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Review Article

Enhancing carrot seed quality: a review of the impact of priming and storage containers on *Daucus carota* L. seeds

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ABSTRACT
Carrots, belonging to the Apiaceae family, are versatile ingredients used in various culinary forms. However, carrot cultivation faces a persistent challenge of poor seed germination, which significantly affects crop yield. The application of seed priming techniques, such as hydro-priming and various chemical treatments like GA_3 and KNO_3, has shown promise in enhancing seed quality, promoting rapid germination, and improving seedling vigor. Moreover, the choice of suitable storage containers plays a crucial role in preserving seed longevity. Hermetic storage options like sealed containers, metal bins, and super grain bags have been found effective in maintaining seed viability over extended periods. Vacuum storage conditions, in particular, have proven beneficial for extending the shelf life of primed seeds. The relationship between seed moisture content and storage container choice also influences seed quality during storage. Improving carrot seed quality through priming techniques and employing appropriate storage containers is vital for successful cultivation and sustainable seed production. These practices contribute to increased germination rates, enhanced seedling vigor, and overall crop productivity, ensuring a consistent supply of high-quality carrot seeds for agricultural purposes.

1. Introduction

Vegetables, being rich sources of essential vitamins and minerals, offer a diverse range of nutrients, including carbohydrates, proteins, fats, vitamins, minerals, and water when consumed in adequate quantities. Carrots (*Daucus carota* L.), a significant root vegetable, belong to the Apiaceae family. They are a versatile ingredient used in various culinary forms such as salads, cooked dishes, and pickles. Carrots are also well-suited for processing into products like pickles, sweet dishes (such as Gazar ka Halwa), carrot powder, and kanji. Their nutritional value is notably high, primarily due to their rich carotene content, a precursor of vitamin A. Carrots also possess antioxidant properties that help combat harmful free radicals and reduce the risk of heart diseases. Fresh edible carrots typically contain 88.6% water, 1.1% protein, 0.2% fat, 9.1% carbohydrates, 1.0% fiber, and essential vitamins like A, B_1, B_2, C, as well as trace minerals [1]. Carrots are cultivated as an annual crop for root production and biennially for flowering and seed production. They thrive in cooler seasons, but certain tropical varieties can withstand higher temperatures. Carrots can be categorized into two distinct groups: Tropical (or Asiatic) and Temperate (or European) carrots. The temperate varieties form roots under both temperate and tropical climates but only set seeds under temperate conditions, requiring a specific low-temperature period for flowering. In contrast, the Asiatic types are high-yielding and can produce seeds under tropical conditions. Afghanistan is considered the primary center of origin for carrots, with global production being led by countries like China, Uzbekistan, Russia, and the United States [2]. In India, carrots are cultivated on a significant scale, with Haryana leading in production. However, one persistent challenge in carrot cultivation is poor seed germination, attributed partly to the rudimentary embryos of the seeds and their smaller size [3]. This poor germination directly affects yield, highlighting the need to improve carrot seed quality, particularly under adverse conditions. Seed priming, a pre-sowing treatment that enhances germination and seedling vigor, can be a simple yet effective technique for achieving this. Seed priming involves controlled hydration of seeds, allowing them to germinate more efficiently, especially in unfavorable environmental conditions [4]. It facilitates rapid germination, uniform emergence, increased stress tolerance, and reduced dormancy in many plant species. The primary goal of seed priming is to hydrate the seeds partially, initiating the germination process without completing it [5, 6]. In addition to seed priming, the choice of suitable storage containers is vital for preserving seed quality from harvest to the next sowing season. Packaging materials significantly affect the interaction of seeds with their environment. While seed deterioration is an ongoing process, it can be slowed down by employing appropriate containers. Packaging materials with superior barrier properties are essential for maintaining good seed germination over extended periods [7]. Moisture-proof containers can also be employed to control issues like fungal contamination and aflatoxin accumulation in seeds [8]. In summary, carrots are nutritionally valuable vegetables, and improving seed quality through techniques like seed priming and proper storage containers is crucial for successful cultivation and sustainable seed production. These practices contribute to higher germination rates, seedling vigour, and overall crop productivity while ensuring a continuous supply of high-quality carrot seeds.

