Development of Synthetic Seed Technology in Plants and its Applications: A Review

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Abstract

Artificial/Synseed/Synthetic seeds are produced by encapsulation of plant micropropagules (somatic embryos, shoot buds/shoot tips, calli, nodal segments, embryogenic masses, protocorms and protocorm like bodies) with specific coating materials. The outer coating matrix provides protection and nutrition to the encapsulated plant tissues. Calcium alginate gel is the most preferred among other available protective coverings as it enhances capsule formation and provides sufficient firmness to alginate beads to withstand mechanical injury to propagules. Nutrients, growth regulators, antibiotics and other adjuvants are incorporated into coating matrix to facilitate normal development of plant propagules leading to synseed germination and healthy plant formation. Somatic embryos are the commonly used explant propagule for synseed development because of the availability of well-established in vitro culture protocols for somatic embryogenesis. Synthetic seed technology has important application in large scale multiplication of commercially valuable plants which are difficult to propagate through conventional vegetative methods. Another significant aspect of synthetic seeds is the possibility of conserving germplasm of rare and endangered economically important plants through short term cold storage and cryopreservation. Inspite of its bright prospect, synseed technology is besotted with several drawbacks due to limited availability of appropriate micropropagules in large scale, immature and asynchronous somatic embryo development and very low conversion rate of synseeds into normal plants. Refinement of technology is the need of hour to make its wide applications at commercially level. The review aims to stress on various aspects of synseed technology development in several commercially important plants using different explant propagules. The various applications and limitations of the technology in plant science research have also been emphasized in the present article.

Keywords: synthetic seeds, desiccation, protocorms, somatic embryos, callus

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Introduction

Plants are generally propagated mostly through seeds in nature. In some crops, propagation through seeds has not achieved success because of seed heterozygosity, minute size, and absence of endosperms and absolute necessity of fungal infection for germination (Saiprasad, 2001). Some plants can be vegetatively propagated but conventional methods are time consuming, expensive and cannot produce plants at larger scale. Production of artificial seeds/synseeds using synthetic seed technology can play an important role as alternative to other conventional methods for large scale propagation and
long term germplasm storage of useful crop varieties. The typical plant seeds have embryos with one or two cotyledons which are associated with endosperms containing food reserves for developing embryos. The whole structure is enclosed by rigid covering called testa which protects the inner delicate structure from injury and desiccation and also helps in maintaining embryo viability till its germination. In synthetic seeds, artificial coating materials like sodium alginate, agar, gelrite and sodium pectate replace the function of seed coat by encapsulating somatic embryos (SEs), shoot buds, nodal segments or any other plant tissues (Gantait et al., 2015). The naked somatic embryos or shoot buds when exposed to natural environment will not survive as they are highly sensitive to desiccation and other infectious pathogens. The encapsulating agents give protection to enclosed explant propagules apart from giving nutrition for their proper development. The derived artificial seeds/synseeds when sowed should possess the ability to convert into plants under in vitro and ex vitro conditions (Bapat and Mhatre, 2005). The plant micropropagules for synthetic seed production are obtained through somatic embryogenesis, organogenesis, axillary bud, protocorm and protocorm like bodies (PLBs) proliferation systems using in vitro culture methods. This encapsulation technology has been applied to produce synthetic seeds of a number of plants belonging to angiosperm and gymnosperm. The present review aims to highlight the past and present status of synthetic seed development, use of different explant propagules for synseed preparation along with limitations and applications of the technology in the field of agriculture and forestry.

