Principles of Quality Seed Production

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Abstract

Plant breeding and seed technology are the two arms of crop improvement programmes. The ultimate goal of any plant breeding programme is to make available quality seeds of new improved varieties in adequate quantity to farmers. Modern plant breeding techniques have enabled the development of crop varieties with desired traits at a much higher pace than ever before, addressing the challenges of food and nutritional security. A large number of new crop varieties are being bred continuously to address specific needs viz. productivity, quality, tolerance against abiotic and biotic stresses, cropping intensity, etc. However, to the farmers, all these scientific achievements would be of little use unless they have access to seeds of these varieties, which are genetically pure, physiologically sound (germination, vigour), free from physical impurities and seed-borne diseases. The pace of progress in food production largely depends upon the speed with which a country is able to multiply quality seeds of high-yielding varieties. Hence, the quality seed supply chain must be supported by desired policy and technically sound systems both in national and international domains. In order to achieve this, every country needs a well-established infrastructure for seed production, quality assurance, storage and marketing. Similarly, the regulatory framework for the variety testing, release and notification, and regulation of the seed market are also important to preserve the interests of the farming community. Successful seed production requires establishing variety identity, adherence to maintaining variety purity, and the application of good

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farming practices along with careful management of crops, following widely accepted production technologies, and quality standards.

Keywords

Variety release · Seed quality · Isolation distance · Field inspection · Roguing · Genetic purity · Seed conditioning · Seed marketing

1 Introduction

Quality seed is the most important input for enhancing crop production. The use of quality seed, along with the standard package of practices, enhances the crop yield by 15–20% or more (Prasad et al. 2017). Profit maximization is achieved when productivity augmentation is realized per unit of inputs used (seed, water, fertilizer, pesticides and manpower). The basic objective of a seed production programme is to supply quality planting material at the right time, and at affordable prices. Low seed quality can potentially decrease the rate of germination and seedling emergence (Finch-Savage and Bassel 2016) leading to poor stand establishment in the field and consequently yield loss in many crops such as direct sown rice (Rahman and Ellis 2019), corn (García et al. 1995; Moreno-Martinez et al. 1998), wheat (Ganguli and Sen-Mandi 1990), cotton (Iqbal et al. 2002), barley (Samarah and Al-Kofahi 2008) and garden pea (Hampton and Scott 1982). The quality of seed depends on how and when it was grown, and whether the seed producer was fully acquainted with the genetic constitution of the variety, its flowering and pollination behaviour, and other basic principles of quality seed production. Using cleaned grain as seed, and using farm-saved seed repeatedly cause deterioration of genetic constitution due to cross-contamination, as well as poor germination, vigour and seed health due to improper management, that result in overall decline in performance, yield penalty, non-uniform harvest and poor quality (Fig. 1).

Hence, strict measures need to be followed during seed production, harvesting and post-harvest operations to maintain the desired varietal purity. Similarly, seed agronomy, which may vary from general crop agronomy; care in the selection of a proper site for seed production (based on the previous crop history); seedbed preparation; timely completion of tillage operations; irrigation; supplementary pollination measures, if required; weed control; pest and disease control measures; identification and removal of the contaminants, off-types, obnoxious weeds, objectionable crop plants, diseases with seed-borne nature, etc. differentiate seed production from general crop husbandry.

Policy support from institutions, support from the regulatory system, and state-of-the-art facilities for production, processing, quality assurance, storage and distribution are considered necessary for undertaking a well-orchestrated seed programme for ensuring the supply of quality seed to the farmers. This chapter discusses variety release procedures and limited generation schemes followed for the seed production of crop varieties; causes for genetic deterioration and measures to safeguard the

Fig. 1 Effect of repeated use of farm-saved seed on crop quality. Roadside view at Phurlak village, Haryana (India) (Courtesy: Dr. Rakesh Seth, ICAR-IARI, RS, Karnal)

genetic identity and purity in crop varieties, and the general agronomic and seed technology principles that are to be followed for production of quality seed.

