Producing high quality

PEPPER SEED

World Vegetable Center

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1. Introduction

Peppers (*Capsicum* spp.) are widely cultivated and constitute an economically important crop. All species within this genus are native to the Americas and are extensively grown in tropical and subtropical regions worldwide. Peppers are prized for their unique aroma, spiciness (Jamir & Jha, 2020), and high economic value, particularly for small-scale farmers, who are predominant in the major production regions across Asia and Africa. Global production and consumption of peppers have steadily increased over the past five decades, with a sharp rise beginning in the early 1990s (FAOSTAT, 2024).

Variety development and seed production are complementary activities, and one without the other holds little significance in agriculture. With the increasing demand for peppers and the expansion in cultivation, new varieties are developed and released each year based on the needs of various stakeholders throughout the value chain. New varieties possess traits resulting from years of meticulous breeding and selection, designed to perform well across specific and diverse production environments while ensuring high yield and quality. To realize the genetic potential of new and improved varieties, strong seed production must be effectively linked to their distribution.

The cultivation and conservation of pepper genetic resources remain key concerns among agricultural researchers. Many traditional pepper landraces and improved varieties have been lost or adulterated due to improper seed production practices (Patra et al., 2019). Numerous studies have reported the genetic variability of morpho-agronomic traits within accessions from genebanks and commercial varieties (Rego et al., 2015). The cross-pollination rate in *Capsicum* species is not always well-documented; however, in open-field conditions, outcrossing rates can be as high as 91% (Franceschetti, 1971; Odland & Porter, 1941; Tanksley, 1984). Careful seed production management is essential to maintaining seed purity and genetic uniformity, thereby minimizing varietal deterioration and to in successful pepper cultivation.

High-quality seed is not merely the starting point for cultivation but is fundamental to the success and profitability of farmers. Farmers require seeds with high germination rates that are free from pests, diseases, and contaminants, and that are true to type without segregation, while also matching the specifications of the purchased cultivar.This guide provides a comprehensive overview of the principles and practices of quality seed production in peppers, offering a foundation for producing seeds that meet the highest standards of genetic purity and viability.

2. *Capsicum* seed

2.1. Floral biology and pollination

Peppers have an extra-axillary cymose inflorescence with solitary flowers or small flower clusters. A typical pepper flower is bisexual, pentamerous, actinomorphic, and hypogynous, consisting of two to four or more locules. The calyx is campanulate, while the corolla is bell-shaped and rotate. Typically, five, or occasionally six, stamens are present, with bluish or yellow anthers attached at the base of the corolla. The stigma is club-shaped, with two-locule ovaries in wild forms, whereas domesticated varieties may have between two and four or more locules. Peppers are photoperiod-insensitive, meaning day length does not affect flowering or fruit set. The flowers usually open early in the morning, generally between 5:00 and 8:00 a.m., with anther dehiscence occurring mid-morning, typically between 8:00 and 11:00 a.m.

The stigma exhibits its highest receptivity on the day of anthesis, favoring self-pollination. As the stamens dehisce longitudinally, pollen is exposed, facilitating self-pollination. Although peppers can self-pollinate natural cross-pollination has also been widely reported. Maximum fruit set occurs when pollination takes place at anthesis; after this period, the chances decrease significantly, especially beyond 24 hours, due to the drying of the stigmatic surface (Dhall et al., 2011). Fruit set is generally hindered when mean daytime temperatures fall below 18°C or rise above 32°C, as this negatively affects and pollen tube germination. High nighttime temperatures, particularly above 25–30°C, often result in flower drop.

Fig.1: Developmental stages of typical flowers of *C. annuum*

Fig.2: Diversity in flower shape, size, and color and anther color in *C. annuum*

2.2. *Capsicum* - a facultative outcrossing genus

Pepper was historically considered a self-pollinating crop (Allard, 1960); however, beginning in the 1940s, researchers started observing outcrossing in open-field conditions at rates high enough to impede progress in breeding and seed production (Franceschetti, 1971; Odland & Porter, 1941; Tanksley, 1984). Pepper was later identified as a facultative outcrossing crop, exhibiting both self-pollination without inbreeding depression and cross-pollination at comparable frequencies.

Outcrossing in pepper is influenced by multiple factors, including floral structure, functional characteristics, and insect pollinators (Yourstonea et al., 2021). The club-shaped stigma is typically positioned slightly below the anthers, favoring self-pollination. However, in some cases, the stigma extends beyond the anthers, depending on the cultivar and growing environment. This structural trait, known as heterostyly, increases the likelihood of cross-pollination. Functionally, all pepper species are protogynous, meaning the stigma becomes receptive before anther dehiscence, which further promotes cross-pollination.

Pepper flowers attract a diverse range of insect pollinators, including honey bees (*Apis mellifera*), bumble bees (*Bombus* spp.), and other wild bees (Klein et al., 2007). Among pollinators, bees account for approximately 98% of flower visits in peppers. There is a significant positive impact of insect pollination on both yield and fruit quality (Cauich et al., 2006). When bees are excluded, self-pollination in pepper is common and can reach up to 100% (Bosland, 1991).

To prevent unintended outcrossing, seed producers must implement strict isolation or controlled pollination techniques to minimize inadvertent pollination during seed production.

2.3. Classes of seed

The primary goal of seed certification in pepper is to ensure the production of high-quality, true-to-type seeds that meet established standards for purity, germination, moisture content and health. Certification guarantees that seeds are free from diseases, pests, and genetic abnormalities, providing assurance to farmers and growers. Additionally, certification helps preserve the integrity of specific pepper varieties, ensuring consistency in crop performance. By adhering to certification standards, seed producers can support growers to achieve higher yields and mitigate the risks associated with poor-quality or contaminated seeds.

The common seed certification classes are defined as:

Breeder seed the seed of a new variety that has the highest purity and is produced, developed, controlled, and provided directly by breeders or their institutions for further multiplication.

Foundation seed the progeny of the breeder seed, produced by trained officers of an agricultural station or seed company in conformity with regulated national standards and handled to maintain genetic purity and identity of the variety.

Registered seed the progeny of the foundation seed grown by selected farmers or seed company or contracted institution, handled to maintain genetic purity and identity, and has undergone field and seed inspections to ensure conformity with standards.

Certified seed the progeny of foundation, registered, or certified seeds, handled to maintain sufficient varietal identity and purity, grown by selected farmers, seed distributors, etc., under prescribed conditions of culture and isolation, and subjected to field and seed inspections prior to approval by the certifying agency. Harvest from this class is used for commercial planting.

In order to be designated as certified seed, land planted to peppers for the production of seed must not have been planted to peppers the previous year unless such crop was of the same variety and equal or higher classification, in New Mexico.

The Organisation for Economic Co-operation and Development (OECD) has also developed other seed certification classes under the *OECD Seed Schemes*, established in 1958 to promote the use of certified agricultural seed of consistently high quality. Under the OECD international system, seed generations are designated as follows: breeder seed > pre-basic seed > basic seed > certified seed. There may be one or two generations of certified seed, designated as C1 and C2. These are sold to farmers for crop production but are not intended for further multiplication.

