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SEED ENHANCEMENT INTERVENTIONS IN ORNAMENTALS: MECHANISMS, EFFICIENCY AND FUTURE SCOPE

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ABSTRACT

Seed quality plays a defining role in the successful establishment and commercial value of ornamental crops, where uniform emergence, vigorous growth, and synchronized flowering are critical for market acceptance. Many ornamentals possess small, delicate, or physiologically complex seeds, making them highly responsive to targeted post-harvest enhancements. This review synthesizes recent progress in seed enhancement technologies, encompassing conventional, physiological, physical, biological, and nanotechnological interventions. Dormancy-breaking strategies such as scarification, stratification, and hydropriming continue to support germination in hard- or slow-germinating species, while seed protection treatments using fungicides, beneficial microbes, and botanical extracts improve seedling survival under nursery conditions. Seed coating technologies-including film-coating, encrusting, and pelleting-enable precise sowing and controlled delivery of active compounds, particularly in species with ultra-small seeds. Advanced techniques such as nanopriming, plasma exposure, magnetopriming, ultrasonic stimulation, microwave-assisted treatment, and low-dose irradiation have demonstrated significant improvements in seed vigour, stress tolerance, and metabolic activation by modulating biochemical pathways and enhancing water uptake. Applications in major ornamentals such as marigold, petunia, chrysanthemum, and zinnia confirm the effectiveness of these technologies in improving establishment and physiological performance. Despite substantial progress, challenges remain regarding the storability of primed seeds, safety of engineered nanomaterials, and the need for standardized, species-specific protocols. Future advancements integrating molecular diagnostics, sustainable biomaterials, and precision-based physical treatments will shape the next generation of seed enhancement strategies for ornamental horticulture.
***Keywords*:** Seed quality enhancement, ornamental horticulture, seed coating and pelleting, nanopriming, plasma seed treatment**,** germination and seedling vigour

Introduction

Seeds represent the fundamental biological and commercial unit in ornamental horticulture, serving as the primary means for propagating a wide range of floricultural species. High seed quality is essential for successful cultivation because it directly determines germination capacity, seedling vigour, emergence uniformity, and overall plant performance (Ellis, 1992; Finch-Savage & Leubner-Metzger, 2006). In the ornamental industry where aesthetic value, uniformity, and synchronized flowering are critical seed quality assumes even greater importance. Variations in emergence or early growth not only reduce visual appeal but also compromise market value and productivity. Many ornamentals such as petunia, begonia, snapdragon, and pansy possess extremely small or physiologically complex seeds, making them particularly sensitive to environmental fluctuations and handling challenges (Taylor *et al.*, 1998; Pedrini *et al.*, 2018). Consequently, growers increasingly rely on scientifically developed seed enhancement technologies to achieve reliable and efficient crop establishment.

Seed quality is shaped by multiple pre- and post-harvest factors including genetic background, maternal environment during seed development, physiological maturity, drying practices, storage conditions, and the ageing process (Panda & Mondal, 2020). While genetic improvement and optimized seed production techniques contribute significantly, post-harvest seed enhancement has emerged as a powerful and rapidly expanding frontier in improving seed performance (Halmer, 2003; Weissmann *et al.*, 2023). Seed enhancements include a broad range of physical, chemical, biological, and nanotechnological treatments designed to modify seed physiology, strengthen stress tolerance, improve sowing precision, and enhance germination behaviour. These technologies act at both external and internal levels by modifying seed coat characteristics, delivering active compounds, restructuring metabolic pathways, enhancing enzymatic activation, and improving repair mechanisms during early seedling establishment (Ventura *et al.*, 2012).

Many ornamental species exhibit inherent limitations such as hard or impermeable seed coats, physiological dormancy, suboptimal hydration rates, uneven germination, susceptibility to damping-off pathogens, and sensitivity to abiotic stresses (Finch-Savage & Leubner-Metzger, 2006). Traditional enhancement methods including scarification, stratification, priming, and seed protection have long been used to address these issues. However, recent scientific advancements have introduced highly innovative technologies such as nanopriming, plasma treatment, magnetopriming, microbial coating, and ultrasonic stimulation each offering new mechanisms and higher precision for improving seed performance (Atak *et al.*, 2003; Dhayal *et al.*, 2006; Mahakham *et al.*, 2017; Teixeira da Silva & Dobránszki, 2014; Naveed *et al.*, 2022). This review synthesizes both conventional and advanced seed enhancement strategies for ornamental crops, emphasizing their mechanisms, efficiencies, and future prospects in high-value floriculture.