2 Variety Release and Seed Certification

Development and release of new crop varieties for commercial cultivation by crop breeders from research institutions and private seed companies is a continuous process. In most countries, notification for release or registration of varieties is a mandatory requirement for seed certification. For being eligible to registration, candidate varieties need to undergo multi-location agronomic evaluation to confirm their value in cultivation and use (VCU) before release for commercial cultivation. When plant breeders have a promising candidate for release, they submit the release proposal to the appropriate review committee, which contains comprehensive information on the candidate variety, viz. breeding history, description of the variety, and its performance data for two or more years. Variety identification and release may consist of two or more steps during which after the initial evaluation of a candidate variety, it is submitted to higher committee for consideration. The first group provides closer knowledge of the candidate variety, while the second group observes uniformity of release proposals and provides a more objective and comparative evaluation of the candidate variety with other checks and justification for its release based on one or more important criteria. In the USA, for the purpose of certification, state seed certification agencies are aided in determining the eligibility of varieties for certification by a national review board established by the Association of Official Seed Certifying Agencies (AOSCA). The board evaluates the new variety and advices AOSCA on their acceptability for certification purpose (Copeland and McDonald 2001) (see chapter 'Role of Seed Certification in Seed Quality Assurance' for more). Under Organization for Economic Cooperation and Development (OECD) seed certification system, a variety which is part of 'OECD list of varieties' accepted by any of the National Designated Authorities (NDA) are eligible for certification in accordance with rules of the OECD seed schemes. Seed production can be taken up in any country, if a given variety is part of OECD list of varieties.

In India, new varieties are tested for VCU under All India Coordinated Research Project (AICRP) trials at multi-locations following a two-tier system referred as the initial varietal trials (IVT) and advanced varietal trials (AVT). After a comprehensive testing for three years, superior entries are identified by varietal identification committee (VIC) constituted under the AICRP for a specific crop/crop group. The proposal of the qualifying entries identified by the VIC is forwarded to the central sub-committee on crop standards, notification and release of varieties for evaluation. The latter recommends to the Central Seed Committee for Release and Notification of Variety (Chand et al. 2020). The notification of approved varieties is published in official gazette of India. This is followed by the notification of the variety by the Seeds Division, Department of Agriculture and Farmers Welfare, Government of India, along with its area of adaptation and standard descriptors. Only notified crop varieties are eligible for certification process as per The Seeds Act, 1966.

3 Generation Scheme of Seed Multiplication

The generation scheme of seed multiplication is integral to the concept of certification, and permits only limited seed classes to be produced from a given lot of breeder or pre-basic seed. The guiding principle followed in generation system recognizes that maintaining the desired levels of variety purity is difficult in one-step large-scale seed production. Hence, stringent methods are followed for maintaining the highest purity in the first step of multiplication, which then is taken to the subsequent levels increasing the scale of multiplication. In most systems prevailing in the world, seed multiplication follows four generations, though these may be designated and used differently. The AOSCA follows a (four-generation) system that includes breeder seed, foundation seed, registered seed and certified seed. The breeder seed is produced under the control of a plant breeder and is labelled with white tag. The foundation seed is produced from the breeder seed under the contract with the foundation seed-producing organizations authorized by the plant breeder, and is also identified by a white tag. The registered seed is produced from the foundation seed by the registered seed producers and labelled with a purple tag. The certified seed is produced from the registered seed by the certified seed producers/growers, and marked with a blue tag. The first three generations are for non-commercial use (only for the purpose of controlled multiplication), while the certified seed is marketed for crop production (McDonald and Copeland 1997).

Similarly, under the OECD seed schemes, though three generations are recognized viz. pre-basic, basic and certified seed, a successive generation of certified seed is also permitted. The pre-basic and basic seed are controlled by the official maintainer or designated authorities and produced by the recognized institutions only. Pre-basic seed carries a white label with violet stripes, while basic seed carries a white label (without any stripes). Certified seed is produced by the certified seed growers under the administrative control of the designated authorities. First generation of the certified seed carries a blue label, whereas successive generations of certified seed are identified by a red label. The pre-basic and basic seed are used for the multiplication of succeeding classes, while certified seed is used for the commercial purpose of cultivation. In addition to the above-mentioned seed classes, two more seed classes exist under OECD seed schemes, viz. not finally certified seed and standard seed. Not finally certified seeds are the ones which are to be exported from the country of production after field approval, but have not been finally certified, which is mostly done by the recipient country after testing the other seed quality parameters. It carries a grey label. Standard seeds are only pertinent to vegetable seed scheme, where seed is declared by the supplier as 'true to the variety'. These conform to the other conditions in the scheme, and carry a dark yellow label.

In India and other SAARC countries, a three-generation system of seed multiplication is followed (Huda and Saiyed 2011). Breeder seed is exclusively produced by the originating breeder or by a sponsored institution in India. While the foundation and certified seed are produced by any of the State Seeds Corporations, National Seeds Corporation, seed cooperatives, public sector undertakings, non-governmental organizations, private seed companies and the farmers' producer organizations. As per the Indian Minimum Seed Certification Standards (IMSCS), only three generations are allowed beyond the breeder seed (Trivedi and Gunasekaran 2013). Seed quality pertinent to the foundation and certified seed classes are assured by the concerned third party (state seed certification agencies).