Pre-Basic seed of generations preceding basic seed is known as pre-basic seed and may be at any generation between the parental material and the basic seed.

Basic seed which has been produced under the responsibility of the maintainer according to the generally accepted practices for the maintenance of the variety and is intended for the production of certified seed. It must conform to the appropriate conditions in the scheme and the fulfillment of these conditions must be confirmed by an official examination.

Certified seed which is the first generation of multiplication of basic seed of a variety and is intended for vegetable production. It must conform to the appropriate conditions in the scheme.

Pre-basic, basic, and certified seeds are produced and officially regulated according to a set of harmonized procedures implemented across the 62 OECD member countries. The OECD also stipulates a color-coding system for labeling each seed generation, which is often adopted by national certification agencies.

2.4. Seed certification standards and isolation measures

Guidelines for *Capsicum* seed certification can vary by country or region, and in some cases, may not exist. In the absence of national standards, a widely accepted reference is the *New Mexico State University Seed Certification Manual* (see Table 1).

Table 1. Minimum isolation distances from other pepper crops for various certification classes, as specified in the *New Mexico State University Seed Certification Manual*.
Source: New Mexico State University Seed Certification Manual

	Minimum isolation distance from another pepper crop			
Certification class	Meter	Km	Yard	Mile
Foundation	1,610	1.6	1,760	1
Registered	805	0.8	880	0.5
Certified	400	0.4	440	0.25

*Breeder or pre-basic seed is not included in this table because it cannot be produced using distance isolation. Instead, it requires the exclusion of pollinators, achieved through methods such as net cages or cultivation in protected structures.

According to existing seed regulations, field inspections must be conducted by authorized inspectors from national inspection services or accredited private inspection agencies.

In New Mexico, an authorized inspector must perform a field inspection each year at a stage when varietal identity can be determined and before crop harvest. In Taiwan, representatives from the Animal and Plant Health Inspection Agency conduct three inspections: after transplanting, during flowering, and at harvest.

In Economic Community of West African States (ECOWAS) countries, where harmonized seed regulations are in place, at least four field inspections must be conducted throughout the cropping cycle.

First inspection: Preliminary Inspection
The first inspection takes place before seed production starts, to check whether or not the land meets the minimum characteristics and standards required for the species to be multiplied.

Second inspection: Pre-Flowering Phase
The second inspection takes place during the vegetative phase, from transplanting to the start of inflorescence emergence.

Third inspection: Flowering Phase
The third inspection shall take place when 50 percent of the plants are in flower; the flowers are open, the stigmas are receptive and the spores release pollen.

Fourth inspection: Pre-Harvest Phase
The fourth inspection shall take place a few days before harvest: the seed is sufficiently firm and has attained physiological maturity.

After field inspections, laboratory analyses are made to evaluate the quality of seed after harvest and processing. The seed lot should be tested for purity, moisture content, germination and health. According to regulations in each country, standards are put in place for each seed quality parameters per crop.

3. Seed health and quality begins with plant health and quality

The health and quality of pepper seeds are directly influenced by the overall vitality of the parent plant. A strong, well-nourished plant produces seeds that are more robust, viable, and capable of yielding healthy future crops. Key factors such as soil fertility, pest control, and proper watering play essential roles in maintaining plant health, which in turn affects seed quality. By prioritizing plant care, seed producers can enhance the genetic potential and germination success of their pepper seeds.

3.1. Seed selection

The genetic purity of any seed-propagated crop begins with the purity of the seeds planted. The type of seed selected significantly impacts both the quality and quantity of the resulting yield. High-quality seeds exhibit genetic purity, physical and physiological integrity, and overall seed health.

For seed production, only the highest quality seeds should be selected, harvested from a nuclear plant (described in a later section) to ensure genetic purity. Seeds must be free from disease, debris, and non-uniformity. Any mixed, damaged, or discolored seeds should be discarded and not used for seed production.

3.2. Seedling production

Good nursery management is essential for producing healthy, vigorous pepper seedlings. The process begins with selecting high-quality seeds, which are sown in a nursery bed or seedling tray. Germination depends on the potting mixture, variety, seed quality, and environmental factors such as temperature and irrigation.

For optimal germination, sow seeds in a well-drained, sterile soilless mix at and water daily or twice daily, maintained between 25 and 28°C. Under these conditions, seeds will germinate in about eight days. At 20°C, germination takes about 13 days, while at 15°C, germination extends to 25 days. Seeds may not germinate at all if temperatures fall below 15°C or exceed 35°C. In certain pepper species, particularly *C. chinense*, germination can be slow and sporadic due to high capsaicin levels on the seed coat (Barchenger & Bosland, 2016). Briefly washing seeds in 70% ethanol (Barchenger & Bosland, 2016) or treating them with 6% gibberellic acid (GA subscript 3) for one hour (Khaba et al., 2020) may improve germination rates. However, further research is needed before making definitive recommendations.

For successful seedling growth, the ideal potting mix should provide good drainage, aeration, and sufficient nutrients to promote healthy root development. A suitable mix can include various components such as soil, compost, rice hulls, vermiculite, peat, moss, or sand, blended in appropriate proportions to create a well-draining, nutrient-rich medium with good water retention. Sterilizing the potting mixture, either by autoclaving or baking at 150°C for two hours is recommended. However, when possible, using a reputable commercial germination medium that has been pre-sterilized ensures the best success.

After sowing, seed trays can be stacked and covered with polythene to conserve moisture and generate heat, which aids germination. However, this should be closely monitored. Once germination begins, trays should be spaced out on benches to prevent etiolation. Seedlings should be irrigated daily or twice daily, ensuring adequate moisture while avoiding overwatering to prevent damping-off and root rot.

Before transplanting, pepper seedlings require balanced nutrition to support strong root development, healthy foliage, and overall growth. A diluted, balanced fertilizer (e.g., 10-10-10 or 5-5-5 NPK) should be applied every 1–2 weeks to ensure adequate nutrition, while preventing fertilizer toxicity. It is advisable to stop fertilization a few days before transplanting to minimize transplant shock.

Seedlings grown outdoors on raised soil beds should be covered with an insect-proof net to protect against arthropod vectors. Regular scouting, ideally every three to four times a week, is essential for monitoring arthropod pests and diseases. This is crucial, as whiteflies (*Bemisia tabaci*), aphids (*Aphis* spp., *Myzus* spp., *Macrosiphum* spp., *Aulacorthum* spp.), and thrips (*Thrips* spp., *Frankliniella* spp., *Scirtothrips* spp.) cause direct damage and also transmit viral diseases that may remain latent, with symptoms appearing only after transplanting. This can lead to roguing or failure to pass quarantine inspections.

Preventive pest control measures, such as pheromones, colored sticky traps, and biocontrol methods—should be implemented. However, it is important to note that seed production differs from food production, as no disease tolerance exists in seed production. To manage arthropod pests effectively, systemic insecticides should be applied 7–10 days before transplanting.

Seedlings are ready for transplanting once they have developed 4–6 true leaves and are sufficiently sturdy. To ease the transition to field conditions, harden off seedlings by gradually exposing them to outdoor conditions over a prior to transplanting. Begin with 3–4 hours of direct sunlight on the first day, increasing the duration daily until the seedlings receive full sun by the last day.