Concept and scope of seed enhancement

Seed enhancement comprises any post-harvest treatment that improves seed performance without altering its genetic integrity (Taylor *et al.*, 1998; Halmer, 2003). In ornamental horticulture, these interventions are especially important because many species possess small, delicate seeds that are difficult to handle, slow to germinate, or susceptible to environmental and pathological stresses. Seed enhancements aim to improve germination speed and uniformity, increase seedling vigour, enhance tolerance to abiotic and biotic stresses, suppress seed-borne pathogens, extend storage longevity, achieve seed-size uniformity for precision sowing, and deliver nutrients, stimulants, or beneficial microorganisms directly to the seed surface. The major categories of seed enhancement relevant to ornamentals include dormancy-breaking treatments such as scarification and stratification, protective treatments using chemical fungicides, biological control agents, or botanical extracts, and seed-coating technologies such as film-coating, encrusting, and pelleting that improve sowing accuracy and facilitate the targeted delivery of active compounds. Physiological enhancement methods such as priming, fortification, and infusion activate key metabolic pathways before germination, thereby strengthening early seedling establishment. In recent years, advanced physical and nanotechnological treatments have expanded the scope of seed enhancement through innovative approaches including plasma exposure, ultrasonication, magnetopriming, microwave-assisted treatments, and ionizing radiation, all of which modulate seed physiology, improve water uptake, or stimulate beneficial biochemical responses (Ventura *et al.*, 2012; Rifna *et al.*, 2019). Collectively, these enhancement strategies play a critical role in improving the reliability, efficiency, and productivity of ornamental crop production.

Dormancy-breaking treatments in ornamentals

Dormancy mechanisms in ornamental species include physical, physiological, and combinational types. Appropriate dormancy-alleviation strategies significantly improve germination. Hydropriming enhances hydration, leaches inhibitors, and accelerates metabolism (Heydecker, 1973). Cold-water soaking is effective for *Nigella*, *Papaver*, and *Consolida*, while hot-water treatments break hard seededness in *Cassia* and *Acacia*. Scarification improves permeability to oxygen and water. It is widely used for *Clitoria ternatea*, *Lathyrus odoratus*, and *Delphinium*. Mechanical abrasion disrupts lignified or waxy coat layers. Sulphuric acid treatments effectively break physical dormancy in hard-coated ornamental seeds by dissolving cuticular and lignified layers (Vanangamudi *et al.*, 2010). Cold stratification (3–5°C) breaks physiological dormancy by activating enzymes and modulating ABA/GA balance (Finch-Savage & Leubner-Metzger, 2006). Temperate ornamentals such as *Primula*, *Delphinium*, and *Digitalis* require stratification for optimal emergence.

Seed protection treatments

Seedling mortality due to damping-off, fungal rots, and soil-borne pathogens is a major concern in ornamentals grown under greenhouse conditions. Active ingredients such as thiram, captan, carbendazim, metalaxyl, and imidacloprid minimize infection risks. Fungicidal seed dressing is effective for marigold, zinnia, and chrysanthemum and improves stand establishment (Rocha *et al.*, 2019). *Trichoderma*, *Bacillus*, and *Pseudomonas* strains improve plant vigour through antagonism, ISR activation, and nutrient mobilization (Naveed *et al.*, 2022). Trichoderma-coated ornamental seeds often exhibit improved root morphogenesis and pathogen resistance. Botanical extracts such as neem or pongamia contain antifungal phenolics and terpenoids that reduce pathogen incidence (Panda & Mondal, 2020).

Seed coating technologies

Seed coating transforms small, irregular ornamental seeds into uniform units suitable for mechanical sowing and targeted delivery of actives (Pedrini *et al.*, 2018; Sohail *et al.*, 2022). Thin polymer layers improve flowability and enable precise ingredient delivery, without altering seed shape (Afzal *et al.*, 2020). Widely adopted in petunia and verbena. Seed encrusting adds moderate thickness to improve size uniformity while retaining seed morphology. Pelleting is indispensable for extremely small seeds such as petunia and begonia. Pellet materials (silica, clays, diatomaceous earth) increase seed size 5–10 times, facilitating automated sowing (Taylor *et al.*, 1998). Colour additives aid in quality control and brand recognition, without affecting physiological performance.

