
2. Disease Free Plants: Produces pathogen free plants by starting with clean meristem tissues, reducing the risk of spreading diseases.
3. Year Round Propagation: Independent of seasonal constraints, allowing consistent supply of planting material.
4. Conservation of Germplasm: Helps preserve rare or endangered plant varieties and valuable genetic resources.
5. Improved Yield and Uniformity: Plants grown via micropropagation are genetically identical and often show enhanced growth and productivity (El-Esawi, 2016)

Limitations:

1. High Initial Costs: Requires investment in lab infrastructure, skilled personnel, and sterile conditions, which may be a barrier for small scale farmers.
2. Technical Expertise Needed: The process demands trained technicians and precise handling to avoid contamination or failure.
3. Risk of Somaclonal Variation: Though rare, genetic mutations can occur during tissue culture, leading to off type plants.
4. Acclimatization Challenges: Plantlets need careful handling when moved from lab to field conditions, or they may suffer high mortality rates.
5. Limited Accessibility: In many rural or low income regions, micropropagation labs and services may not be readily available.

Macropropagation: Technique, Benefits, and Limitations

Macropropagation is a technology method that involves the stimulation of suckers from prepared corms through techniques such as decapitation, paring, and application of growth regulators. It is particularly useful for farmers who lack access to tissue culture facilities (Langford *et al.,* 2017).

Technique:

Macropropagation involves the use of larger plant parts to produce new plants. In bananas and plantains, it commonly includes:

- Sucker Propagation: Using suckers (shoots or offshoots) that grow from the base of the parent plant. These suckers are separated and replanted to grow into new plants.
- Rhizome Division: Splitting sections of the underground rhizome that contain buds or shoots, which then grow into new plants.
- Corm or Cormel Planting: Planting small corms or cormels (bulb like structures) that sprout and develop into new plants.

This method is traditional, widely used by farmers, and relies on vegetative propagation to maintain genetic uniformity.

Benefits:

1. Simplicity and Accessibility: Requires minimal technical knowledge and no specialized equipment, making it practical for small scale farmers.
2. Low Cost: Uses naturally occurring plant parts, eliminating the need for expensive laboratory setups.
3. Genetic Uniformity: Propagates true to type plants since it uses vegetative material from the

parent.

4. Widely Used: The most common and accepted method for banana and plantain propagation worldwide.
5. Suckers Often Ready to Plant: Many suckers are available on mature plants, providing a steady supply of planting material.

Limitations:

1. Limited Propagation Rate: Suckers are produced slowly and in limited numbers, restricting rapid expansion of plantations.
2. Disease Transmission: Suckers often carry pests and diseases (like Fusarium wilt or nematodes) from the parent plant, which can spread throughout plantations.
3. Variable Quality of Planting Material: Not all suckers are healthy or vigorous; some may be weak or infected, affecting crop performance.
4. Labour Intensive: The process of selecting, removing, and preparing suckers is time consuming and physically demanding.
5. Seasonal Dependency: Availability of healthy suckers may be influenced by seasonal factors and the crop's growth cycle.

Contribution to Genetic Conservation and Sustainable Agriculture

Both micropropagation and macropropagation play important roles in the conservation of banana and plantain genetic resources (Crouch *et al.,* 1998). Micropropagation supports ex situ conservation by enabling the maintenance of germplasm collections under controlled conditions, while macropropagation aids in the on farm conservation of landraces and farmer preferred varieties.(Landoni *et al.,* 2024; Hammer and Tekl, 2008). These methods help prevent genetic erosion and support crop improvement efforts. Banana and plantain cultivation, through both traditional and modern propagation methods, plays a critical role in preserving genetic diversity (Brown *et al*., 2017). Diverse local varieties and landraces adapted to specific environments hold valuable traits such as disease resistance, drought tolerance, and unique nutritional qualities. Conserving these genetic resources safeguards the crop's resilience against pests, diseases, and climate change. Techniques like micropropagation aid in conserving rare or endangered varieties by producing disease free, true to type plants in large numbers without losing genetic identity. Maintaining genetic diversity also supports breeding programs aimed at developing improved cultivars (Chokheli *et al.,* 2020).