**Synthetic seed production**

The first synthetic seeds were produced by encapsulated carrot somatic embryos with polyoxyethylene followed by desiccation (Kitto and Janick, 1982). The encapsulated somatic embryos and calli of carrot were dried for several hours on teflon surface under the lamina flow cabinet followed by rehydration after inoculating them in freshly prepared medium. The polyoxyethylene was favorable for use as coating materials for synthetic seeds as it was non-toxic, readily soluble in water, could be easily dried to form thin film and did not support the growth of microorganism. Redenbaugh et al. (1984) developed a technique for encapsulation of single, hydrated somatic embryo of alfalfa plant and since then encapsulation of somatic embryos of several plant species in hydrogel have been successfully performed by several workers. The production of synthetic seeds was primarily based on encapsulation of somatic embryos before it was extended to other plant tissues generated under in vitro culture condition. The somatic embryos were employed for synthetic seed production mainly due to presence of radicle and plumule which ultimately differentiated into roots and shoots (Gray et al., 1993; Dodeman and et al., 1997). They were developed from somatic cells in in vitro condition unlike zygotic embryos which were obtained from fusion of male and female gametes. The normal embryos have protective seed coat and endosperms which provide protection and nutrition to developing embryos. The somatic embryos on other hand lack both endosperms and protective covering which make them inconvenient to store and handle normally.
The naked somatic embryos are generally enclosed in protective coating materials to produce synthetic seeds. The coating materials however should not produce damaging effect to the embryos, be mild enough to allow germination, be sufficiently durable for rough handling during manufacture, storage, transportation and planting and also give nutrition to embryos for germination (Sharma et al., 2012). The synthetic seeds successfully prepared should be transplantable using existing farm machinery. Several gels like agar, alginate, carboxymethyl cellulose, gelrite, guar gum, sodium pectate etc. have been tested for encapsulation of plant propagules for synthetic seed development (Redenbaugh et al., 1987). However, calcium alginate encapsulation is the most favorable for providing protective covering as it enhances capsule formation and provides sufficient firmness to alginate beads to withstand mechanical injury (Saiprasad, 2001). Also its moderate viscosity and reduced toxicity to somatic embryos with low cost and bio-compatibility characteristics make it the most sought after hydrogel for synseed encapsulation (Khor and Loh, 2005; Kikowska and Thiem, 2011). The encapsulating matrix is provided with nutrients and other growth regulators which play the role of artificial endosperms (Germana et al., 1998). Seed germination efficiency and somatic embryo viability are enhanced with the incorporation of nutrients and growth regulators into coating materials. Other adjuvants like fungicides, pesticides, antibiotics and microorganisms (eg. Rhizobia) may be included into the encapsulation matrix to instill different properties to synthetic seeds to suit to prevailing conditions (Kikowska and Thiem, 2011) Addition of antibiotics may prevent bacterial contamination of encapsulated plant propagules (Bekheet, 2006). Khor and Loh (2005) reported improvement of conversion potential and vigor of synseeds when activated charcoal was supplemented in coating gel. Charcoal can break up the alginate and helps in increasing the respiration of somatic embryos inside the coat. Charcoal is also presumed to play a role in retaining nutrients within the hydrogel capsule and also helps in releasing them slowly to developing embryos. Absorption of harmful polyphenolic exudates released by encapsulated explant propagules in vitro is also facilitated by activated charcoal (Ganapathi et al., 1992).

The primary goal of synthetic seed technology is to produce somatic embryos that resemble more closely to normal seed embryos in terms of storage and handling capabilities by providing nutritive covering. The synthetic seeds can later be used for large scale clonal propagation and germplasm conservation of rare and commercially useful crop varieties. Apart from using popular somatic embryos, other unipolar structures like apical shoot tips, axillary shoot bud, embryogenic calli, protocorm and protocorm like structures (PLBs) are widely utilized for development of synseeds. Redenbaugh et al. (1991) first treated shoot tip and axillary bud micropropagules for root induction before they were encapsulated. Root induction treatment with auxins was avoided for alginate encapsulation of shoot tips of mulberry and banana to produce synseeds and their successful conversation to plantlets (Bapat and Rao, 1990). The procedure for synthetic seed production starting from different plant micropropagules are diagrammatically represented in figure 1.

Different types of synthetic seeds

The plant propagules obtained from different sources are encapsulated with coating materials which
act as artificial endosperms by proving nutrition to embryos apart from their protective function. Synthetic seeds are broadly classified into desiccated and hydrated seeds depending on different approaches undertaken for their development as per the requirement.