Fig 3. Optimum germination of pepper seeds under a controlled environment.

3.3. Climate and soil requirements

Peppers thrive in tropical and subtropical climates, with ideal temperatures ranging from 18°C to 30°C and moderate humidity levels of 50% to 70%. Temperatures below 15°C can slow plant growth and fruit development, while those above 35°C may cause flower drop, reduced pollen viability, and lower fruit set. Although peppers tolerate heat, fruit set declines when night temperatures exceed 24°C.

Low relative humidity and dry winds can reduce fruit set and seed production by drying out the stigma, hindering pollination. Peppers are also sensitive to cold stress, with symptoms appearing at temperatures below 5°C, even briefly. Cold stress reduces photosynthetic capacity, fruit set, and seed production. The ideal temperature range for fruit set and seed production is 18–26°C. As a day-neutral plant, peppers can be cultivated year-round, provided temperatures remain within the optimal range.

Peppers can also be grown as a rainfed crop in regions receiving 600–900 mm of rainfall over 4–5 months. However, having irrigation available is recommended in case of sporadic rainfall. The best conditions for seed production include a relatively dry season to reduce foliar diseases, with cool but optimal temperatures, supplemented by irrigation.

Proper soil selection and preparation are essential for a successful pepper crop. Crop rotation should be followed, avoiding planting peppers immediately after another Solanaceous crop, such as tomato (*Solanum lycopersicum*), eggplant (S. *melongena*), or potato (S. *tuberosum*). For seed production, peppers should never follow another pepper crop to prevent soil-borne pathogens and genetic contamination from volunteer plants. Ideally, peppers should be planted in the same field only once every 3–4 years (Bosland & Votava, 2012).

A preceding rice (*Oryza sativa*) crop can be beneficial, as flooded soils help deplete soil-borne pathogens and weed seeds. Conversely, sweet potato (*Ipomoea batatas*) should be avoided in rotation with peppers, as it produces allelopathic compounds that may inhibit growth.

Peppers grow best in loam or silt loam soils with good water-holding capacity, provided the soil is well-drained. The ideal soil should be rich in organic matter, with a pH of 5.8 to 6.8 to ensure proper nutrient availability and root development. Peppers do not perform well in compacted, flood-prone, or drought-prone soils, making proper drainage and soil preparation crucial for successful cultivation.

3.4. Field preparation

Field preparation is crucial for cultivating peppers and involves plowing, deep chiseling, and discing. Additionally, deep plowing before summer sowing is essential for improving soil structure, enhancing moisture retention, and reducing the population of hibernating pests. Deep plowing also helps interrupt disease cycles by burying plant residues, diseased material, and pathogens deeper into the soil, making them less likely to survive or affect future crops.

Deep tillage before planting is necessary to break up compacted soil layers, improving aeration and facilitating better root penetration. A soil preparation depth of 30 to 45 cm is considered optimal (CNFA, 2019). After tillage, incorporating organic matter, such as well-rotted compost or manure, enhances soil fertility and structure. Organic matter also improves the soil's water-holding capacity, nutrient content, and microbial activity, creating a more favorable environment for plant growth.

Additionally, ensuring adequate drainage is critical to prevent waterlogging, which can lead to root diseases and poor plant performance. Constructing raised beds or ridges helps improve drainage, enhances root aeration, and minimizes losses due to root diseases, especially in areas prone to heavy rainfall.

Fig 4. Land preparation and plot design using a tractor for transplanting pepper seedlings

3.5. Planting

To prepare for transplanting, select seedlings with 4–5 true leaves and sturdy, disease-free stems that are free from flowers. Carefully remove them from the seedbed or seedling tray, discarding any damaged or poor-quality plants. Bundle the healthy seedlings for easy transport to the field.

Proper spacing is essential for optimizing plant health and maximizing yield, as fruit yield directly correlates with seed yield. To minimize transplant shock, transplant seedlings in the late afternoon or on a cloudy day. It is crucial to keep seedlings cool, moist, and shaded between lifting from the seedling bed or tray and transplanting to prevent stress.

Spacing requirements vary based on varietal architecture and soil type. The recommended row spacing for effective planting is 45–70 cm, ensuring adequate air circulation and sunlight penetration, both critical for reducing disease risk and promoting robust growth. Individual plants should be spaced 30–45 cm apart, minimizing competition for nutrients, water, and light and allowing each plant to develop fully, ultimately producing a higher quantity of quality seeds.

Applying mulch on the planting beds helps suppress weed growth, conserve soil moisture, and improve soil agro-physical properties, leading to better growth and higher yields. Mulching can also reflect light in a way that deters insect pests such as whiteflies, aphids, and thrips, thus enhancing pest management. Research has shown that black plastic mulch results in maximum fruit setting in peppers, followed by blue and transparent mulches, demonstrating the positive effects of mulching on fruit production (Ashrafuzzaman et al., 2011).

Fig 5. Transplanted healthy pepper seedlings with the use of plastic mulch.

3.6. Weeding

Weed management is crucial and can be one of the most costly aspects of pepper cultivation. Pepper plants are particularly vulnerable to weeds during their early growth stages, with the critical period typically between 30 and 60 days after transplanting.

Weeds act as reservoirs for pests and diseases, providing shelter and alternative food sources. Weeds can harbor pests such as aphids, mites, and whiteflies, which may migrate to pepper plants, spreading viruses and causing direct damage. Additionally, some pepper-pathogens can infect weeds, increasing the risk of disease transmission to pepper plants and negatively impacting crop health and seed yield.

Regular hoeing and manual weeding help keep the field free of weeds, improve soil aeration, and promote proper root development. Hand weeding and mulching are recommended as eco-friendly and cost-effective methods (Faruq et al., 2022). However, these approaches can be labor-intensive, particularly given rising labor costs and workforce shortages.

For chemical control, pre-emergence herbicides such as pendimethalin and imazethapyr (0.075 kg/ha each) provide effective weed suppression (Hajebi et al., 2015). Post-emergence herbicides, such as those that contain glyphosate or paraquat, can also be used after planting, but care must be taken to prevent drift onto pepper plants to avoid damage. Herbicide selection, application rate, and method should be tailored to the weed species, soil type, and environmental conditions.

Integrated weed management (IWM), which combines multiple control methods, is more effective and environmentally friendly. For example, using pre-emergence herbicides such as metolachlor + prometryn or butachlor (2.0 kg/ha), followed by hand weeding 40 days after transplanting, has been shown to significantly reduce weed density, leading to higher seed yields (Doramola et al., 2020).

Fig 6. Plot preparation and application of plastic mulch covering production beds

3.7. Irrigation

Pepper is particularly sensitive to water shortages as well as to excessive soil moisture and poor soil aeration during the flowering and fruiting stages, as well as to excessive soil moisture and poor soil aeration (Mackic et al., 2023). Shallow-rooted by nature, pepper plants have low tolerance for drought and flooding. Fields should be irrigated if wilting is observed at midday, as this indicates moisture stress.

