

Advancements in Seed Treatment Methods and Storage Techniques of Marigold Seeds: An Overview

Abstract

Floriculture plays a pivotal role in boosting national economies by driving foreign exchange revenues. However, current productivity levels in floriculture, particularly in marigold (*Tagetes spp.*), are insufficient to meet the escalating global demand for ornamental flowers. Marigold, being one of the most commercially significant crops in this sector, requires improved seed quality to achieve optimal performance and higher yields. Major constraints, such as the limited availability of high-quality seeds, and the rapid decline in seed viability during storage, continue to hamper productivity. Additionally, conventional seed treatment practices and storage methods often fail to sustain seed vigour and germination rates over extended periods. This review offers an in-depth analysis of the latest advancements in seed treatment technologies and storage practices to enhance germination, disease resistance, and seedling establishment. By integrating the insights from seed treatments and post-harvest storage of seeds, this review paper addresses key challenges faced by the floriculture industry and aligns with the growing global demand for high-quality floral crops.

Keywords: Marigold, *Tagetes erecta*, Seed pelleting, Seed priming, Seed Treatment, Storage, Gamma irradiation, Oil content, Moisture content, Relative humidity, Temperature, Storage containers.

Introduction

Marigold is a flower crop belonging to the Asteraceae family^[1]. Commonly cultivated marigold species are *Tagetes erecta* (African Marigold) and *Tagetes patula* (French Marigold), originated from Mexico and South Africa, respectively^[2]. The colours of African marigold flowers range from yellow, orange, gold, and red^[3]. In India, loose marigold flowers are used to create garlands, and ornamental flowers are used in landscape gardening^[4].

Marigold has enormous potential for value addition, so it is gaining significant importance in the industry^[5]. Natural pigments and dyes have a wide range of usages currently including the culinary, cosmetic, medicinal, and fabric sectors. The risks associated with using artificial dyes and pigments on organisms and the environment made natural pigments and dyes an

alternative^[6]. Flowers of marigold can be used as a natural source of phenolics^[7]. The main constituents of marigold flowers are patulitrin, quercetagenin, isorhamnetin, kaempferol and patuletin^[8]. The lutein pigment naturally present in marigold can be extracted from marigold flower petals^[9, 10]. Lutein can be used for colouring and enhancing food with nutrients^[11]. Lutein has antioxidant properties and it is a wise choice for eye health protection^[3].

The essential oil and carotenoid extracts of marigold have wide use in the food, medicine, cosmetic, and textile industries^[12, 13]. Marigold flowers are utilized in the production of poultry feed as they enhance the colour^[14]. It can be also used as an analgesic and as a medicine for anti-inflammation^[15]. Marigolds have antibacterial, fungicidal, insecticidal, mosquito-cidal, herbicidal qualities^[16-19] which make them useful in many organic agricultural domains, particularly in vegetable culture^[20]. Marigold plantation as intercrop reduces nematode population^[21] and it can also be used as a trap crop for tomato fruit borer^[22].

Since seeds are living things, during storage, their viability and vigour begin to decline even on the parent plant gradually, and consequently, they lose the capacity to germinate and produce healthy seedlings^[23]. Until subsequent sowing and marketing per demand, the seeds with optimum germination, vigour, and seed health must be maintained. The biggest bottlenecks in marigold production are poor seed set, non-availability of quality seeds^[24], and loss of vigour and viability of the seeds during post-harvest storage^[25]. Production and supply of quality and vigorous seeds are important for the successful cultivation of flower crops. The demand for quality seeds is increasing among farmers and specific technologies are needed to improve seed yield and quality. Thus, management practices such as seed treatments, proper storage of seeds, *etc.* are required to achieve the same.

Seed enhancements may boost the quality to guarantee the accessibility of high-quality seed lots for sowing. Seed enhancement can be defined as the post-harvest treatments which improve seed germination or growth of seedlings that must be applied before sowing. Also, seed treatments play a key role in protecting the seeds from insects and pathogens at the emergence and early growth stages^[26] and preserving the seeds for a long period without any contamination or deterioration. To maintain the planting value of seeds in field circumstances, it is also crucial to select proper seed packaging materials and storage conditions that will help to lengthen the longevity of the seeds. Careful handling throughout the storage phase can lessen the quantitative and qualitative loss of seed^[27]. This review encompasses current

advances in improving the marigold seed quality through various pre-sowing seed treatments and proper post-harvest storage of seeds.