Desiccated synthetic seeds

Encapsulation of somatic embryos is performed using polyoxyethylene followed by desiccation under controlled conditions. Desiccation can be performed slowly or rapidly depending upon the requirement. It takes one or two week times to gradually desiccate the encapsulated seeds in chamber of decreasing humidity while instant desiccation involves the opening of sealed petridish containing synseeds and leaving directly open overnight for quick drying (Ara et al., 2000). The desiccated synthetic seeds can be developed for those plant species which have somatic embryos resistant against desiccation. The carrot SEs can be encapsulated with polyox by mixing equal volumes of embryonic suspension and a 5% (w/v) solution of polyox to give a final concentration of 2.5% polyox. The suspension was dispensed as 0.2 ml drops from the pipette on to telfon sheets and dried to wafers in a laminar flow hood. The drying time was based on the ability of water to separate from teflon plate and it usually took about 5 hours. The embryo survival and conversion of seeds were determined by redissolving the wafers in freshly prepared embryogenic medium and culturing the rehydrated embryos. High conversion frequency of somatic embryos of celery could be obtained by incorporating abscisic acid (ABA) and mannitol to maturation medium (Halal, 2011). The synthetic seeds with desiccation to 10-15% potential of seeds. More healthier seedlings could be derived from dried somatic embryos when compared to seedlings obtained from undried embryos (Senaratna et al., 1990).

Hydrated synthetic seeds

Hydrated artificial seeds consist of somatic embryos or suitable plant tissues enclosed by a hydrogel. Many substances like potassium alginate, agar, gelrite, sodium pectate have been examined but calcium alginate was found to be most effective coating material for hydrated synthetic seeds (Redenbaugh et al., 1987). Alginate is a straight chain, hydrophilic, colloidal polyuronic acid composed primarily of hydro-b-D mannnuronic acid residues with 1-4 linkages. For production of hydrated seeds, the plant materials are mixed with sodium alginate gel (0.5-5.0 % w/v) which is followed by dropping into the calcium chloride solution (30-100 mM) using pipette. Round and firm beads of calcium alginate containing somatic embryos are formed as the ion exchange occurs resulting in the replacement of sodium ions with calcium ions (Reddy et al., 2012). The hardness and rigidity of capsules mainly depend upon the number of sodium ions exchanged with calcium ions. So, hardness of calcium alginate gel can be modulated by changing the concentration of sodium alginate and calcium chloride solution along with change in duration of complexing. In most cases 2% of sodium alginate gel when complexed with 100 mM Calcium chloride solution produced desirable quality synthetic seeds for many plant species (Redenbaugh et al., 1987; Oceania et al., 2015). Ca-alginate capsules are difficult to handle as they are very wet and tend to stick together slightly. Moreover, the Ca-alginate loses water rapidly and dries very fast to form hard pellet within few hours.
when the beads are exposed to normal atmosphere. However, these problems can be solved by coating the capsules with Elvax 4260. Antibiotic mixture containing rifampicin, cefatoxine and tetracycline-HCl can also be added to the matrix to avoid bacterial contamination (Bekheet, 2006). When there is encapsulation of plant materials exuding high phenolic compounds, activated charcoal (0.1-0.4%) may be incorporated to the matrix to absorb the phenolic exudes (Ganapathi et al., 1992).

**Propagules for synseed production**

The somatic embryos were earlier employed as the only explant for synthetic seed development in several plants. But subsequent reports by different workers showed the use of varieties of plant micropropagules like unipolar apical shoot tips and buds, nodal segments, embryogenic masses and calli along with hosts of other explants like protocorms or protocorm like bodies, bulb, bulblets, hairy roots and microtubers (Reddy et al., 2012; Gantait and Sinniah, 2013).

**Somatic embryos**

Embryos which are obtained asexually from somatic cells without the union of gametes are called somatic embryos. *In vitro* development of plant somatic embryos was first reported by Reinert (1958) and Steward et al. (1958) independently. The direct SEs develop directly from explanted cells while indirect SEs derive from explant tissues through intervening callus phase (William and Maheswaran, 1986). The SEs undergo globular, heart, torpedo and cotelydonous stages like zygotic embryos to germinate and develop into fertile plants. SEs however do not go through desiccation and dormancy unlike normal embryos and enter the germinating phase as soon as they are fully formed (Zimmerman, 1993). They are the most favorable propagules use for production of synthetic seeds due to presence of radicle and plumule which develop in single step into roots and shoots respectively without subjecting to any specific treatment (Standardi and Piccioni, 1998).

With the advancement of plant tissue culture technology, somatic embryos have been induced successfully in number of plants making somatic embryos more preferable for artificial seed production as they can be more easily available. The SEs can be preserved in viable state for longer duration if the moisture content can be maintained at 10% like normal seeds by drying (Ara et al., 2000).