Sustainably increasing banana and plantain production requires access to healthy and diverse planting materials. By improving the availability and quality of propagules, these techniques contribute to enhanced productivity, reduced input use, and greater resilience to biotic and abiotic stresses(Mustaffa and Kumar, 2012). When integrated into seed systems, they offer a pathway for scaling improved cultivars and strengthening food systems. Banana and plantain production contributes to sustainable agriculture by providing food security, supporting livelihoods, and promoting eco friendly farming practices (Adi, 2024). Their perennial growth and ability to produce multiple ratoon crops reduce the need for frequent replanting, lowering soil disturbance and erosion. Intercropping bananas and plantains with other crops enhances biodiversity and optimizes land use, and adopting integrated pest management, organic fertilizers, and water efficient irrigation improves environmental sustainability. (Leonel *et al.,* 2024). Propagation techniques that reduce disease spread and improve planting material quality minimize the need for chemical inputs, supporting healthier ecosystems and long term productivity.

Genetic Diversity in Banana

The critical importance of conserving and utilizing the genetic diversity of bananas and plantain a crop of global significance for food security and rural livelihoods (Debnath *et al.,* 2019). Edible banana cultivars are derived primarily from two wild progenitor species, Musa acuminata and Musa balbisiana, and have undergone a complex history of domestication and hybridization. These evolutionary events have given rise to a wide range of genomic combinations, including diploid (AA, AB, BB), triploid (AAA, AAB, ABB), and tetraploid (AABB, ABBB) forms, each with distinct agronomic characteristics and geographic adaptations (de Jesus *et al.,* 2013).

The taxonomy, geographic distribution, and genomic classification of Musa species are comprehensively addressed, with emphasis on the diversity found across some major regions Asia-Pacific, Africa, and Latin America and the Caribbean (Debnath *et al*., 2019). These regions represent both primary and secondary centers of diversity, hosting a wide array of landraces, wild species, and cultivated clones. Such diversity is foundational for breeding, crop improvement, and resilience against biotic and abiotic stresses.

The collection and conservation of banana germplasm. Conservation strategies are broadly categorized into in situ (on farm and natural habitat preservation), ex situ (field genebanks and botanical gardens), and cryopreservation (long term storage under ultra low temperatures) (Engelmann, 2012). The International Transit Centre (ITC) in Leuven, Belgium, plays a central role in global Musa conservation, maintaining over 1500 accessions through in vitro and cryoconservation protocols (Christelová et al., 2017). Characterization and evaluation of banana germplasm are essential for understanding genetic relationships and facilitating its effective use. Morphological characterization has historically been used, though it is limited by environmental variability and phenotypic plasticity. Therefore, molecular tools such as Simple Sequence Repeats, flow cytometry, and AFLP have been widely adopted for more precise genotyping and ploidy analysis (Benjamin *et al.,* 2018: Elshafei *et al.,* 2024)

The practical utilization of Musa genetic resources in breeding programs and direct use by farmers. Initiatives like the International Musa Testing Programme (IMTP) have been instrumental in identifying and disseminating improved cultivars with enhanced yield, disease resistance, and climate resilience. These efforts not only contribute to sustainable banana production but also to the broader goals of biodiversity conservation and agrobiodiversity management. (Debnath et al., 2019).

Table 1: Comparative Analysis of Macropropagation and Micropropagation

Aspect	***Macropropagation***	***Micropropagation***	
Rate of Multiplication	Slow and limited number of suckers per plant per season	Very fast hundreds to thousands of plantlets from a single explant in a short time	Kumar, 2024
Input Requirements	Low relies mainly on natural plant parts, minimal equipment	High requires lab facilities, sterile media, skilled labor	Njukwe *et al.,* 2013
Labor Intensity	High manual selection, removal, and planting of suckers	Moderate skilled lab work but less manual field labor initially	Njukwe *et al*., 2013

Table 2: Suitability by context of Macropropagation and Micropropagation

Context	*Macropropagation*	*Micropropagation*	
Commercial Farms	Suitable for established farms with access to suckers; cost effective for moderate scaling	Ideal for large scale, high tech commercial farms needing rapid multiplication of disease free plants	Mat and Othman., 2022
Smallholders	Highly suitable due to low cost, ease, and local availability	Less accessible due to cost and technical demands but useful through community or government support programs	Tinzaara *et al.,* 2018
Regional Application	Widely used in all banana growing regions, especially in rural areas	More common in regions with infrastructure and institutional support, often linked to research centers and nurseries	Ayele *et al.,* 2025

Integration Potential of macropropagation and micropropagation

Both macropropagation and micropropagation can be integrated into seed and planting material systems to complement each other:

- Foundation Material: Micropropagation produces clean, disease free foundation plants that serve as a high quality source for further multiplication.
- Mass Multiplication: Macropropagation can then multiply these disease free plants at the farm level using suckers, enabling farmers to access improved material affordably.
- Decentralized Systems: Community nurseries can use micropropagation derived plants as stock, distributing healthy planting materials while training farmers in macropropagation techniques.
- Sustainability and Resilience: Combining both approaches enhances genetic diversity, disease management, and availability of planting materials, strengthening overall seed systems.