4 Genetic Deterioration in Crop Varieties

Several factors are responsible for the deterioration of a variety over a period of repeated use (Kadam 1942; Laverack 1994; Singhal 2001; Singhal 2016) which are summarized here with some modifications.

4.1 Genotypic Constitution and Pollination Behaviour

Cross-pollinated and often-cross-pollinated species are more prone to outcrossing and genetic contamination than the self-pollinated species. Similarly, maintenance of the genetic constitution of the synthetic and composite varieties needs more care than pure-line varieties. Residual heterozygosity and occurrence of aneuploidy (as in bread wheat, an allohexaploid species) can cause occurrence of off-types and genetic deterioration even in highly self-pollinated species (Atwal 1994).

4.2 Developmental Variation

Modern crop varieties are mostly bred to perform in a specific environmental condition. In such a scenario, if seed production is undertaken in the changed environmental backdrop (different soil fertility conditions, altered photo and thermo periods, relative humidity and elevations), developmental variations in the form of dissimilar plant phenotype may arise sometimes due to differential growth responses. To minimize the chance for such shifts to occur in the varieties, it is advisable to grow the seed crops in their areas of adaptation for the variety and in recommended growing seasons.

4.3 Mechanical Mixtures

It is a physical process by which the seeds of other varieties may get mixed inadvertently and deteriorate the genetic purity of the given variety (Fig. 2). This may happen through the seed drill during sowing, through wind carrying the harvested crop from one field to another, in the threshing yard where many varieties are kept together, during processing operations, etc., and also through rodents or other interferences. Hence, care is needed during production (roguing), harvesting, threshing and further handling to avoid mechanical admixtures. Proper hygiene needs to be maintained at stores and seed processing equipment needs to be thoroughly cleaned after operating each seed lot. In case of hybrid seed production, the male parent rows are to be harvested first and removed from the field before harvesting the seed crop (female parent rows).

Fig. 2 Level of varietal mixtures in paddy as a result of mechanical mixture during seed production and post-harvest operations (Source: ICAR-IARI, RS, Karnal)

4.4 Natural Out-Crossing

This is the major source of contamination in sexually propagated plant species through the flow of genes from dissimilar genotypes (which are cross-compatible). The extent of contamination depends upon the extent of the natural cross-fertilization with off-types, and diseased plants. To overcome the natural crossing, seed crop should be sufficiently isolated from the contaminants. The extent of contamination also depends on the intensity and direction of the wind and activity of the pollinators. Highly cross-pollinated species belonging to genus brassica, cucurbits, etc., need to be sufficiently isolated from fields of dissimilar varieties to avoid natural outcrossing.

4.5 Influence of Pests and Diseases

In case of foliar diseases, the size of the seed gets affected due to the poor supply of photosynthates from the infected plant parts. In case of seed and soil-borne diseases, use of infected seeds can cause widespread disease occurrence in the commercial crop (Fig. 3). Control of diseases through the use of healthy seed, and in some cases pesticide-treated seeds provide an effective means minimizing the pesticide use.

Fig. 3 Bakane disease caused by *Giberella fujikuroi* resulting in the abnormal elongation of culm in paddy (Source: ICAR-IARI, RS, Karnal)

Similarly, vegetative propagules deteriorate fast, if infected by viral, fungus or bacterial diseases. Hence, during seed production, plant protection measures need to be deployed at the right stages to check the incidence of pest and diseases.

4.6 Genetic Drift

In cross-pollinated crop species and multi-line varieties, the population is represented by a group of plants with distinct individual genetic constitution. Hence, during the maintenance of such varieties, if few gene combinations are missed out due to improper sampling, the resultant generation will not be representing the entire set of gene combinations present in genotype of the original variety. The genetic equilibrium that was supposed to be present in such population is lost suddenly (Nagel et al. 2019). This is known as genetic drift. This can be reduced to near-zero level by maintaining sufficiently large plant populations and following proper sampling methods during the maintenance of varieties (OPVs of cross-pollinated crops, synthetics, composites and multi-lines).