Attempts have been made to desiccate somatic embryos before encapsulation to exploit this potential. Desiccation tolerance was induced in somatic embryos of Alfalfa plant by exogenous application of abscisic acid (Senaratna et al., 1989). When the somatic embryos after encapsulation were dried to 10-15% and stored in dry state for about 4 weeks, 65% of somatic embryos survived and germinated like true seeds. Sometimes emergence of shoot and root meristem during synthetic seed germination was prevented by nutritive outer covering. In order to avoid this scenario, gel capsules had been prepared which were self-breaking under humid conditions. This involved the rinsing of beads thoroughly in running tap water which was followed by immersion of beads in a 200 mM solution for 60 mins and finally desalting them by rinsing them in running tap water for 40 minutes (Onishi et al., 1994). The synthetic seeds showed 50% conversion in two weeks when sowed in greenhouse conditions. The use of somatic embryos as explant propagules have been demonstrated in several plants like *Armoracia rusticana* (Shigeta and Sato, 1994); *Asparagus officinalis* (Mamiya and Sakamoto,
Protocorms and protocorm-like bodies

The miniature exalbuminous orchid seeds when inoculated in culture medium in vitro started swelling in one or two weeks indicating successful germination due to imbibition of water and nutrients (Nongdam and Chongtham, 2011). The embryos underwent several division to develop into irregularly shaped parenchymatus cell mass called spherules (Nongdam and Tikendra, 2014). The hairy globular spherules developed into protocorms which are oval, elongated, branched and spindle shaped bodies considered to be an intermediate structure between embryos and plants (Fig. 1a). The protocorms directly differentiated into complete seedlings after undergoing morphogenetic changes (Fig. 1b). Protocorm-like bodies are similar to protocorms in their function and morphology but are developed from plant parts other than seeds of orchids under in vitro conditions. In different orchids like Cymbidium giganteum, Dendrobium wardianum and Spathoglottis plicata, synthetic seeds have been produced by encapsulating protocorms or protocorm-like bodies with calcium alginate gel (Sharma et al., 1992; Corrie and Tandon, 1993; Nagananda et al., 2011). The encapsulated protocorms of C. giganteum developed into healthy plantlets when grown on nutrient medium in vitro or in sterile soil and sand mixture under greenhouse conditions. The frequency of synthetic seed conversion was higher in vitro as compared to conversion of germinated seeds in sand and soil mixture. Mohanty et al. (2013) produced synseeds in Dendrobium nobile using PLBs and observed conversion of synseeds significantly high at 80% as PLBs being highly potential for direct plantlet generation.

Embryogenic masses and Calli: Regenerative and stable embryogenic masses can be used for production of clonal plants and for studies of genetic transformation. But maintaining them for longer duration in bioreactors and culture vessels is difficult due to frequent subculturings (Ara et al., 2000). The laborious and expensive subculturing procedure can be overcome by encapsulating the embryogenic masses with sodium alginate and store them at 40°C after 6-benzyl amino purine (BAP) treatment (Redenbaugh et al., 1991). The synthetic seeds can be stored for around 2 months without losing its viability and original proliferative capacity. But more research needs to be done to understand whether the storage period of synthetic seeds can be extended and efficiency and proliferative nature of embryogenic masses decrease with the increase in the storage period. Regenerative embryogenic masses have been utilized for synthetic seed production in few plants like Anthurium andreanum (Nhut et al., 2004) and Arnebi euchroma (Manjkhola et al., 2005). Plant callus is
unorganized mass of proliferative cells produced by isolated cells, tissues or organs under the influence of in vitro culture conditions (Fig. 1c). Callus formation is associated with the development of progressively more random planes of cell division, lower cell specializations and loss of organized structures (Wagley et al., 1987). The acceptance of calli as explant propagules for synseed preparation is limited due to their undifferentiated nature and low differentiation potential (Gantait et al., 2015). The use of calli for synseed development was successfully observed for the first time in *Allium sativum* by Kim and Park (2002) showing high conversion and regeneration rate of synseeds to plants. Zych et al. (2005) and Reedy et al. (2005) also attempted successfully to formulate synseeds from callus derived from in vitro culture of *Rhodiola kirilowii* and *Rauvolfia serpentina* respectively.