Seed characteristics: Marigold seeds are called achenes and have a simple, dry, one-seeded, indehiscent fruit with a thin but protective layer around the seed. Marigold seeds are plentiful in carotenoid chemicals, namely zeaxanthin and lutein. Essential oils extracted from marigold seeds have several constituents, including limonene, ocimene, and β -caryophyllene^[28] and a significant quantity of fatty acids^[29]. Pusa Narangi Gaiinda genotypes had the maximum oil content in seeds (36.73% and 33.10%), followed by Pusa Basanti Gaiinda (35.47 and 31.26%) at physiological and harvest maturity^[30]. The oil content of the mature seed heads increases and then begins to decrease as they approach harvest maturity^[31]. Proteins or carbohydrates did not affect the longevity of seeds, but seeds with oil as their primary seed storage component had a shorter lifespan^[32]. Therefore, the viability of these seeds gets reduced within a short period. Proper management techniques are needed to maintain the vigour and viability of marigold seeds. Using the right pre-sowing seed treatments and optimizing seed storage are the two key actions that may be taken to improve the quality and maintain the viability of the seeds.

1. Enhancing marigold seed quality through pre-sowing seed treatments: Seed treatments will help improve the germination percentage, seedling quality characters, and crop growth. When treated, seeds become more resistant to pests, diseases, and environmental stresses. To promote seed development and address their challenges, seed treatment is an essential step. Seed treatments include physical, physiological, chemical, and biological treatments. Numerous plant aspects that boost production can be optimized by applying physical treatments in the right amounts^[33]. Physiological seed treatments assisted in overcoming dormancy and enhanced the seed germination percentage^[34]. Chemical seed treatments can be used against insects, and soilborne and seed-borne pathogens to enhance vigour and crop growth^[35]. The relatively low quantity of pesticides used reduces environmental impact compared to broadcast applications. Biological seed treatments have gained more popularity within a short time^[36] and it also improves the seed parameters^[37]. Due to their socioeconomic benefits and safety for the environment, physical and biological seed treatments are being utilized extensively as substitutes for chemical treatments, either alone or in tandem with one another. **In terms of ease of implementation, chemical treatments are generally simple and quick to apply, requiring minimal technical knowledge. Biological**

treatments, however, may require more expertise in handling live microorganisms and ensuring optimal conditions for their efficacy. Physical treatments, although effective, often involve the use of specialized equipment and may be less accessible to small-scale farmers due to higher initial costs. Continued research and innovation focused on increasing efficacy, safety, and ease of adoption of seed treatments will further help farmers and communities dependent on thriving agriculture.

1.1. Physical seed treatments: Physical ways of stimulating plant growth have gained popularity recently since they have less negative environmental effects. Physical factors can be utilized to induce positive changes in seeds^[38]. The application of physical factors in appropriate doses can be an effective way to enhance many plant parameters that increase their productivity. Seed coating, seed pelleting, gamma irradiation, seed encrustation, seed colouring and other techniques are examples of physical seed treatment techniques. The two most promising of these are magnetic seed treatment and irradiation with ionizing radiation^[39].

1.1.1. Gamma irradiation: In comparison to other ionizing radiations, gamma rays are more cost-effective and have a greater penetration power, which allows for a wider range of applications for enhancing the performance of seeds^[40]. It has been depicted that gamma irradiation at low concentrations can improve seed traits^[41, 42]. Low levels of gamma irradiation may improve the adaptive properties of seeds in unfavourable conditions^[43]. Ionizing radiation quickly pervades the polysaccharide granule, allowing for a quicker, simpler, and more effective radiation treatment^[44].

Marigold seeds can be treated with lower doses of gamma irradiation for improved seed germination percentage (86%)^[45]. Seeds of African marigold cv. 'Pusa Narangi Gaiinda' were exposed to gamma rays at doses of 0, 100, 200, 300, and 400 grays to induce mutation. Shortly after radiation, seeds were sown, and 30 days old seedlings were transplanted. African marigold seeds exposed to 100 grays of gamma rays increased the growth and yield attributes^[46].

1.1.2 Magnetic Seed Treatment: The bio-stimulation of seeds through magnetic field treatment is probably the least problematic, least expensive, and least harmful to the environment. In many plants, seed germination and yield can be enhanced by using a magnetic field treatment^[47-51]. The magnetic field enhances the respiration of the seed as well as its powerful metabolism, and under adverse conditions, the magnetic field speeds up

germination and plant growth by aiding in the restoration of the normal metabolism of energy and respiration intensity^[47]. The application of magnetic treatment^[47] may also encourage cell elongation and division, as it increases the root length and shoot length^[52]. It can also increase the integrity of the seeds outer membrane and decrease electrical conductivity and cellular leakage in the seeds^[53]. The magnetic fields affect the production of free radicals and contributes to increased seed vigour.