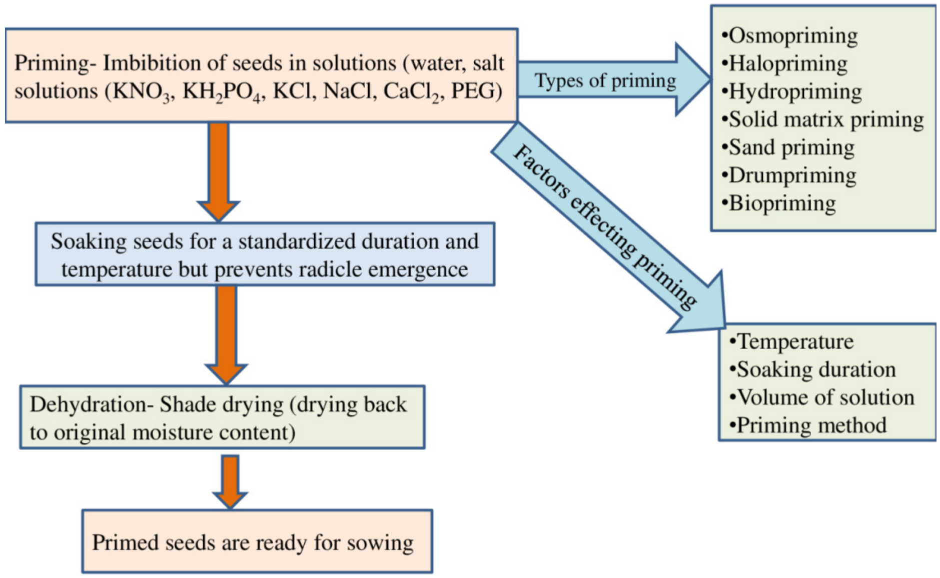

Figure 1: Graphical process of seed priming.