Physiological and germination-enhancing treatments

Priming reactivates metabolic pathways prior to radicle protrusion (Heydecker, 1973; Jisha *et al.*, 2013). Types include: Hydropriming, Osmopriming using PEG (Rifna *et al.*, 2019), Halopriming (KNO_3), Hormonal priming with GA_3, Biopriming using beneficial microbes (Naveed *et al.*, 2022), Chemical priming with chitosan, micronutrients, antioxidants Priming improves germination uniformity, seedling vigour, and stress tolerance. Nutrient soaking enriches seeds with essential minerals such as Zn, Mn, and B, enhancing enzyme activation (Panda & Mondal, 2020). Organic solvent-mediated infusion allows penetration of hydrophobic seed coats for species sensitive to water soaking. Repeated wet–dry cycles improve membrane stability and drought tolerance. Partial germination (radicle emergence) accelerates establishment for slow-germinating ornamentals.

Advanced and emerging technologies

Recent advancements in physical, microbial, and nanotechnological seed enhancement methods have significantly improved seed vigour, stress tolerance, and early growth in ornamental crops. A comparative evaluation of major enhancement methods is presented in Table 1. Nanoparticles (NPs) such as Ag, ZnO, TiO_2, and Fe have demonstrated substantial benefits by enhancing water uptake, enzymatic activity, antioxidant metabolism, and chlorophyll synthesis, leading to improved germination and biomass accumulation (Mahakham *et al.*, 2017; Guha *et al.*, 2018; Nile *et al.*, 2022). Nanofiber-based coatings further enable controlled nutrient release and protection against abiotic stress (Xu *et al.*, 2020). In marigold, nano-ceria significantly enhanced seed vigour by improving antioxidant capacity (Jahani *et al.*, 2022).

Microbial encapsulation using biodegradable polymers enhances the survival and delivery of plant growth-promoting microorganisms (PGPMs), ensuring improved nutrient uptake, growth stimulation, and disease suppression (Rocha *et al.*, 2019; Naveed *et a*l., 2022). Magnetic-field exposure is another promising non-chemical technique shown to improve enzyme activation, germination speed, and antioxidant regulation (Atak *et al.*, 2003; Bilalis *et al.*, 2012). Magnetopriming in marigold increased both germination and seedling biomass (Niculita *et al.*, 2008).

Low doses of gamma irradiation induce hormesis, stimulating metabolic activity, enzyme systems, and seedling emergence (Bottino *et al.*, 1975; Wang *et al.*, 2022). Enhanced germination and early growth have been reported in chrysanthemum and Rosa hybrida under optimized irradiation levels (Giovannini *et al.*, 2015). Ultrasonic priming improves imbibition by creating microfractures in hard seed coats (Miyoshi & Mii, 1988; Teixeira da Silva & Dobránszki, 2014), with significant improvement in vigour reported for marigold and tomato (Ramteke *et al.*, 2015).

Cold plasma technology represents an emerging frontier, generating reactive oxygen and nitrogen species (RONS) that sterilize seeds, enhance surface wettability, and stimulate early metabolism (Dhayal *et al.*, 2006; Brandenburg *et al.*, 2009; Sera *et al.*, 2010;). Plasma-treated chrysanthemum synseeds showed higher viability and greenhouse establishment (Henselová *et al.*, 2012). Microwave-assisted seed treatment has also shown promise by reducing fungal contamination and improving hydration kinetics (Schmidt *et al.*, 2018). In zinnia, controlled microwave exposure significantly enhanced germination and seedling uniformity (Szopinska & Dorna, 2023).

Table 1: Comparison of Seed Enhancement Techniques for Ornamental Crops

Technique	Advantages	Limitations	Suitability	References
Film coating	Improves seed flowability and enables precision delivery of nutrients and protectants	Cost of polymers and coating equipment	Excellent	Taylor *et al*. (1998)
Pelleting	Facilitates uniform sowing of small or irregular seeds	May impede emergence in high-moisture soils	Essential	Taylor *et al*. (1998)
Priming	Enhances speed and uniformity of germination; improves vigour	Reduced storability due to early metabolic activation	Highly suitable	Ventura *et al*. (2012)
Nanopriming	Increases stress tolerance, water uptake, and enzymatic activity; boosts vigour	Potential ecotoxicity and regulatory concerns	Highly promising	Mahakham *et al*. (2017); Nile *et al*. (2022)
Plasma treatment	Provides sterilization, improves wettability, enhances early growth	Requires specialized plasma equipment	Ideal for high-value seeds	Dhayal *et al*. (2006); Sera *et al*. (2010)
Magnetopriming	Eco-friendly; improves enzyme activation, germination speed, and vigour	Mechanisms not fully understood	Moderately applicable	Atak *et al*. (2003); Niculita *et al*. (2008); Bilalis *et al*. (2012)
Ultrasound	Improves imbibition and germination via microfracturing of seed coat	Risk of tissue injury if exposure exceeds threshold	Selective	Miyoshi & Mii (1988); Teixeira da Silva & Dobránszki (2014)
Radiation	Low doses induce hormesis, improving germination and metabolism	High doses may cause mutations or tissue damage	Limited	Bottino *et al*. (1975); Giovannini *et al*. (2015); Wang *et al*. (2022)