**Apical shoot tips/ shoot buds and nodal segment**

The shoot buds and apical shoot tips are unipolar structure without root meristem. The conventional shoot tip culture in vitro requires higher space and culture media as compared to micropropagation of shoot tip/buds encapsulated synseeds (Gantait et al., 2015). The requirement of smaller space ensures easy transportation of plant propagules from one center to another. The shoot tip explants were induced to root before encapsulation by exposing to indole-3-butyric acid (IBA) treatment for 3-6 days. Successful conversion to plantlets from synseeds developed by encapsulating banana and mulberry buds without auxin treatment was also reported (Bapat and Rao, 1990; Ganapathi et al., 1992). Figure 1(d) represents synseeds developed by enclosing in vitro derived shoot tips with calcium alginate covering. The use of apical shoot tips/ buds as explants for synseeds development have been successfully reported in different plant such as *Catalpa ovate* (Wysokinska et al., 2002); *Stevia rebaudiana* (Andlib et al., 2011); *Glycyrrhiza glabra* (Mehrotra et al., 2012); *Terminalia arjuna* (Gupta et al., 2014); *Cucumis sativus* (Adhikari et al., 2014) and *Solanum tuberosum* (Ghanbarali et al., 2016). The nodal explants derived either from natural or in vitro regenerated plants can be encapsulated for synseed production (Fig. 1e). The plantlet conversion frequency of in vitro derived nodal explants would be significantly higher as compared to that of mature nodal tissues obtained from field grown plants due to higher meristematic and organogenetic potential. Nodal explants have been employed for the production of synseeds in number of plants like *Hibiscus moschatus* (Prince and West, 2006); *Pogostemon cablin* (Swamy et al., 2009); *Eclipta alba* (Singh et al., 2010); *Vitex negundo* (Ahmad and Anis, 2010); *Picrorhiza kurrooa* (Mishra et al., 2011); *Stevia rebaudiana* (Khan et al., 2013); *Phyllanthus fraternus* (Upadhya et al., 2014); Blackberry (Jadan et al., 2015); *Physalis peruviana* (Yucesan et al., 2015) and Tomato (Oceania et al., 2015).

**Applications of synthetic seeds**

There are increasing numbers of medicinal plants whose population are declining in an alarming rate and are in the verse of extinction. Rampant deforestation, rapid expansion of cities and industries in the expense of natural forested areas, excessive exploitation of rare and medicinally important plants for economic gains are the main reasons for increasing number of plants becoming rare and endangered in their natural habitats. Large scale propagation for medicinal plants through conventional
methods has limitations as majority of plants are either seedless varieties, or have reduced endosperms and lower germination rate (Rai et al., 2009).

**Fig. 1.** The procedure of synthetic seed production using different plant propagules

![Diagram of synthetic seed production procedure](image)

**Fig. 2 (a-e).** (a) *In vitro* protocorm formation in orchid (bar 4 mm), (b) Protocorms directly differentiated into seedlings (bar 6 mm), (c) *In vitro* callus formation in pea (bar 6 mm), (d) Synthetic seeds with shoot tip explant propagules (bar 5 mm) and (e) Synseeds developed by encapsulating nodal segments (bar 6 mm).
Many of them are also desiccation-sensitive or have recalcitrant seeds because of which they cannot be stored for longer period. The synthetic seed technology can be employed for mass propagation and conservation of rare and threatened medicinal plants by encapsulating somatic embryos and meristematic vegetative propagules with suitable coating materials. Artificial synseeds have been successfully developed using different plant propagules in several medicinally important plants like *Allium sativum, Cannabis sativa, Catalpa ovata, Rauwolfia serpentine* and *Slevia rebaudiana* (Wysokinska et al., 2002; Belkeet, 2006; Ray and Battarcharya, 2008; Lata et al., 2009; Andlib et al., 2011).

The germplasm preservation of difficult to propagate ornamental plants and recalcitrant species like mango, cocoa and coconut can be performed by cryopreserving their synseeds in liquid nitrogen (−196°C). The metabolic function of cells during cryopreservation is arrested and supplementation of sucrose, salicylic, mannitol and other nutrients to encapsulating matrix is essential which may improve cell viability and tolerance to dehydration and other abiotic stresses (Janda et al., 2007; Katouzi et al., 2011). There are several potential uses of synthetic seeds for important crops such as citrus, grapes, mango etc. which are vegetatively propagated and have long juvenile periods. The planting efficiency can be increased by use of synthetic seeds instead of cuttings. The synthetic seeds are considered to be highly advantageous for germplasm conservation in grapes and other similar crops. Banana is considered as one of the most important crops because of its large consumption and considerable export potential. They are normally propagated by suckers as they do not produce viable seeds (Matsumoto et al., 1995). Conventional method of propagation does not guarantee large scale production of banana, so synthetic seed technology can be used as another option by encapsulating the shoot-tips excised from tissue culture raised plants and somatic embryos developed from callus tissues obtained from *in vitro* culture of male flower buds (Ganapathi et al., 2001; Hassanein et al., 2005; Sandavol-Yugar et al., 2009).