4.7 Minor Genetic Variations and Pre-mature Release of Varieties

Often, some small proportions of genetic heterogeneity may exist in the variety appearing phenotypically uniform and homogenous at the time of release. This may result in different plant types arising during repeated multiplications. Thus, pre-mature release of a variety may lead to quicker varietal deterioration. For instance, if a variety is bred for disease resistance and the gene(s) conferring this trait is not sufficiently fixed at the time of release, it may segregate producing susceptible and resistant plants during subsequent reproduction cycles. This not only impacts yields and other agronomic traits, but also poses serious problems in the process of certification with respect to the occurrence of off-types in the seed plots (Fig. 4). Post-control grow out testing of the breeder seed, and production of the nucleus seed after every few years following stringent measures are recommended to avoid such genetic variations. This type of genetic inconsistency is more common in cross-pollinated and often cross-pollinated species needing more care during variety maintenance.

5 Principles of Quality Seed Production

During quality seed production, utmost care is needed for ensuring genetic purity, physical and physiological quality and seed health. This may be attained by implementing a defined set of interventions and corrective measures, which are broadly classified under genetic, agronomic and seed technology principles as discussed in the following sections (for more see chapter ‘Role of Seed Certification in Seed Quality Assurance’).

Fig. 4 Occurrence of early flowering trait in paddy cv. Pusa 44 due to presence of residual heterozygosity (Courtesy: Dr. Rakesh Seth, ICAR-IARI, RS, Karnal)

5.1 Genetic Principles of Seed Production

Production of genetically pure seed is a challenging task and requires high technical know-how, skill and comparatively high financial investment (Agrawal 1994). During seed production, due attention is essential for maintenance of varietal purity and one should have a detailed understanding of underlying genetic principles. Varied interventions, depending on flowering pattern, determinate or indeterminate; floral structure and pollination behaviour—self- and cross-pollinated; genetic constitution of the variety—pure line, multi-line or composite, or hybrid; photo- and thermo-sensitivity and need for special stimulus with respect to floral initiation, are to be followed to avoid genetic deterioration of a crop variety. Following are the safeguards for maintaining genetic purity during seed production.

5.1.1 Maintenance Breeding

Maintenance breeding is the backbone of a quality seed production programme. Varietal maintenance (used synonymously as maintenance breeding) is a simple, but key technique for purification and stabilization of released genotypes. Though based on the basic principles of genetic constitution, it has a profound role in varietal spread, popularization and life of a variety. Maintenance procedures are the extension of normal breeding process, but selection is mild and aims not to improve the variety, but only to keep the genetic constitution unchanged (Peng et al. 2010). Based upon the original characteristics of a variety, minute deviations or poor-performing lines are discarded and seeds only from the uniform 'true-to-type' plants are pooled to form the pre-basic seed, which is the basis for generation system of seed multiplication under OECD seed schemes and other established systems of seed quality assurance (see chapter 'Principles of Variety Maintenance for Quality Seed Production' for more).

5.1.2 Confirmation of the Seed Source

For raising a certified seed crop, the initial seed should be of appropriate class and from the approved source. In a generation scheme of seed multiplication, specific class of seed is used for multiplication of the ensuing seed class. For instance, under the OECD seed scheme, pre-basic seed is used for the production of basic seed, which in turn is employed for the production of certified seed class. The source of the seed can be ascertained through the labels attached to the containers or bags used for seed production purpose (Table 1).

5.1.3 Previous Cropping History

The primary objective of this step is to avoid any genetic contamination through volunteer plants (grown from self-sown seeds of the previous crop). Seed production in related or similar crops in rotation may be followed to address other issues such as plant nutrition, maintenance of soil physical condition and minimizing the risk of soil-borne pathogens and weeds common to a particular group of crops (George 2011). Similarly, the dormant seeds from previous crop may lead to genetic contamination in planned seed crop. Under OECD seed schemes, previous crop requirement for crucifer species, grass species and legume species are five, two and three years, respectively, for production of basic and certified seeds.

5.1.4 Isolation Requirement

Isolation is required to avoid natural crossing with cross-compatible species and undesirable types from nearby fields, mechanical mixtures (at the time of sowing,

Table 1 Minimum varietal purity standards for non-hybrids under OECD seed schemes

Crop	Basic seed	Certified seed first generation	Certified seed second generation
Triticum aestivum	99.9%	99.7%	99.0%
Oryza sativa	99.7%	99.0%	98.0%
Zea mays	99.5%	99.0%	99.0%
Helianthus annuus	99.7%	99.0%	98.0%
Arachis hypogaea	99.7%	99.5%	99.5%
Glycine max	99.5%	99.0%	99.0%
Pisum sativum	99.7%	99.0%	98.0%

(OECD Seed Schemes Rules and Regulations, 2022, https://www.oecd.org/agriculture/seeds/documents/oecd-seed-schemes-rules-and-regulations-2022.pdf) threshing, and processing) and contamination due to seed-borne diseases from adjoining fields. Protection from these sources of contamination is necessary for maintaining desired genetic purity. Three types of isolation can be achieved during seed production.