Afzal, Mukhtar^[54] reported that the marigold seeds treated with 100 mT produced a higher emergence percentage (4-fold) and emergence index (5-fold). They also stated that through magnetic seed treatment, the starch metabolism of the seed is enhanced and hence it leads to improved seed parameters.

1.1.3 Seed pelleting: Pelleting is a method by which size, shape and weight of seeds are increased by using fillers and binders. Binder is a liquid polymer formulation with adhesive qualities, and filler is a solid powder that makes up the majority of the seed pellets and seeds are stirred by rotating in cycles to get pelletized^[55]. It has a positive impact on seedling emergence speed^[56]. As marigold seeds are light in weight, it is difficult for the precise sowing of the seeds. Pelleting of seeds helps the farmers to handle the seeds easily, making planting easier and facilitating seedling growth faster. When pelleting marigold seeds, 0.3% w/v methyl hydroxyethyl cellulose (MHEC) was the best binder option^[57] and it was also pointed out that the best choice for pelleting marigold seeds is the MHEC CaSO₄ matrix^[58]. By pelleting the seeds, sowing can be done precisely making the thinning operation more easier^[59]. Pelleting also improves the seeds ability to uptake moisture and oxygen, which eventually results in a greater rate of germination^[60].

1.2 Physiological seed treatment: Physiological seed treatments alter the internal metabolic mechanisms of the seeds, thereby it enhances seed germination by breaking dormancy and also improves the seed quality. It includes seed priming, stratification of seeds (warm and cold), and alternate wetting and drying of seeds.

1.2.1 Seed priming: Priming is a physiological method that involves wetting and drying of seeds to accelerate the pre-germinative process of metabolism for quick germination, development of seedlings, and overall yield under both normal and stressful settings. The overall aim of seed priming is to partly hydrate the seeds to a stage where germination events start, however under normal or stressful conditions, they would show quick germination^[61]. Seed priming improves the biochemical and physiological characteristics of seeds^[62]. There are various forms of priming (Fig 1), including hydro priming, osmo-priming, halo

priming, sand matric priming, and bio priming. The more recent ones are magneto priming and nano priming.

Hormonal pri
Magneto primin
Matri-prim

Fig 1: Types of seed priming

Priming prolongs the shelf life of seeds and improves their germination rate, homogeneity, and speed of germination (Table 1). Additionally, it improves tolerance to extreme temperatures and water stress^[70]. Seed priming has become popular because of its effectiveness, affordability, and adaptability in enhancing the performance of marigold seeds. Primed seeds germinate more quickly and uniformly when compared to unprimed seeds because of early imbibition, altered activation of enzymes, metabolism, biochemical mechanism of repair of cells, synthesis of proteins, strengthening of antioxidant defence system, and greater availability of ATP^[71, 72]. Future research has to concentrate on creating suitable on-farm priming techniques and optimum priming protocols for different cultivars and types of marigolds in various agroclimatic zones.

Table 1: Different seed priming methods of marigold

SL No.	Treatment	Results	References
1	Seeds primed with deionized water for 12 hrs (Hydro priming)	Plants exhibited highest percentage of germination, plant establishment, height, 1000 seed weight, number of branches, and blossom yield.	Damabi, Singh [63]
2	Seeds primed with 50mM CaCl ₂ for 24 hrs (Halo priming)	Improved germination index (24), germination percentage (88%), shoot length (5.10 cm), and root length (4.90 cm)	Afzal, Ashraf [64]
3	Seeds primed with GA ₃ at 25 ppm for 30 mins	Improved germination percentage, stem height, flower number, size, and weight	Sharoa, Motial [65]
4	Priming the seeds with 15 ml/L seaweed	Enhanced seed germination by two-fold (84%)	Tavares, dos Santos [66]
5	Seeds primed with Ascorbate (100 ppm) for 24 hrs at 25°C	Increased germination percentage and minimized salinity effects	Afzal, Rahim [67]
6	Seeds primed with de ionised water (2 ml) and applied a temperature drop treatment from 22 °C to 10 °C for 2 hrs every 24 hrs, for 6 days before sowing	Increased plant height (7.58 cm), leaf dry matter (209 mg), stem dry matter (195 mg), root dry matter (50.5 mg), flower dry matter (280 mg), plant dry matter (734.5 mg)	Sysoeva, Markovskaya [68]
7	Seeds primed with 0.5% KNO ₃ for 6 hrs and	Enhanced germination percentage in the genotype Hissar Jafri (89%)	Sindhu and Sehwat [69]