Ensuring an adequate water supply to the roots is especially crucial during critical growth phases, such as flowering and fruiting. Consistent irrigation helps maintain uniform soil moisture, which is essential for optimal plant health and fruit development. However, over-irrigation should be avoided, particularly during seed maturation, as excessive moisture can cause seed deterioration. High soil moisture levels also create favorable conditions for major soil-borne diseases in peppers, such as Phytophthora root rot and bacterial wilt.

Water management also affects fertilizer efficiency. Nitrogen (N) and potassium (K) are highly water-soluble and in sandy soils and can be leached away if irrigation exceeds soil water-holding capacity (Hochmuth, 1996).

Furrow or drip irrigation is recommended, with drip irrigation being particularly effective in enhancing water and fertilizer use efficiency by delivering precise amounts of water and nutrients directly to the root zone. Overhead irrigation should be avoided, as wet leaves and fruits increase the risk of disease. If overhead irrigation is necessary, it should be applied early in the day to allow leaves to dry before nightfall, reducing the likelihood of fungal and bacterial diseases.

3.8. Nutrition

The cropping system (open field or greenhouse) and soil parameters (fertility, fertilizer recovery rate, soil organic matter, nitrogen mineralization, and leaching) determine the timing and amount of fertilizer application required. To optimize fertilizer use, a soil test is recommended, providing a basis to establish the appropriate frequency and quantity required for maximizing pepper seed yield and quality (Berke et al., 2005). Nutrient-deficient pepper plants produce lower seed yields.

At the field preparation stage, compost or manure should be incorporated into the soil before sowing or transplanting. Peppers require a consistent supply of nitrogen (N) to promote vigorous growth and ensure the development of a well-branched plant before the first fruit set. However, nitrogen levels must be carefully managed, as excessive nitrogen can prolong the vegetative phase and delay flowering.

In addition to nitrogen, peppers require adequate phosphorus (P) and potassium (K), especially during flowering and fruit development, to ensure optimal seed formation. Phosphorus should be applied before transplanting, as it is essential in the early stages for root and stem development. Nitrogen and potassium fertilizers should be applied at two-to-three-week intervals to maximize uptake and efficiency.

A fertility imbalance, particularly potassium and phosphorus deficiencies, can significantly reduce seed quality and yield (Arthur et al., 2024). Potassium deficiency can cause a high proportion of abnormal seeds, characterized by dark-colored embryos and seed coats (Bosland & Votava, 2012). To address nutrient requirements, potassium nitrate serves as an effective potassium source, while monoammonium phosphate (MAP), bone meal, and rock phosphate provide a steady, slow-release source of phosphorus.

Micronutrients play a crucial role in plant growth and development and are essential for seed production in pepper, though they are required in smaller quantities.

Zinc (Zn) supports hormone production and proper flower development, which are critical for pollination and seed set.

Boron (B) is vital for pollen viability, flower formation, and seed development. Boron deficiency can result in poor seed set or malformed seeds.

Iron (Fe) is essential for chlorophyll production and energy transfer, promoting overall plant health and vigor, which is important for successful seed production.

Manganese (Mn) plays a key role in photosynthesis and reproductive structure formation, ensuring high seed quality.

Copper (Cu) is crucial for reproductive growth, aiding in flower formation and seed development.

Ensuring an adequate supply of micronutrients contributes to high-quality seed production and maximized seed yield in pepper plants. Micronutrients can be applied through soil amendments or foliar sprays, but applications should be based on soil test results to prevent overuse or imbalances.

A multi-nutrient foliar spray is recommended 15–20 days after transplanting to enhance nutrient uptake. Pepper plants are particularly sensitive to calcium deficiency, which can cause blossom-end rot in fruit , especially under hot and humid conditions. To ensure proper seed maturation, fertilizer applications should be discontinued late in the season, and irrigation should be reduced, which encourages fruit ripening and allows the fruit to partially dry to a leather-like condition, which is ideal for seed maturation and harvest readiness (Wall et al., 2003).

Table 3. Nitrogen, phosphorus, and potassium requirements, expected recovery rate, and total amount to apply for an optimal seed yield (Berke et al, 2013)

Nutrient	Nutrient requirement (kg/ha)	Nutrient recovery (%)	Amount needed (kg/ha)
N	180	40	450
P	22	10	220
K	200	50	400

*Assuming no nutrients are available in the soil; the actual amount of fertilizer applied should be adjusted downward based on the soil test results.

3.9. Disease and pest management

Pests and diseases pose significant challenges in pepper cultivation, impacting all production systems. Major pathogens include bacteria, fungi, oomycetes, viruses, and arthropod pests. To minimize disease incidence, which can lead to low-quality or contaminated seeds, it is essential to implement a comprehensive pest and disease management , including prophylactic measures and a well-structured control schedule to ensure healthy plant growth and optimal seed quality.

3.9.1. Seed-borne disease

Seed-borne diseases in pepper are caused by pathogens such as fungi, bacteria, viruses and viroids that are transmitted through contaminated seeds. Seed-borne diseases can lead to poor germination, stunted growth, and reduced yields. Infected seeds can spread these pathogens to healthy plants, making disease management challenging. Ensuring seed health through proper seed treatments, certification, and disease-resistant varieties is crucial in preventing the spread of seed-borne diseases in pepper. There are several seed-borne diseases that seed-producers need to be aware of and to control.

Cucumovirus

Members of *Cucumovirus,* particularly Cucumber Mosaic Virus (CMV), are significant pathogens in pepper, causing stunted growth, mottled or deformed leaves, and reduced fruit quality. CMVs is transmitted by aphids in a non-persistent manner, meaning the virus can quickly spread quickly spread the virus from infected plants to healthy ones. CMV can also be seed-transmitted, posing a threat to future crops if infected seeds are used. To manage CMV, prevention is the most effective approach. The best preventative measures include starting with disease-free seed, controlling aphids, the primary vector of CMV through insecticides, reflective mulches, or natural predators such as ladybugs or ladybird beetles (*Coccinella septempunctata*), implementing weed control to eliminate virus reservoirs, roguing infected plants, and practicing crop rotation with non-hosts to disrupt the disease cycle. Members of Solanaceae, Brassicaceae, Cucurbitaceae, and Fabaceae can also serve as hosts for CMV and should not be included in rotation with pepper.

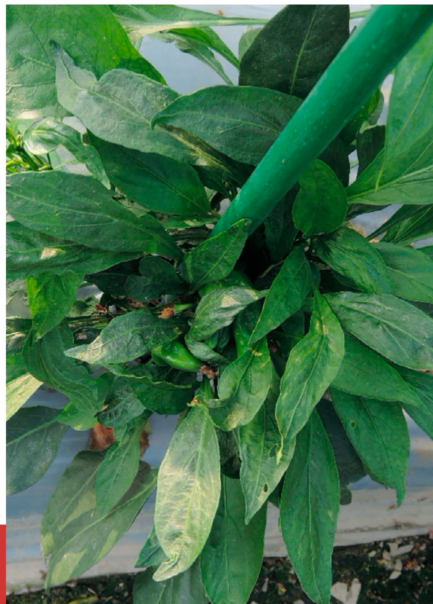


Fig 7. Pepper plant with typical CMV symptoms

Tobamovirus

Several tobamoviruses infect and cause disease in pepper, including Tobacco mosaic virus (TMV), Tomato mosaic virus (ToMV), Pepper mild mottle virus (PMMoV), and, most recently, Tomato brown rugose fruit virus (ToBRFV). Tobamoviruses are highly stable and can survive for long periods in plant debris, soil, tools, and seeds. Infected plants may exhibit symptoms such as mosaic patterns on leaves, distorted growth, and reduced fruit yield and quality. Tobamoviruses are primarily transmitted through mechanical means, such as handling plants and using contaminated tools, as well as through infected seeds.