Isolation in Time

The planting time of two varieties of the same crop or two cross-compatible varieties of related crops can be staggered over time. The time isolation should be a minimum of 15 to 20 days or more depending on the flowering habit of the crop. As the plants will not blossom at the same time, cross-pollination becomes impossible (McDonald and Copeland 1997). Time isolation is only applicable to crops having determinate flowering habit. Time isolation in the case of paddy can be achieved by providing a time of over 25 days (flowering stage of other varieties over a 100 m range should be 25 days earlier or later as compared to variety in seed production plot) (Fig. 5).

Isolation by Distance

This type of isolation is based on the concept that if a seed crop is sufficiently distant from any other cross-compatible crop then the adverse pollen contamination will be negligible. The distance isolation is efficient and practical type to achieve in most of the crops. The isolation distance recommended in regulations for specific crop take into account the method of pollination (self or cross-pollinated) and mode of pollination (insect or wind). However, in practice, it is impossible to completely prevent foreign compatible pollen reaching a crop, because the wind or pollen-carrying insects can transfer pollen grains over relatively long distances. Under OECD seed schemes, distance isolation can be disregarded when there is sufficient protection from undesirable pollen sources (Table 2).

Isolation by Barrier

The isolation can also be achieved through physical barriers. It may include natural means like the use of such land for seed production, which are physically isolated by

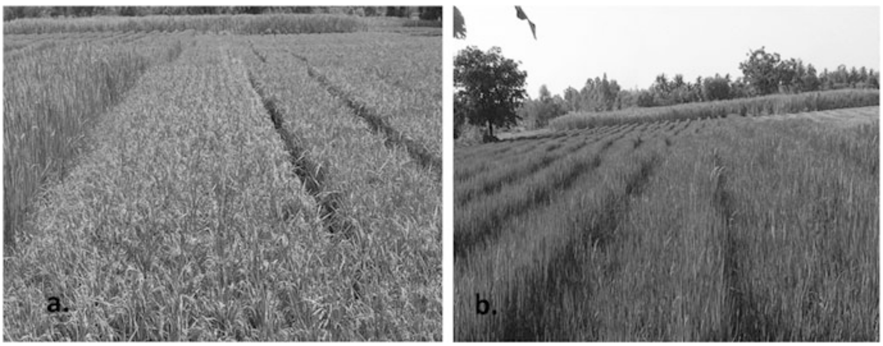

Fig. 5 Isolation achieved in (**a**) time and (**b**) through a barrier crop (sugarcane) in the background in paddy seed production plot (Source: ICAR-IISS, Mau)

Table 2 Minimum isolation distance prescribed under the AOSCA seed certification (in North Dakota State, USA as an example)

Crop	Foundation seed (in feet)	Registered seed (in feet)	Certified seed (in feet)
Wheat, barley & oats	5	5	5
Millets (self-pollinating)	5	5	5
Mustard	1320	–	600
Rapeseed	600	–	300
Hybrid canola & rapeseed	2640	–	2640
Soybean, chickpea & lentils	5	5	5

(North Dakota Legislative Branch, Title 74, Seed Commission, Article 74-03, Seed Certification Standards; https://www.ndlegis.gov/information/acdata/html/74-03.html)

mountains, forests and rivers between the cross-compatible crops or growing taller crops like sorghum, maize, pearl millet, sugarcane, sesbania, etc., in between them (minimum 30 meters wide) or by artificially erecting large sleeves that surround an entire seed crop (up to two meters height) (Fig. 5). If the barrier crop is used, it should be planted in such a manner that it minimizes the flow of contaminating pollen from nearby sources to seed plot. Raising barrier crops is commonly practised in hybrid seed production plots of paddy, sunflower and pearl millet.

5.1.5 Compact Area Approach

Under this approach, seed production of single variety is allowed in a wide stretch of area. By allowing only one variety to be grown in a specified area or zone, the chances of undesirable cross-pollination are minimized. In the USA, compact area approach is followed for seed production of sweet corn in Idaho State (Delouche 1980). This approach is also advantageous in seed production of hybrid seed by making available sufficient pollen mass in a compact area.