	dehydrating at room temperature		
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1.3 Chemical seed treatment: Chemical seed treatments offer the benefit of protecting seeds from pests, diseases, and unfavourable soil conditions, enhancing germination rates and seedling vigour. However, they pose potential risks, such as environmental contamination and harm to non-target organisms, including beneficial soil microbes and pollinators. Additionally, overuse may lead to chemical resistance in pests, reducing long-term effectiveness. Numerous research has examined into how various chemical seed treatments affect marigold performance. Seeds treated with fungicides have shown to boost marigold flower yields^[73]. All of the fungicides, including aureofungin solution, bavistin, thiram, roko, difolatan, indofil M-45, captan, and blitox 50 enhanced seed germination, boosted seedling vigour, reduced seed mycoflora and pre and post-emergence mortality of marigold seeds as compared to the control^[74]. Application of mancozeb (3.5g/kg) and chlorothalonil (5g/kg) to marigold seeds decreased the seed borne infection without having any adverse effects on seed germination^[75]. Insecticidal seed treatments are also significant for enhancing the seed quality. Aphids, beetles, weevils, red spider mites and leaf hoppers are some of the major pests of marigold. Seed treatment with chlorax was effective in controlling the pests of marigold seeds^[76]. Fungicidal and insecticidal seed treatments have clearly demonstrated plant protection abilities that translate into improved productivity in marigold. When applied judiciously as one component of integrated management, seed treatments help in managing threats posed by fungi and insects during this critically vulnerable stage of the marigold life cycle.

1.4 Biological seed treatment: Seed treatment with biofertilizers is one of the biological seed treatments. Bio-fertilizers are ready-to-use live formulations of advantageous microorganisms that, when applied to seeds, increase the availability of nutrients primarily through their biological activity, support the development of the microflora, enhance soil health, and add significantly to crop yields^[77]. Through a variety of processes, including phosphate

solubilization and mobilization, atmospheric nitrogen fixation, composting, phytohormone generation, and disease suppression, biofertilizers enhance plant growth and productivity. Microbes that promote plant growth restrict plant infections by producing antibiotics, siderophores, HCN, and ammonia, as well as hydrolytic enzymes like chitinase and β -1,3-glucanase. These processes also trigger the plant defense mechanism and competition for resources and habitat areas^[78].

Marigold seeds treated with PGPR strains including *Azospirillum*, *Azotobacter*, *Bacillus*, *Pseudomonas*, *Rhizobium*, and *Serratia* increased germination rate, germination speed, seedling emergence, plant height, flower yield, and vase life^[79]. Treating marigold seeds with *Bacillus azotoformans* (1×10^9 CFU/ml) was effective against the seed-borne fungus *Alternaria tagetica*^[80]. Marigold seeds soaked in solutions containing 20% effective microorganisms, 2.4 g dm^{-3} Trichoderma, and 1% Goemar Goteo for 30 minutes enhanced germination energy^[81]. Using 20% vermicompost for marigold seed treatment also enhanced seed germination and boosts the growth of the plants^[82].

Biological and physical seed treatments are considered superior to chemical treatments as they offer eco-friendly solutions with minimal environmental impact and reduced risks to non-target organisms. Biological treatments utilize naturally occurring microorganisms to enhance seed health, while physical methods like ensure seed protection without harmful residues. These alternatives promote sustainable agriculture by improving seed quality and resilience without contributing to soil degradation.

2. Optimizing marigold seed storage: Unsuitable post-harvest storage conditions can impact seed quality by speeding up the loss of viability and shortening the seed's lifespan^[83]. Marigold seeds might become less vigorous and viable if not stored properly^[25]. Temperature, moisture, and humidity are some of the abiotic variables that can impact the storability of seeds^[84]. The soluble sugar, protein, and fat contents of the seeds gradually decreased as storage time increased, whereas the starch content increased^[85]. The antioxidant activity of the seeds decreased and hydrogen peroxide activity increased during the seed storage^[86]. Appropriate storage techniques may help to increase the profit and prevent undesired losses. The market value of the produce shall rise with any sort of packaging technology that emphasizes extended storage periods and thus can minimize the losses^[87]. Based on research studies, the following methods can help to preserve marigold seed vigour and viability.