To manage tobamoviruses, several strategies can be deployed. It is essential to start with certified, disease-free seeds or treat seeds with heat or chemical disinfection (e.g., trisodium phosphate) to reduce the risk of virus transmission. Regular cleaning and disinfection of tools, equipment, and hands when working with plants are crucial, using disinfectants such as bleach to reduce viral contamination. Minimizing mechanical injury and excessive handling of plants can further lower the risk of virus transmission through contact. Growing pepper varieties that are resistant or tolerant to tobamoviruses is one of the most effective ways to prevent disease, with the L4 gene providing resistance to many serious tobamoviruses, including ToBRFV. As with CMV, it is also recommended to practice crop rotation with non-hosts, as the virus can persist in soil for long periods. Additionally, removing and destroying any symptomatic plants can help prevent further spread.

Fig 8a. Pepper plant with typical Pepper mild mottle virus symptoms

Fig 8b. Pepper plant with typical *Tobamovirus* symptoms

Viroids

Viroids are small, circular RNA molecules that infect plants, including peppers, causing severe growth and yield problems. Unlike viruses, viroids do not code for proteins, yet they interfere with plant cellular processes. Several viroids have been reported to infect peppers and have been detected in seeds. Pepper chat fruit viroid (PCFVd) causes symptoms such as stunted growth, chlorosis, and fruit malformations. Although primarily associated with tomatoes, Tomato apical stunt viroid (TASVd) can also infect pepper plants. Columnea latent viroid (CLVd) has a broad host range, including peppers, and has been detected in pepper seeds, though it is less common. Tomato planta macho viroid (TPMVd), known for causing severe stunting and deformation in tomatoes, can also infect peppers, and there is some evidence of seed transmission in peppers. Though mainly affecting tomatoes, Tomato chlorotic dwarf viroid (TCDVd) has been detected in peppers and is potentially seed-transmitted.

Viroids are mechanically transmitted, meaning they spread through contaminated tools, seeds, and plant handling. They pose a significant threat to pepper crops due to their ability to spread through seeds, making it essential to start with viroid free seeds to prevent infection. Implementing stringent sanitation measures and monitoring for symptoms are key strategies for managing viroid infections in pepper plants.

Fig 9a. Pepper fruit with pepper chat fruit viroid symptoms

Fig 9b. Pepper plant with typical virods symptoms

Bacterial leaf spot

Bacterial leaf spot in pepper, caused primarily by *Xanthomonas campestris* pv. *vesicatoria*, is a serious disease affecting leaves, stems, and fruit. Symptoms include water-soaked lesions that darken and develop yellow halos, leading to defoliation, fruit spotting, and reduced yields. The disease spreads through infected seeds, rain splash, and contaminated tools, thriving in warm, humid conditions. Infected seeds can harbor the bacteria without showing immediate symptoms, potentially leading to outbreaks as seedlings grow. Once introduced, the bacteria spread rapidly via rain splash, irrigation water, and handling during cultivation. Using certified disease-free seeds and treating seeds with hot water or disinfectants are crucial strategies for preventing bacterial leaf spot from being introduced and transmitted through seeds. Other management strategies, similar to those for seed-borne viruses and viroids, include using resistant varieties, practicing crop rotation, maintaining strict sanitation, and removing diseased plants. Additionally, employing drip or furrow irrigation to minimize leaf wetness and applying copper-based pesticides as a preventive measure, particularly under conditions favorable for bacterial growth, can help manage the disease effectively.

Fig 10a. Pepper fruit with bacterial leaf spot symptoms

Fig 10b. Pepper plant with typical bacterial leaf spot symptoms

3.9.2 Other common pepper diseases in subtropical and tropical regions

In subtropical and tropical regions, peppers are susceptible to a wide range of diseases due to warm, humid climates that favor pathogen growth. Effective management strategies focus on prevention, sanitation, and disease resistance. When integrated into a comprehensive disease management plan, several common strategies can help protect pepper from destructive pathogens, ensuring better crop health, seed quality, and yield.

Key disease management strategies include regularly scouting fields for early signs of disease and pest infestations. Infected plants should be immediately rogued (removed) and destroyed to prevent disease spread. Using certified disease-free seeds is essential to avoid introducing seed-borne diseases, and treating seeds with hot water or chemical disinfectants can further reduce pathogen risks. Growing pepper varieties that are resistant or tolerant to common diseases provides an additional layer of protection.

Crop rotation with non-host plants (e.g., cereals or legumes) helps reduce pathogen buildup in the soil, while avoiding consecutive planting of peppers or other Solanaceous crops (such as tomatoes and eggplants) in the same field minimizes disease carryover. Removing and destroying infected plant debris after harvest prevents pathogens from overwintering and infecting future crops. Additionally, tools, equipment and surfaces that come into contact with plants should be regularly cleaned and disinfected to prevent pathogen spread.

Irrigation practices play a crucial role in disease prevention. Drip irrigation is preferred, or watering should be done early in the morning to allow foliage to dry quickly, reducing disease development. Proper soil drainage is necessary to prevent waterlogging, which can lead to diseases such as root rot and Phytophthora blight. Incorporating organic matter improves soil structure and promotes beneficial microbial activity that suppresses pathogens.

Managing arthropod vectors, such as aphids, which spread viral diseases, is another important aspect of disease control. This can be achieved through insecticides, biological controls (e.g., natural predators), reflective mulches and insect barriers that deter aphids. Organic or plastic mulch also helps reduce weed competition, conserve soil moisture, and minimize the splashing of soil-borne pathogens onto plants. Weeds, which can harbor pests and diseases, should be regularly removed.

Preventive applications of copper-based fungicides and bactericides can help manage bacterial diseases, especially during wet periods. To prevent pathogen resistance, pesticides should be rotated with different modes of action.

Below are some of the most common diseases affecting peppers in tropical and subtropical regions. However, this is not an exhaustive list. The availability of control measures will vary by country and change over time. Therefore, specific pesticides are not listed here; instead, descriptions of the typical diseases are provided to assist in accurate diagnosis.

Anthracnose

Anthracnose is caused by species of *Colletotrichum*, often in a complex. The disease affects both green and ripe fruits, causing sunken, dark, water-soaked lesions with concentric rings, which often develop pink or orange spore masses. The disease can result in fruit rot, premature fruit drop, and reduced marketability. Warm, humid conditions, common in tropical and subtropical areas, favor anthracnose outbreaks. Prevention is extremely important in controlling anthracnose, as symptoms often do not appear until at the time of or just right before harvest.