5.1.6 Discarding the Peripheral Strip

In wind-pollinated crops, the pollen concentration in the air over a field is higher at the windward end and tends to decline towards the leeward end (Dark 1971). The marginal strip is important in the production of genetically pure seeds. When a cloud of contaminant pollen passes over the field, it is possible that some quantity of pollen grains drop out at random. Those falling over the centre of the plot will compete with the relatively high concentration of the crop's own pollen source and have a negligible chance of fertilizing, whereas those falling on the marginal areas will not have so much competition and will therefore have a higher chance of fertilization. The seeds from a five-meter-wide strip around the perimeter of the plot are harvested separately and these can either be destroyed or placed in a lower seed category. The bulk of the seed harvest will come from the inner area of the plot (George 2011).

5.2 Agronomic Principles of Seed Production

Agronomic interventions in a seed crop vary from that of commercial crop production. The basic principles are aimed at economically viable seed production practices.

5.2.1 Selection of the Agro-Climatic Region

A crop variety employed for seed production in a given area must be adapted to the photoperiod and temperature conditions prevailing in that area. Regions of moderate rainfall and humidity are more suited for seed production than the regions with high rainfall and humidity. Most crops require a dry sunny period and moderate temperature for induction of flowering and pollination (Neenu et al. 2013). Excessive rainfall during flowering will reduce the seed set and may lead to incidence of diseases in onion and other crops. Too high temperatures during flowering may result in pollen abortion. In general, regions with extreme temperatures should be avoided for seed production, unless particular crop is especially adapted to grow and produce seed under these conditions.

5.2.2 Field Preparation

Field preparation consists of eliminating any weeds and volunteer plants and making flat or raised seed beds, as required. Well-tilled seed bed help in improved germination, good stand establishment and removal of potential weeds during tillage operations. To avoid contamination of site with other crop or weed seed, equipment employed during field operations need to be cleaned of soil, residual weed or crop seeds before entering into the site. Stale seedbed technique, in which the seed beds are formed about a week before it is to be sown, can be adopted. This allows the weed seeds to germinate first, so these can be removed to minimize the weed competition in the seedbed before the seed crop is sown (George 2011).

5.2.3 Selection of a Variety

For certified seed production, the variety must be authentic, duly released/registered and must be clearly identifiable by a set of stable characteristics, which can be employed for field inspection by the certification agency. However, for quality declared seed (QDS) class or truthfully labelled seed (TLS) class, production of a non-registered variety is also taken by seed production agencies. A good market demand for the variety is desirable for successful seed business. Generally, the improved varieties having resistance against major pests and diseases and tolerance against extreme weather conditions are more in demand.

5.2.4 Seeding and Stand Establishment

Though the seeding method and seed rate vary from crop to crop, a desired plant stand is achieved by adopting good agricultural practices. However, the row-to-row distances are generally kept wider in a seed crop than in a commercial crop, to facilitate field inspection. The sowing of seed crops in wide-spaced rows also helps in conducting effective plant protection measures and roguing operations. In case of hybrid seed production, suitable planting ratio needs to be followed for obtaining optimum seed yield. Besides, to allow synchrony in the flowering of the parental lines, staggered sowing may be followed (see chapter 'Hybrid Seed Production Technology' for details). The seed crops should be sown during the most favourable season, though, depending upon the incidence of diseases and pests, some adjustments could be made, if necessary.

5.2.5 Roguing of the Seed Crop

Roguing is the selective removal of undesirable plants from a seed crop on the basis of distinct morphological characteristics in order to improve one or more parameters (genetic purity, free from diseases and noxious weeds) of seed quality (Laverack and Turner 1995). Rogues include off-types, diseased plants, objectionable weeds and other crop plants (Parimala et al. 2013). Adequate and timely roguing is important in seed production. Roguing of off-types at flowering stage is more important than at vegetative stages. The undesirable plants, which are often not distinguishable at vegetative stage, should be identified by the distinctiveness and be removed soon after the emergence of the earheads or tassel or flowers, to avoid any genetic contamination. If cytoplasmic genic male sterile (CGMS) system is used, special attention is required to remove the pollen shedders in the female population. Diseased plants are also rogued out from the seed crop to avoid the spread of pathogens. Many off-type plants exhibit variations only after they mature, hence roguing at the maturity stage is also crucial (Table 3).