Future Prospects Banana and Plantain Cultivation

The future of banana and plantain cultivation is being shaped by significant advancements in propagation technologies (Kumar *et al.,* 2025). Continued development of tissue culture techniques especially through automation and improved protocols will lower production costs and expand access to high quality micropropagated planting material (Rout *et al.,* 2022). Emerging innovations such as synthetic seeds and cryopreservation are poised to support long term conservation and facilitate the global distribution of elite germplasm (Ghosh *et al.,* 2025)

Biotechnology and molecular breeding, when integrated with micropropagation, will play a crucial role in accelerating the development and dissemination of disease resistant and climate resilient banana and plantain varieties (Abigarl *et al.,* 2024). This is particularly important in combating threats like Fusarium wilt and in adapting to increasingly variable climatic conditions.

Parallel to biological advancements, digital and precision agriculture tools are being adopted to enhance propagation and production systems. Smart farming technologies including sensors, remote monitoring, and data driven management practices can optimize resource use, improve productivity, and reduce input waste (Nazish *et al*., 2025).

Strengthening local and regional seed systems remains essential. Empowering farmer cooperatives, community nurseries, and agricultural extension services can ensure wider distribution and adoption of high quality planting materials, whether produced through macro or micropropagation. These integrated approaches will collectively support sustainable, resilient, and inclusive banana and plantain production systems.

Recommendations

Advancing propagation technologies is key to transforming banana and plantain cultivation into a more sustainable, productive, and resilient sector. A multifaceted approach is needed to harness the full potential of both traditional and modern methods, supported by strong institutional and farmer level engagement. A hybrid propagation model should be promoted combining micropropagation for producing disease free foundation stock with macropropagation techniques for localized, cost effective multiplication. This integrated approach can maximize efficiency, ensure rapid dissemination of quality planting material, and improve access for smallholder farmers.

To support these technologies, there must be investment in infrastructure and capacity building. Establishing well equipped tissue culture laboratories in strategic regions and providing targeted training for technicians, extension agents, and farmers will enhance propagation practices and improve overall productivity.

In parallel, advances in propagation must be aligned with enhanced disease management strategies. Integrating tissue culture with comprehensive pest and disease control especially against major threats like Fusarium wilt will reduce crop losses and enhance sustainability across production systems.

Policy support and funding are also critical. Governments and development partners must prioritize research, infrastructure development, and adoption of advanced propagation technologies. Enabling policies and increased access to finance can significantly boost market access and innovation within the banana and plantain sector.

Equally important is farmer engagement through participatory breeding and propagation efforts. Actively involving farmers in varietal selection and propagation initiatives ensures the development and adoption of locally adapted, culturally accepted cultivars. This participatory approach fosters ownership, enhances adoption rates, and ensures that propagation efforts are grounded in real world needs.

Together, these strategies provide a roadmap for scaling up improved propagation technologies making banana and plantain farming more productive, resilient, and inclusive.

Conclusion

Micropropagation and macropropagation offer transformative pathways for addressing the critical challenges facing banana and plantain cultivation. Their integration into propagation systems enhances access to clean, high quality planting materials, preserves genetic diversity, and supports climate resilient agriculture. Micropropagation, with its potential for rapid multiplication and pathogen free plantlets, is indispensable for modern, large scale systems, while macropropagation provides a low cost, accessible solution for smallholder farmers. By leveraging the strengths of both methods, the agricultural sector can develop more inclusive and sustainable models of banana and plantain production. Strengthening institutional support, expanding infrastructure, and empowering local communities are essential for scaling these technologies. As the demand for food security and climate smart agriculture intensifies, micro and macropropagation stand as vital tools in ensuring the long term sustainability, productivity, and resilience of banana and plantain based systems and preserving valuable genetic resources and genetically uniform planting stock, to support commercial agriculture and the preservation of valuable germplasm

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