Applications in major ornamentals

Seed enhancement technologies have been increasingly adopted in major ornamental crops to improve emergence, vigour, uniformity, and post-transplant performance. In marigold (*Tagetes* spp.), nanotechnology-based treatments such as nanoceria priming and magnetopriming have been reported to significantly enhance seed vigour, germination rate, and seedling robustness (Jahani *et al*., 2022; Niculita *et al*., 2008). Additionally, microbial seed coatings using beneficial rhizobacteria improve nutrient uptake efficiency and prolong vase life by strengthening physiological resilience (Naveed *et al*., 2022).

In petunia, seed pelleting is widely employed to facilitate precision sowing due to the extremely small seed size, enabling mechanised planting and uniform seedling establishment (Taylor *et al*., 1998). Advanced physical treatments, particularly cold plasma and laser irradiation, have been shown to stimulate early growth, metabolic activation, and seedling vigour (Dănăilă-Guidea *et al*., 2011).

For chrysanthemum, plasma-assisted treatments have demonstrated enhanced synseed viability, rooting efficiency, and overall greenhouse performance by improving physiological responsiveness during early development (Henselová *et al*., 2012). Seed priming strategies have also been associated with accelerated flowering and improved crop scheduling in commercial production systems.

In zinnia**,** microwave-assisted seed sanitation effectively reduces fungal contamination without damaging seed quality, offering a rapid, chemical-free method for phytopathogen control (Szopińska & Dorna, 2023). Priming protocols further enhance germination uniformity and synchronized flowering, which are essential traits for ornamental bedding plant production.

Challenges and future prospects

Seed enhancement technologies offer significant potential for improving propagation efficiency in ornamentals; however, several challenges must be addressed to enable their widespread and sustainable adoption.

Storability- A major limitation of primed seeds is their reduced shelf life, as hydration-mediated metabolic activation accelerates deterioration. Without adequate protective measures, these seeds lose vigour rapidly during storage. The use of protective polymer coatings, osmotic regulators, and molecular stabilizers, including antioxidants and membrane protectants can help slow down ageing and improve the storage life of primed seeds.

Safety Concerns- While nanopriming and nanoparticle-mediated seed coatings are highly effective, concerns remain regarding the ecotoxicity, environmental persistence, and unintended soil–microbe interactions associated with engineered nanomaterials. Comprehensive toxicological, fate, and transport studies are required before large-scale deployment.

Standardization- Seed enhancement protocols often lack standardization across species. Factors such as plasma exposure duration, ultrasound frequency, laser intensity, and magnetic field strength differ widely across studies, hindering reproducibility and industrial adoption. Establishing species-specific dose–response databases and international guidelines is essential (Rifna *et al*., 2019).

Molecular Insights- Although physiological improvements due to priming and physical treatments are well documented, the molecular mechanisms governing these responses remain poorly understood in ornamentals. Integration of transcriptomics, proteomics, metabolomics, and advanced molecular markers will allow precise prediction of seed responses and accelerate the development of optimized enhancement strategies.

Species-Specific Protocols- Ornamental crops display wide variability in seed morphology, dormancy behavior, and physiological responses. Therefore, one-size-fits-all approaches are ineffective. Development of customized, species-specific, and even cultivar-specific protocols is crucial for achieving consistent improvements in uniformity, vigour, and growth.

Sustainable Materials- Future seed coating and pelleting technologies must transition towards environmentally sustainable and biodegradable materials, particularly plant-based polymers, polysaccharides, and bio-derived nanofibers. These materials reduce environmental burden while offering controlled hydration and protection during storage.

Conclusion

Seed enhancement technologies ranging from priming, pelleting, plasma treatment, and magnetopriming to advanced nanotechnological and microbial approaches offer transformative potential for improving germination, vigour, stress tolerance, and uniformity in ornamental crops. While significant progress has been made, future research must focus on improving storability, ensuring environmental safety, and developing standardized, species-specific protocols. The integration of molecular biology tools with sustainable materials and precision technologies will shape the next generation of seed enhancement strategies, enabling higher productivity and quality in the ornamental horticulture industry.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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