2. Effect of priming on the seed quality

Hydration-dehydration process, also known as hydro-priming, was highly effective in tomato seeds with low vigor. This study indicated that hydro-priming is a viable method for enhancing the performance of medium-quality tomato seeds [9]. Priming techniques helped overcome sub-optimal environmental conditions, leading to improved germination and field emergence through osmo-priming and hydro-priming, in bitter gourd seeds [10]. Seeds primed in water for 24 hours exhibited enhanced germination and seedling growth, particularly under salt stress conditions in cumin seeds [11]. Parsley seeds subjected to hydro-priming for 12 hours at 10°C exhibited a significantly higher germination rate compared to non-primed seeds [12]. Highest germination percentage, seedling vigour, and seedling dry weight were achieved after nine hours of hydro-priming in cumin seeds [13]. Hydro-priming for up to 12 hours resulted in a significantly higher germination percentage and seedling dry weight in fenugreek [14]. Hydro-priming for 24 hours recorded an 11% increase in the speed of germination and a 12% increase in germination percentage compared to the control in carrot seeds [15]. Hydro-priming is considered a crucial technique for achieving rapid germination, improved seed growth, and uniform stand establishment in various crops [16]. Hydro-priming for 12 hours with seed volume doubled was the most effective in enhancing seed quality for beetroot seeds. [17]. Significantly higher germination, seedling vigor index, and seedling length was recorded in hydro-primed carrot seeds for 24 hours at 25°C particularly under saline stress conditions [18]. Aged cucumber seeds subjected to hydro-priming exhibited higher electrical conductivity compared to fresh seeds. They attributed the enhanced viability and vigor in primed seeds to lower membrane injury and increased enzyme activities viz., dehydrogenase and amylase [19]. Hydro-priming improved germination speed, germination synchrony, and seedling vigor index, but it did not significantly affect final germination percentage or mean daily germination compared to non-primed seeds [7]. Effect of priming on fennel seeds was assessed under saline conditions and noted that priming with GA_3 for 24 hours at 25°C resulted in increased germination under varying salinity levels [20]. Impact of priming on carrot seed quality was examined and observed that increasing gibberellin (GA_3) concentration from 50 ppm to 100 ppm enhanced emergence rates [21]. Cumin seed germination, germination speed, seedling length, and seedling fresh and dry weights significantly increased with higher GA_3 concentrations, with the best growth parameters achieved at 400 ppm and 25°C [22]. GA_3 at 200 ppm resulted in the highest germination percentage and test weight in treated plants, significantly different from untreated controls [23]. Tomato seeds primed with 1 ppm GA_3 exhibited a 30.56% increase in germination and a 41.3% increase in root length compared to unprimed seeds [24]. Maximum flowering, seed yield, plant growth, and quality seed production were observed when sweet pea seeds were primed with GA_3 at 100 ppm for 24 hours [25]. Among various priming treatments, carrot seeds primed with panchagavya at 5% showed significantly higher field emergence, germination percentage, and germination speed, followed by GA_3 at 100 ppm [26]. Effects of different growth regulators, including Indole Acetic Acid (IAA) and Gibberellic acid (GA_3) was assessed on sunflower seeds and found that lower concentrations (1 and 5 ppm) of these hormones promoted seed growth, while higher concentrations had a retarding effect on both scarified and unscarified seeds [27]. A priming experiment was conducted on okra seeds using various techniques and found that GA_3 priming was the most effective for improving germination percentage, germination rate, seedling growth, mean germination time, and tolerance to abiotic and biotic factors, while hydro-priming and tricho-priming could serve as alternatives to GA_3 priming [10]. Seed priming with 0.01 M KNO_3 for 24 hours before sowing was the most effective method for improving growth and yield characteristics in carrot cultivar Pusa Yamdagni [28]. Beneficial effects of seed priming with a KNO_3 solution was observed on seed germination under salt stress conditions in pea [29]. Seed priming of sunflower with KNO_3 solution improved tolerance to salinity by increasing seedling fresh weight and peroxidase enzyme activity [30]. Study was conducted on primed cucumber seeds with various solutions, including KNO_3, K_2HPO_4, and NaCl, at different concentrations and temperatures and found that priming treatments significantly affected germination percentage, seedling fresh weight, seedling dry weight, and root volume [31]. In another study, GA_3 and KNO_3 treatments resulted in the highest vigor index, with GA_3 being slightly more effective [32]. Seed priming with KNO_3 enhanced synchronous germination and germination speed in different okra genotypes [33]. Effect of KNO_3 priming was assessed on cucumber seeds and found that KNO_3-primed seeds exhibited higher first count germination, final count germination, mean seedling length, mean seedling dry weight, seedling vigour index-I, and seedling vigour index-II [34]. Priming onion seeds with potassium nitrate salt or distilled water did not improve standard germination compared to un-primed seeds. Standard germination actually decreased with higher concentrations and longer durations of priming for both KNO_3 and distilled water [35]. The most effective hydro-priming duration for improving seed quality in oats can be achieved by directly soaking the seeds in one and a half times the volume of water for 14 hours all under ambient conditions [36]. Halopriming with 2% KNO_3 and hormo-priming with 50 ppm GA_3 improved the performance of directly seeded rice (DSR). These priming techniques led to faster and higher crop emergence, increased seedling vigor, root density biomass, improved yield attributes, and higher grain yield compared to DSR without seed priming [37]. Pre-sowing seed treatments on cumin and found that ethrel treatment improved seedling emergence, germination speed, seed yield attributes, seed yield, and reduced mean germination time compared to untreated controls [38]. Chemo-priming with ethrel in French bean improved seed quality, including seedling length, seedling dry weight, seedling vigor index, germination speed, and mean germination time [39]. An experiment to investigate the effect of chemo-priming on cucumber seed quality and found that seeds primed with Ethrel at 100 ppm for 48 hours exhibited significantly higher germination, seed vigour index-I, and seed vigour index-II. Hydro-priming of cotton seeds is useful technique for improving seed vigour which enhanced seed quality parameters in both fuzzy and delinted cotton seeds when primed under ambient conditions (temperature 32°C and a relative humidity of 62%) for 10 hours using double quantity of normal water [40]. A study was conducted to establish a standardized hydropriming method for cowpea. They soaked cowpea seeds in water, using three different volumes *viz.,* half, equal, and double the weight of the seeds for varying durations of 1, 2, 4, 8, and 16 hours. Their findings indicated that the most significant enhancement in seed quality parameters occurred when the seeds were soaked for 2 hours in water equal to double the weight of the seeds, demonstrating that this particular soaking condition was sufficient to improve the quality of cowpea seeds [41].