Fig 11. Pepper fruit with typical anthracnose symptoms of pepper

Phytophthora blight and root rot

Phytophthora blight and root rot in pepper is caused by the oomycetes *Phytophthora capsici*. The disease affects all parts of the plant, including roots, stems, leaves, and fruits. Symptoms typically include water-soaked lesions, wilting, and sudden collapse of seedlings or mature plants. In fruits, it can cause dark, sunken spots that lead to rot. Phytophthora thrives in warm, moist conditions, making it particularly problematic in humid climates. Pesticides are typically not very effective in controlling phytophthora blight and root rot because the pathogen is highly motile. Preventing the pathogen from entering the field and use of crop rotation in combination with host resistance is the best strategy to control.

Fig 12. Pepper plant with typical phytophthora root rot symptoms

Begomovirus

Begomoviruses are transmitted by whiteflies (*Bemisia tabaci*), which can rapidly spread the virus within and between crops, especially in warm tropical climates. There are numerous begomoviruses reported to infect pepper in Asia, Africa, and the Americas. Symptoms vary by species or strain of the virus, the variety of the host, and the environment the plant is grown in. Common Begomovirus symptoms include leaf curl, yellowing, stunted growth, and reduced fruit set and quality.

Fig 13. Pepper plant with typical *Begomovirus* symptoms

Powdery mildew

Powdery mildew in pepper is primarily caused by *Leveillula taurica* and is characterized by the presence of white, powdery fungal growth on the leaves, stems, and fruits. Infected plants may exhibit yellowing and premature leaf drop, leading to reduced photosynthesis and overall plant vigor. Powdery mildew thrives in warm, dry conditions with high humidity, particularly in crowded or poorly ventilated environments.

Fig 14. Pepper plant with typical powdery mildew symptoms

Potyvirus

Symptoms of *Potyvirus*-infection in peppers include mottled leaves, leaf distortion, stunted growth, and reduced fruit quality and yield. Potyviruses are transmitted by aphids in a non-persistent manner, meaning they can quickly spread the virus from plant to plant as they feed. The most common potyviruses causing disease in pepper include Chili veinal mottle virus (ChiVMV), Pepper veinal mottle virus (PVMV), Pepper Mottle Virus (PepMoV), Tobacco Etch Virus (TEV), Potato Virus Y (PVY).

Fig 15. Pepper plant with typical *Potyvirus* symptoms

Arthropod pests

The major arthropod pests of pepper include aphids, whiteflies, thrips, and broad mites. Aphids, such as the green peach aphid, feed on the sap of pepper plants, leading to stunted growth and the transmission of viruses like potyviruses. Whiteflies, particularly the sweet potato whitefly, also feed on sap but they are most problematic as vectors for begomoviruses, causing leaf curl and yellowing. Broad mites can cause leaf damage, resulting in stippling and webbing, particularly in hot, dry conditions. Thrips, small and slender insects, can cause damage through their feeding and also serve as vectors for tospoviruses. Effective management strategies are essential to minimize the impact of these pests on pepper crops, including cultural practices, biological control, and targeted insecticide applications.

Fig 16. Pepper plant with typical arthropod pests symptoms

Aphids

Aphid infestation in pepper typically result in a range of noticeable symptoms that can severely impact plant health and yield. One of the most common symptoms is leaf curling, where affected leaves distort and become cupped, limiting their ability to photosynthesize effectively. Additionally, yellowing or chlorosis of the leaves often occurs, as the sap-feeding activity of aphids deprives the plant of essential nutrients, which can lead to stunted growth, with infested plants appearing smaller and less vigorous than their healthy counterparts. As aphids are known vectors of various viruses, mottled patterns may also emerge on leaves due to viral infections, further complicating plant health. Moreover, the excretion of a sugary substance known as honeydew can attract sooty mold, which covers the leaves and reduces photosynthetic efficiency. The combined effects of aphid infestation can result in deformed fruits and reduced overall yield, making early detection and management of aphid populations crucial for maintaining healthy pepper.

Fig 17. Pepper plant with typical aphids infestation

Broad mites

Broad mite (*Polyphagotarsonemus latus*) infestations in pepper plants lead to a variety of damaging symptoms that can significantly affect plant health and productivity. One of the most noticeable symptoms is leaf curling and distortion, where leaves may curl downward, with an extended petiole and take on a deformed appearance due to the feeding activity of the mites. The feeding also causes stunted growth, resulting in smaller plants that exhibit reduced vigor. Additionally, leaves may develop a yellowing effect, particularly at the tips, indicating stress and nutrient loss. A characteristic silvery or bronzed appearance can also be observed on the upper leaf surface, a result of mite feeding disrupting leaf tissue. In severe cases, small necrotic spots may form on leaves, leading to tissue death and a further decline in plant health. Broad mites can also negatively impact flowering and fruit development, causing flower drop or producing misshapen and unmarketable fruits. These combined effects underscore the importance of early detection and management strategies to mitigate broad mite damage in pepper.

Fig 18. Pepper plant with typical broad mites symptoms

Thrips

Thrips infestations in pepper plants typically manifest through a range of damaging symptoms that can severely compromise plant health and yield. One of the most common indicators of thrips activity is the appearance of silvery streaks or patches on the leaves, resulting from their feeding on the leaf surface and the removal of cell contents. Thrips feeding also leads to stippling, where small, light-colored spots develop on the leaves, giving them a mottled appearance. In more severe infestations, the edges of leaves may begin to curl or distort, leading to abnormal leaf shapes that further affect the plant's ability to photosynthesize. Additionally, thrips can damage flowers, resulting in premature flower drop and reduced fruit set. The presence of thrips can also lead to deformed or discolored fruit. The severity of thrips symptoms highlight the importance of monitoring and managing thrips populations to maintain healthy pepper and ensure optimal seed yields.

Fig 19. Pepper plant with thrips infestation

4. Precautions for pepper seed production

As previously outlined, pepper is an outcrossing species under open-field conditions. To ensure self-pollination and maintain genetic purity—meaning the absence of seeds from other lines, cross-pollination, and off-types (plants that differ in appearance from the line being produced)—natural pollinators such as bees must be excluded. Seed certification programs establish isolation requirements to control pollination, with distances reaching up to 1.6 km (Table 1). However, in many countries, space is limited, making it challenging to manage other pepper production near seed production areas. To ensure self-pollination, effective plant isolation is crucial (Bosland, 1993). This can be achieved by using net cages (Bosland, 1993) to exclude bees or by growing plants inside enclosed greenhouses or screenhouses (Berke, 2000). These methods help maintain genetic purity and prevent unintended cross-pollination, ensuring high-quality seed production.

4.1. Pollinator exclusion

Pollinator exclusion cages effectively prevent unwanted cross-pollination by insects (Bosland, 1993; Berke, 2000). These cages should be placed over the plants before flowering and are typically made of synthetic mesh draped over conduit or metal hoops. For larger plant populations, lightweight row cover fabric cages, insect exclusion field net cages, or field net houses of various widths and lengths can be used (Figures 21). The earlier the net cages are applied after transplanting, the better, as delaying this process may require the labor-intensive removal of flowers and fruits to ensure self-pollination. To assist with this, ethephon has been shown to effectively reduce the number of flowers and fruits on a plant, though it does not completely eliminate them (Barchenger et al., 2016). It is common practice to transplant the plants for seed production, apply net cages, and irrigate all on the same day. The use of plastic mulch facilitates this process by reducing weed growth.