5.2.6 Weed Control

Presence of weeds in seed crop not only reduce the yield by competing for space, nutrients, moisture and sunlight, but also lowers the quality standard. Weed plants in the seed field or nearby areas may also serve as the host to a number of diseases. Presence of prohibited weed (objectionable/obnoxious weed) seed may result in the rejection of an entire seed plot/lot. For instance, by the presence of more than 1 and 2 wild rice plants (*Oryza sativa* L. var. *fatua* Prain) (Syn. *O. sativa* L.f. *spontanea* Rosch.) in a population of 10,000 plants of rice (*O. sativa*) crop of foundation and

Table 3 Specific field standards (wheat, barley, oats and rye) under the AOSCA seed certification scheme (in North Dakota State, USA as an example)

Factors	Maximum tolerance		
	Foundation seed	Registered seed	Certified seed
Other varieties[a]	1:10,000	1:5000	1:2000
Inseparable other crops	1:30,000	1:10,000	1:5000
Prohibited noxious weeds[b]	None	None	None

(North Dakota Legislative Branch, Title 74, Seed Commission, Article 74-03, Seed Certification Standards, Chap. 74-03-02; https://www.ndlegis.gov/information/acdata/pdf/74-03-02.pdf)

[a]Other varieties include plants that can be differentiated from the variety being inspected, but shall not include variants which are characteristic of the variety

[b]The tolerance for prohibited or objectionable weeds, or both, in the field will be determined by the inspector

certified seed plots, respectively, will be rejected. Hence, weed control is a critical aspect of seed production. Weed management strategy begins with the selection of a clean site and continues till the seed crop is harvested. Best agronomic practices should be followed for effectively managing the weeds.

5.2.7 Disease and Insect Control

Successful disease and pest control is another important aspect of raising a healthy seed crop. Apart from the reduction of yield, the quality of seed from diseased and insect-damaged plants is invariably poor. There are number of diseases which are systemic and seed-borne in nature. If not checked, the seed thus produced will carry the spores of the pathogens (inoculum) and produce diseased plants in the next generation. Production of disease-free seed can be achieved by using disease-free planting material, producing seed in isolated and disease-free zones, and using recommended plant protection measures. Insects can be managed in the field by the use of insecticides and in storage by proper sanitation, fumigation and seed treatment. Insecticide-impregnated seed packaging material is also effective in managing cross-infestation during storage (Agarwal et al. 2018). Some diseases are identified by the national authorities, as in India, as designated diseases. As per the IMSCS, loose smut in wheat, ashy stem blight in cowpea, halo blight in green gram and downy mildew in sunflower are designated as objectionable diseases during field inspection (Fig. 6).

5.2.8 Soil Fertility and Plant Nutrition

There is no direct association between soil fertility and seed quality although soil fertility and seed yield are positively correlated. However, soils deficient in minor elements may cause seed quality issues. In field beans, cotyledonary discolouration is observed due to deficiency of calcium and boron (McDonald and Copeland 1997). Hypocotyl necrosis in germinating seed of groundnut is common in crop grown in calcium-deficient soils. Nitrogen, phosphorus, potassium and several other elements play an important role for proper development of plants and seeds (White and Brown

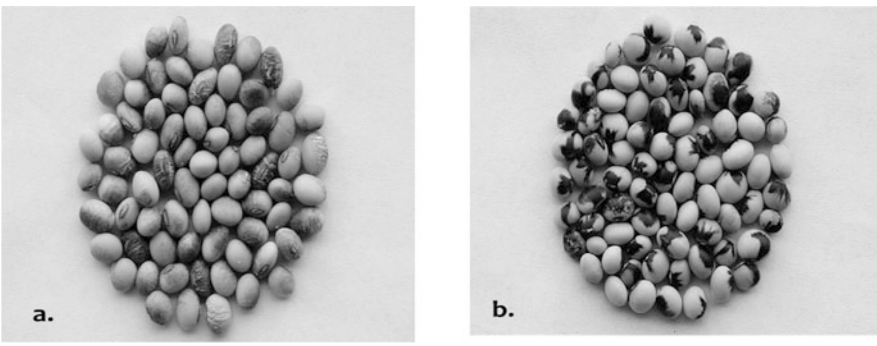

Fig. 6 Seed discolouration in soybean due to influence of disease: (**a**) purple staining of seed due to *Cercospora kikuchii*, (**b**) seed discolouration due to soybean mosaic virus

2010). It is, therefore, mandatory that the soil health is tested, and the nutritional requirements of seed crops are met through the application of required fertilizers in adequate quantity.

5.3 Seed Technology Principles

Quality seed production is a function of not only genetic and agronomic principles but also seed technology principles. Aspects such as selection of field free from volunteer plants, strategies for enhancing the seed set, time and method of harvest, seed extraction, drying and other post-harvest operations constitute seed technology principles crucial for obtaining seeds of highest quality.