Table 1: Effect of seed priming on different field and vegetable crops

Crop	**Type of priming**	**Seed quality parameters**	**References**
Tomato	Hydropriming	Improving performance of medium quality seeds	Penaloza *et al.,* [9]
Bitter gourd	osmo-priming and hydro-priming	Germination and field emergence	Lin and Sung, [10]
Onion	hydro-priming	Mean germination time	Tajbakhsh *et al.* [42]
Onion	Hydroprining and priming with chitosan, GA_3, and Aloe vera	Germination seedling length, dry weight and vigour indices	Singh *et al.,* [43]
Wheat	Hydropriming	Germination and seed vigour	Tanwar *et al.,* [44]
Onion	Hydropriming and priming with KH_2PO_4 (2.0%), KNO_3 (1.0%), K_2SO_4 (1.0%)	Germination, seedling length and vigour index-I	Panghal *et al.,* [45]
Sunflower	Priming with ethrel	Germination percentage	Adam and TeBeest [46]
Melon	Hydropriming	Germination and seed vigour	Paiva *et al.* [47]
Cucumber	ethrel and kinetin	Germination and seedling growth	Sharma [48]
Onion	Priming with GA_3 and IAA	Seed germination and seedling growth	Yarina and Tabrizi [49]
Barley	Hydropriming, Priming with GA_3 Ethanol and ZnO	Enzyme activities	Kurubar *et al.*[50]
Sunflower	Priming with ethrel, benzyl adenine, and gibberellic acid	Germination and dormant seeds	Udayakumar and Shastry [51]
Sorghum	Hydropriming, Priming with GA_3 and sodium molybdate	Viability and vigour parameters	Nisha *et al.*[52]
Barley	Priming with GA_3 Ethanol and ZnO	Germination, seedling length, seedling dry weight and vigour indices	Kurubar *et al.,* [53]
Carrot	Priming with panchagavya, GA_3 and Ethrel	seed vigour and viability	Sowmeya *et al.* [54]
Maize	Priming with KH_2PO_4, KNO_3 (1.0%), and GA_3	Seed germination and other seed quality parameters	Kibaraza *et al.*, [55]