The recommended maximum mesh size is 16-mesh, which has a 1.88 mm sieve opening and is made of nylon. This size is small enough to exclude bees but does not prevent entry of aphids, broad mites, thrips, or whiteflies. While smaller mesh sizes can be used, in many tropical and subtropical regions, they can create excessively high temperatures, negatively impacting seed quality. If row covers are used instead of field net houses, pesticides can be applied directly through the 16-mesh without removing the net cages. However, in countries like India, 40-mesh or 50-mesh is commonly used for pepper seed production during the cool season. To fully prevent the entry of arthropod pests, a 60-mesh size may be necessary. The choice of mesh size depends on local environmental conditions, but a range of 16- to 40-mesh is generally recommended for row covers in pepper seed production.

Additionally, UV-stabilized nets are highly recommended for their durability under intense sunlight. These nets help regulate temperature and reduce heat buildup due to the albedo effect, making them ideal for long-term use in regions with high UV exposure.

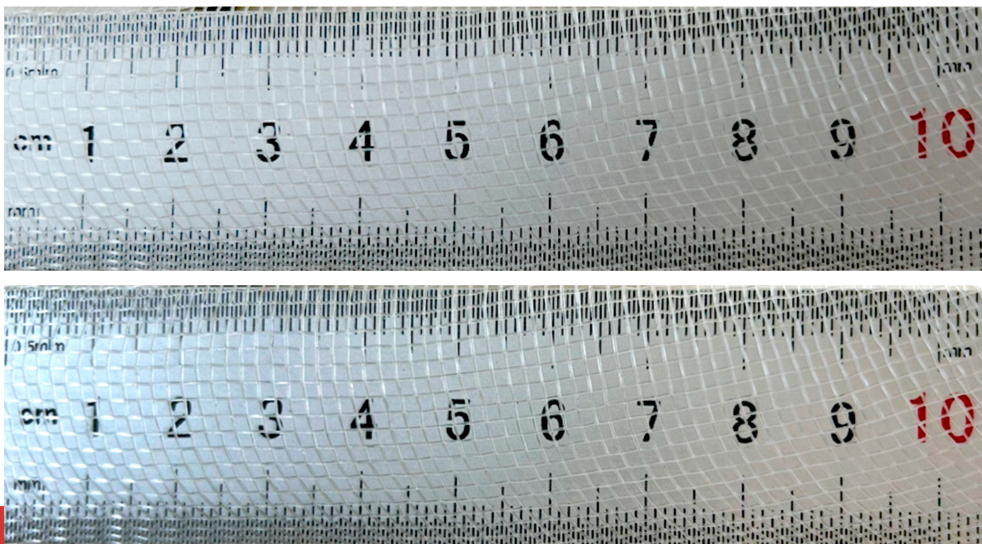


Fig 20. 16-mesh nylon net with 1.88 mm sieve opening

Row covers

Shaded and green colored field nethouse for sweet pepper seed production

Field net house

Fig 21. Field Various field-based pollinator exclusion structures used for pepper seed production in various widths and lengths

Net cages can be purchased in a wide range of dimensions to suit specific needs. At the WorldVeg pepper breeding program in Taiwan, net cages are typically 4 meters wide, which is sufficient to cover rows with a width of 1.5 meters between furrows. Each bed has a double-row spacing of 0.5 meters between rows, with plants spaced 0.45 meters apart within each row. The total row length is 35 meters, and the net cages used are 44 meters long to account for the height of the support frames and to allow for proper closure at both ends of each row. With this setup—0.5 meters between rows and 0.45 meters between plants—a 35-meter bed can accommodate approximately 140 plants, including space for labels and plot separation.

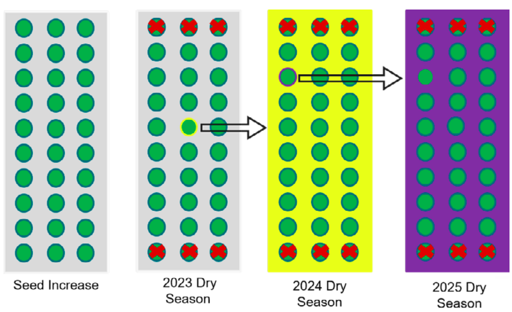
4.2. Roguing

Rouging is critical for producing high-quality pepper seeds and maintaining genetic purity. It helps eliminate accidental crosses from previous generations, accidental seed mixing in the current season, or any mutations. Roguing involves systematically removing undesirable plants, such as those with off-type characteristics, diseases, or poor vigor, to ensure that only the most robust and genetically uniform plants contribute to seed production. When assessing field performance, it is important to consider variable growing conditions, as plants in less favorable areas may perform poorly due to insufficient sunlight, water, or nutrients rather than genetic inferiority. Roguing multiple times throughout the season is often the most effective strategy.

In peppers, roguing is typically done at three key stages. The first roguing occurs at the vegetative stage to remove plants with deviant growth habits, stem structures, or foliage. The second roguing takes place at the flowering and early fruiting stage to eliminate plants with undesirable traits. The final roguing is conducted at the fruit harvest stage to select plants with the desired shape, size, and mature color consistent with the variety for seed extraction. This multi-step approach ensures that true-to-variety material is used in subsequent seed multiplication and that only pure seed reaches farmers. The maximum permitted limit of off-types in pepper is 0.1% for foundation seed and 0.2% for certified seed (Kumar et al., 2014).

4.3. Nucleus seed production

Nucleus seed production aims to produce high-quality, genetically pure seeds for use to produce downstream seed. Nucleus seeds serve as the foundation for subsequent generations, such as breeder or foundation seeds, and are critical for maintaining the genetic integrity of a cultivar. The nucleus seed production process typically begins with the careful selection of parental plants, which are often grown in controlled environments, such as greenhouses or net cages, to minimize the risk of cross-pollination and disease transmission.



This controlled setting allows for optimal conditions for flowering and pollination, ensuring that the seeds produced are true to type.

Once the flowers are pollinated, the fruit is allowed to mature, and the seeds are harvested and processed with great care to ensure high quality. This includes cleaning, drying, and storing the seeds under optimal conditions to prevent damage and maintain viability. The nucleus seeds produced in this phase are then used as the source for generating larger quantities of breeder or foundation seeds, which can be further multiplied for commercial seed production. By focusing on the purity and quality of nucleus seeds, growers can ensure a consistent and reliable supply of high-quality pepper seeds that meet the standards of the market and support successful crop production.

Fig 22. An example of nucleus seed production, wherein a single representative individual plant is selected and seed is harvested separately, as the seed source for the next cycle of seed multiplication. Typically, border plants are not selected for nucleus seed.