2.1 Moisture content and relative humidity on seed storability: Storing the seeds after reducing the moisture content to the optimum level is found to retain the germination percentage of seeds even after long-term storage^[88, 89]. Studies have found that drying the seeds to the optimal moisture content prevents deterioration during storage and maintains viability^[90]. This usually involves drying in low-humidity conditions soon after harvest. It was stated that silica gel when combined with seeds in paper packets was effective for up to 4 months, but drying marigold seeds to a moisture content of about 8% and storing them in sealed moisture-resistant packages retained acceptable levels of germination (above 50 %) for 6 to 10 months at room temperature and relative humidity of 39%. Germination could be prolonged for 8 to 10 months in moisture-resistant containers and 6 to 8 months in paper packets containing silica gel when the seeds were kept at 15 ± 2 °C^[25]. Lower moisture may risk seed death while higher levels might lead to fungal growth. Checking moisture levels periodically with a seed moisture tester allows for adjustments through further drying or humidity regulation within the storage containers.

2.2 Temperature on seed storability: Storing seeds at low temperatures is proven to increase the storage life of the seeds and slow down the biological processes within the seed. Research has shown that storing marigold seeds at temperatures of 0 °C to 10° C maintains vigour and high seed germination percentages even after 24 months of storage. Temperatures below 0 °C, however, may cause freezing damage. Controlled seed storage rooms or commercial freezers work well. Singh, Jain [91] stated that leachate conductivity did not accurately indicate viability loss when marigold seeds were stored at a low temperature. They concluded that seeds with a moisture content of 3% to 6% can be safely stored for a longer duration of time at -20 °C.

2.3. Moisture-proof containers and pre-storage seed treatments on seed storability: Airtight containers are often recommended for storing seeds to maintain seed viability and germination rates over time. It protects against fluctuations in temperature and humidity that can negatively impact seed germination rates^[92]. Interactions between seeds and their environment are greatly impacted by container parameters^[93]. Storing seeds in airtight containers helps prevent fluctuations in seed moisture content during storage by protecting them from ambient humidity. Seeds might be preserved for shorter periods in cloth bags and longer in plastic bags^[94]. The use of laminated aluminium packets or thick polyethylene bags that prevent gas exchange is ideal for seed storage^[95] and can maintain viability for up to two years if stored at optimal low temperatures.

The marigold seeds stored as dry flowers in a double-layered polythene bag with silica gel showed the highest rates of germination, root length, shoot length, vigour index, seedling dry weight, germination rate index, and field emergence with the lowest electrical conductivity after ten months of storage^[96]. An experiment was conducted in which marigold seeds were stored in 6 different types of containers like tin, plastic box, polythene bag, cotton bag, paper bag, and in trays in open condition^[97]. After ten months of storage, they found that seeds stored in tin showed the highest germination percentage, shoot length, root length, seedling dry weight, vigour index, and viability followed by the plastic bag. This might be because the tin box's impermeable nature served as a more effective moisture barrier. On the other hand, in an open environment, changing atmospheric relative humidity may have altered the moisture content of the seeds, which would have led to their degradation. Marigold seeds treated with thiram (2g/kg) + cytozyme (10g/kg) and stored in polyethylene bags resulted in the highest vigour and viability^[98]. Seeds of marigold treated with chlorax and stored in a double-layered polythene bag showed better outcomes in terms of seed quality parameters, including significantly higher germination, shoot length, root length, vigour index, field emergence, and germination rate index^[76]. For marigold, seed storage in a 300-gauge polythene packet or in a refrigerator may be advised for up to three months to preserve its quality^[99]. **By using hermetic containers, seed storage duration can be significantly extended. Hermetic containers create a sealed environment that restricts oxygen and moisture exchange, reducing the risk of seed deterioration caused by fungal growth, insect activity, and seed respiration. This method also maintains optimal seed moisture content, preserving seed vigour and viability for longer periods.**

Conclusion

Several studies have indicated that the quality and viability of marigold seeds can be effectively improved through seed treatment and optimal storage conditions. Seed quality can be improved by different seed treatments which can be physical, physiological, chemical or biological. Marigold seeds are relatively short-lived in storage, losing substantial germination capacity after few years even in cool, dry conditions. Proper storage techniques should therefore be followed for marigold seeds intended for propagation use after extended time periods. **The research evaluated highlights the need for improving uniformity and productivity in commercial marigold production through optimized seed treatments and storage techniques. Future research should focus on developing standardized protocols for seed grading, priming, and coating to ensure consistency in seed quality. Additionally, studies**

should explore the scalability of biological and physical seed treatments, as well as the economic feasibility of advanced storage methods such as vacuum packing and modified atmosphere storage. Addressing these gaps can drive the sustainable intensification of marigold production, enabling growers to meet the rising global demand for this high-value crop.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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