2. Effect of storage containers on seed longevity

Seeds stored in sealed containers maintained relatively high viability, while those stored in unsealed containers deteriorated rapidly, particularly under high temperatures and humidity conditions [56]. Furthermore, seeds stored in alternative storage solutions such as metal bins, super grain bags, and PICS bags (Purdue Improved Crop Storage) retained their viability exceptionally well [57]. In another study, it was found that primed seeds of bitter gourd accumulated a higher total peroxide content compared to non-primed seeds after 12 months of storage. Interestingly, non-vacuum storage conditions led to a noticeable reduction in seed longevity. Therefore, storing seeds in a partial vacuum environment proved to be advantageous in extending the viability of primed seeds for up to 12 months. This was attributed to the enhanced antioxidative activity, which minimized the accumulation of total peroxides during long-term storage [58]. An experiment was conducted to explore the influence of seed containers and storage conditions on onion seed germination. They reported that seeds stored in aluminum foil bags exhibited the highest germination rate (74%), statistically equivalent to seeds stored in plastic containers (72%) and polythene bags (71%) at 140 days after storage. In contrast, seeds stored in earthen pots displayed significantly lower germination (60%) [26]. An another experiment was conducted involving four different storage structures/materials was conducted and results revealed that seeds stored in jute and PICS bags demonstrated significantly higher vigor index and germination percentages compared to seeds stored in metal bins [59]. Seeds stored in earthen pots performed similarly to those in jute and PICS bags at 180 days after storage. Additionally, it was observed that an increase in seed moisture content within storage containers resulted in reduced germination percentages, as well as decreased root and shoot lengths, while increasing the occurrence of abnormal seedlings and dead seeds during germination testing. This underscores the influence of genetic factors on seed deterioration and the aging process [60]. Another study was conducted to evaluate the impact of storage containers and duration on the seed quality of onions under ambient storage conditions and found that the choice of storage containers significantly affected seed quality during storage. The plastic bag container yielded the highest germination rate (77%) and recorded the longest seedling lengths (7.32 cm), as well as the highest vigor indices, including vigor index I (578) and vigor index II (1597). Additionally, this container exhibited the lowest electrical conductivity (37.88 µScm-1g-1), indicating better seed quality. Conversely, the cloth bag container displayed the lowest seed quality parameters [61].

Table 2: Effect of storage containers on seed longevity of different field and vegetable crops

Crop	Type of containers	Seed quality parameters	References
Tomato	cloth bag and > 700-gauge polythene bags	Germination per cent, seedling length, seedling dry weight and seed vigour indices	Nisha *et al.,* [62]
Barley	Cloth and Polythene bags	Enzyme activities	Kurubar *et al.,* [50]
Eggplant	Cloth and Polythene bags	Germination rates, longer seedlings, greater seedling dry weight, and improved vigour indices	Nisha *et al.,* [63]
Jatropha curcas	Muslin cloth, polythene bags (700 µ) and HDPE bags	Germination	Bhuker *et al.,* [64]
Carrot	paper, glass, polyethylene aluminium foil laminated pouches	Seed viability and vigour	Doijode [56]

3. Conclusions

Vegetables, such as carrots, offer a wide range of essential nutrients, making them valuable for a healthy diet. Carrots, belonging to the Apiaceae family, are versatile and widely used in various culinary preparations. They are nutritionally rich, particularly due to their high carotene content, which is a precursor of vitamin A, and their antioxidant properties that help combat free radicals and reduce the risk of heart diseases. Carrots are cultivated annually for their roots and biennially for flowering and seed production. They come in two distinct groups: tropical (Asiatic) and temperate (European) carrots, each with its own characteristics and growth requirements. Afghanistan is considered the primary center of origin for carrots, with major global producers including China, Uzbekistan, Russia, and the United States. In India, Haryana leads in carrot production. One persistent challenge in carrot cultivation is poor seed germination, which can negatively impact yield. Seed priming, a pre-sowing treatment that enhances germination and seedling vigor, is a simple yet effective technique to address this issue. It involves controlled hydration of seeds to initiate the germination process without completing it. Proper storage containers also play a crucial role in preserving seed quality from harvest to the next planting season. Suitable packaging materials with superior barrier properties help maintain good seed germination over time. Several studies have shown the benefits of seed priming with various substances like hydro-priming, KNO_3, GA_3, and Ethrel, leading to improved seed quality and plant performance in different crops. Furthermore, the choice of storage containers and conditions can significantly impact seed longevity, with sealed containers and certain materials proving to be effective in maintaining seed viability during storage. Incorporating these practices into carrot cultivation can lead to higher germination rates, better seedling vigor, and increased overall crop productivity, ensuring a consistent supply of high-quality carrot seeds.

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