5. Seed extraction

The process of seed extraction of pepper

Fig 23. Physiologically mature pepper fruits are harvested and ground to release seed

Fig 24. The crushed pulp and seeds are collected

Fig 25. Using several water washes, the fruit tissue and other debris are removed, leaving behind the cleaned seed

Fig 26. Seed are drained using mesh bags, and prepared for drying

5.1. Seed yield

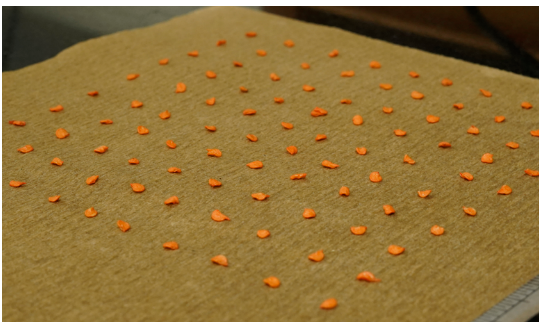
Pepper seed yield varies significantly based on variety, environmental conditions, and management practices. On average, seed yields range from 120 to 200 kg per hectare, with individual plants producing approximately 10 to 15 grams of seed. To prevent seed-borne diseases, seeds from diseased or pest-infected plants must be excluded from the harvest.

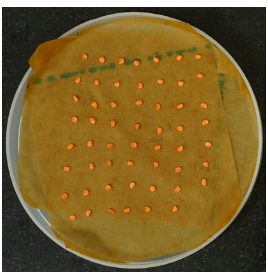
A key concept in seed production is the Multiplication Factor (MF), which represents the ratio between the quantity of seed harvested (after processing) and the quantity of seed initially sown. The MF is specific to each variety and is crucial for production planning. Understanding the MF helps ensure accurate forecasting and efficient seed production management.

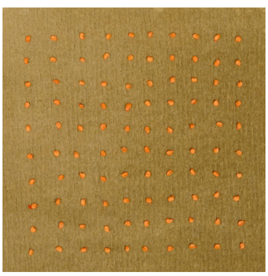
5.2. Testing

It is recommended to conduct grow-outs to determine the purity of the multiplied seed. A standard grow-out consists of 100 plants of a given variety, with 10 plants from the previous seed source used as a check. Each plant should be evaluated for morphological traits, including cotyledon length and width, presence or absence of anthocyanin in the hypocotyl, days to anthesis, and fruit characteristics such as length, width, weight, and color. Any plants that differ from the checks are considered off-types, which should not exceed 2% of the total population.

Seed germination should be tested using standard International Seed Trade Association (ISTA) procedures, either the petri dish method or the rolled paper towel method, with four replicates of 100 seeds each. A germination rate of at least 85% is considered desirable for pepper seeds.







6. Seed treatment and storage

6.1. Seed treatment

Seed treatment is an important process used for eliminating seed borne pathogens, enhancing seed viability, and improving germination rates. The common methods include hot water treatments, soaking in dilute disinfectant solutions (hydrochloric acid (HCl), trisodium phosphate (TSP) ($Na_3PO_4 - 12H_2O$), and seed coating with various approved fungicides.

Hot water treatment has been found to limit the presence of seed borne fungal and also bacterial pathogens. In hot water treatment, seeds are immersed in 50°C water for 25 minutes, which significantly reduces the pathogen load, thereby improving both seed germination and seedling vigor. Additionally, fungicide seed coating with liquid formulations chemicals such as Thiram or Captan or Benomyl. These fungicides create a protective layer around the seed, preventing fungal infections during germination and early seedling development.

To eliminate bacterial pathogens, a 3% sodium hypochlorite solution at 10°-25°C for 20 minutes is highly effective in addition to hot water treatment. For viral pathogens, disinfectants like hydrochloric acid (HCl) and trisodium phosphate (TSP) treatments are used. HCl treatment involves soaking seeds in a 1-3% solution (1 ml of HCl in one liter of water). However, it must be handled carefully as at higher concentration it damages seeds. After HCl treatment, the seeds should be thoroughly rinsed 4-5 times. Follow with a 10% TSP solution (1 gm TSP per liter) for 40 minutes, then rinse in running water for 45 minutes. These treatments can be applied individually or in combination for optimal results, particularly on freshly harvested seeds. After treatment, the seeds should be thoroughly washed, shade-dried, and properly stored.

6.2. Seed drying and cleaning

After extraction and treatment to remove viruses and viroids, pepper seeds should be placed in a warm, dry spot with good air circulation, away from direct sunlight. At physiological maturity, pepper seeds contain approximately 35–40% moisture (Colambari et al., 2021), which needs to be reduced to around 8% for optimal storage. Research suggests that the faster seeds are dried to 7–8% under safe conditions, the longer their shelf life and higher their germination rate. Drying reduces seed moisture, thereby lowering respiration and metabolic rates, which allows for long-term storage.

Common drying methods include shade drying, solar drying, and mechanical drying. Shade drying involves spreading seeds in a well-ventilated, shaded area, allowing natural airflow to evaporate moisture. The optimal conditions for shade drying are temperatures of 20–30°C and relative humidity below 60%. While this method is cost-effective, it can be slow and inconsistent due to fluctuating environmental conditions. Solar dryers, which harness solar energy to accelerate drying, typically operate at 30–50°C. The process can be further enhanced with fans and heating elements, improving drying efficiency and reducing drying time. Mechanical drying, by contrast, utilizes controlled temperatures (40–60°C) and airflow for uniform and rapid drying. This method maintains seed quality and prevents damage, making it ideal for large-scale production. However, prolonged drying under high humidity or rapid drying at very high temperatures can lead to desiccation damage, negatively affecting seed quality (Shafienaz and Zaitialia, 2016).

After drying, the seed lot may still contain undesirable materials such as fruit tissue, coarse dust, damaged seeds, and seeds from other crops and weeds. Seed cleaning is essential to remove impurities, improving physical purity and appearance. A density gradient seed cleaner is recommended for cleaning pepper seeds, while a mechanical seed cleaner equipped with two vibrating perforated screens is commonly used. The upper screen removes impurities larger than the seeds, while the lower screen separates smaller seeds and impurities from the desired seed size. Standard screen apertures for pepper seeds are 4.0 mm (round perforations) for the upper screen and 0.8 mm or 2.1 mm (slotted perforations) for the lower screen (Trivedi and Gunasekaran, 2013).

6.3. Seed storage

To maximize seed lifespan, seeds should be stored in a cool, dark, and dry environment. Maintaining low temperatures and humidity levels slows the metabolic activity of the embryo, reducing the risk of microbial infections and pest infestations, which helps extend seed viability. High moisture conditions increase susceptibility to fungal and bacterial infection and insect damage, all of which can significantly reduce seed germination potential. Optimal storage temperatures for pepper seeds range from 4°C to 15°C.

Storing pepper seeds at approximately 7% moisture content in partial vacuum-sealed packaging using laminated paper-aluminum foil-polyethylene bags can maintain satisfactory germination levels for at least three years, but commonly up to a decade or more (Dadlani, 2023). For short-term preservation (1–2 years) or when moisture content is unknown, seeds should be placed in permeable containers, such as paper envelopes or cloth bags, and stored away from light, moisture, and heat. For long-term storage, seed moisture content must be sufficiently low before using sealed containers and cold storage to maintain viability.

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