Bapat and Rao (1980) used undifferentiated callus produced from stem segments of sandalwood - one of the most commercially valuable forest trees to produce synseeds. High genetic variations among the progenies were observed when seeds were used for propagation of sandalwood. But germination of synthetic seeds produced by encapsulating the somatic embryos with calcium alginate produced plants with genetic uniformity. Mulberry plants are important components of silk industry as their leaves are chief source of food for silkworms. The multiplication of mulberry cultivars is difficult due to restriction in rooting response though cutting and grafting are used for vegetative propagation. Moreover 30-40% cutting can only survive the time period between pruning, transportation and final transplantation (Bapat and Rao, 1990). The synthetic seeds produced by encapsulation of *in vitro* raised axillary buds could be easily packed in bottles and transported which reduced space requirement, increases seed viability and survival rate.

The synthetic seed technology has provided space and equipment saving option for storage of plant materials of different rare and commercially important plants at low temperature. It has the potential for short term and long term storage of plant germplasm in the form of synseeds without losing cell viability by cryopreserving them in liquid nitrogen (Arora et al.,
Other advantages of synthetic seeds are easy handling because of smaller size beads, higher scale up capacity, possibility of automation of the whole production process and direct delivery to field. The artificial seeds with vegetative propagules enclosed within them can be used for exchange of axenic plant materials between the laboratories (Reddy et al., 2012). The transport of synthetic seeds between the countries does not require quarantine department permission. This technology is also independent of seasonal variations as they can be produced in controlled laboratory environments.

Limitations of synthetic seeds

The synthetic seed technology inspite of having bright prospects in large scale propagation and germplasm conservation of rare and important plants is associated with many limitations. Production of good quality micropropagules in high number is prerequisite to production of synthetic seeds. However, there are limitations in the generation of viable micropropagules for use in synseed production. Somatic embryos which are commonly used explant propagules for synthetic seed production should attain proper maturation to germinate out of the coating materials to form healthy plantlets. Improper maturation of somatic embryos reduces the success rate of conversion of synthetic into normal plants. Mature embryos will control germination and conversion rate which are highly significant for successful synseed production. However, asynchronous development of embryos limits the production of normal plants post synseed formation even after induction of successful somatic embryogenesis (Ara et al., 2000). Somatic embryos exhibited immense variation in their morphology in response to prevailing conditions in culture system. Long term treatment of ABA either induced anomalous cotyledon formation in somatic embryos or activated normal embryo development in *in vitro* condition (Crouch and Sussex, 1981).

The conversion of synthetic seeds into plants after successful germination is the most important aspect of synthetic seed technology. Due to various reasons the conversion rate is always very low which limits the commercial application of this technology. Most of the studies reported somatic embryogenesis of plants and their subsequent encapsulation to produce synseeds with very low success in conversion rate. The choice of appropriate coating materials is one of important limiting factors for synseed generation. Low success rate in the use of synthetic seed technology may be attributed to failure in the choice of effective encapsulating materials which should be non-damaging, provide sufficient protection and nutrition to developing embryos (Rendenbaugh et al., 1991). Proper storage of synthetic seeds is affected by lack of dormancy and stress tolerance in somatic embryos. Also storage of synthetic seeds at low temperature reduces significantly the viability of synthetic seeds and its potential for conversion to normal plants (Makowwczynska and Andrezejewska-Golec, 2006).

Conclusion

The artificial seed technology is considered as an alternative to slow and expensive conventional plant propagation methods by generating several important plants rapidly in large scale. Artificial seeds also offer tremendous potential in micropropagation and germplasm conservation of economically significant rare and endangered plants. However, lack of production of high quality micropropagules for synthetic seed
production coupled with low conversion rate to normal plants has restricted the widespread use of synthetic seed technology in the field of agriculture. Further detailed investigations are required to refine this useful technology for its wide applications at commercial scale.

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