5.3.1 Selection of Field

The plot selected for seed production must be levelled and should have an assured source for irrigation. The field must be free from volunteer plants, weed plants, soil-borne diseases and have good soil texture and fertility. It should be feasible to isolate the plot as per the requirements of seed certification. In case space isolation is not possible for some reason, time and barrier isolation may be deployed. For instance, in case of maize, time isolation could be provided and barrier isolation may be achieved by planting rows of a tall barrier crop or additional border rows. Fields that have produced seed crops of small-seeded forage legume (e.g., red clover) in the preceding season should not be used to produce seed of another inseparable legume seed crop (e.g., alfalfa). Seed of such crops tends to remain viable in the soil and continue to germinate and contaminate subsequent crops.

5.3.2 Supplementary Pollination

Pollination occurs naturally without human interference either through the wind or pollinators. Pollen availability on the stigma determines the seed set and ultimately the seed yield. This can be augmented through human intervention or by supplementing the pollinator activity. Various kinds of bees (honey bee, leaf-cutting bee and alkali bee) are common and effective. Seed set and quality in berseem can be enhanced significantly by maintaining three to five honey bee hives in close proximity to seed fields (Prasad et al. 2014). However, safe isolation distance needs to be ensured in such cases to avoid genetic contamination by pollinators. Hand pollination is a commonly used strategy in hybrid seed production of sunflower where pollen is collected from the heads of male plant and applied gently over receptive stigma of female plants. In hybrid seed production (please see chapter ‘Hybrid Seed Production Technology’ for details) of rice, rope pulling or beating the male parent with stick is generally practised to release the pollen grains from the male parent (Fig. 7).

5.3.3 Harvesting

The development of seed is characterized by two distinct stages of maturity viz. physiological (or mass) maturity and harvest maturity. Physiological maturity is the end of seed filling period (Harrington 1972; Tekrony and Egli 1997), whereas, harvest maturity is the point of time that coincides with the maturation drying

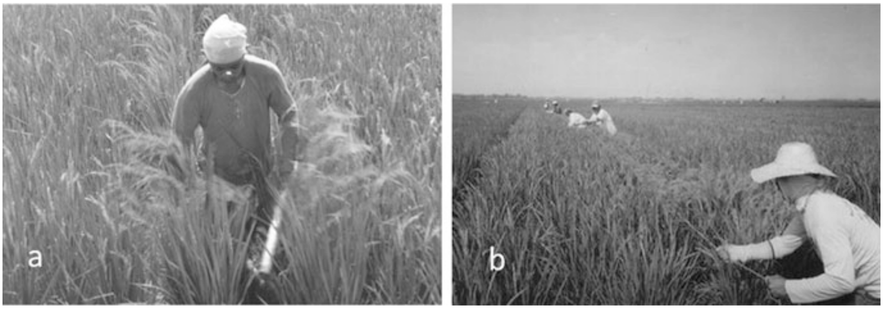

Fig. 7 Supplementary pollination in hybrid seed production of paddy: (**a**) by beating the male parental lines with wooden stick and (**b**) by polling the rope over male parental lines. (Courtesy: Dr. S.K. Chakrabarthy, ICAR-IARI, New Delhi)

when it is harvested. The germination and vigour of the seed are at peak when the seed attains physiological maturity (Ghassemi-Golezani et al. 2011). However, as the seed moisture is quite high at this stage, seed is harvested only once it attains a safe moisture level that allows safe processing and storage (Ellis 2019). In plants with determinate flowering habit, seed maturity is uniform, whereas in crops with indeterminate flowering habit (carrot, sugarbeet, etc.), harvesting needs to be timed to obtain maximum seed yield and quality. Method of harvesting also influences seed quality, hence selecting the right method of crop-appropriate harvesting is important. Harvesting and threshing equipment must be thoroughly cleaned before harvesting each variety to avoid mechanical mixtures.

5.3.4 Drying and Storage of Raw Seed

Drying seeds to a safe level is critical to maintain the seed viability and vigour during the storage, and to keep seeds free from pests and disease incidence. Drying should be done using an optimum combination of temperature and airflow maintaining a temperature that does not adversely impact seed quality. In warmer environments, and natural drying by spreading the seeds in thin layer under the sun, or forced air drying at ambient air temperature can be performed. In case of mechanical drying, care should be taken to avoid any mechanical admixture. Pre-processing sheds and bags containing pre-processed seed also need to be well-cleaned (see chapter 'Seed Storage and Packaging' for more).

5.3.5 Seed Conditioning and Upgradation

After seed has been harvested and before it is dried and stored, it must be cleaned. Seed as it comes from the field, contains varying quantities of physical impurities such as trash, dried leaves, weed seeds, other crop seeds, etc. (McDonald and Copeland 1997). The purpose of conditioning is to remove these physical impurities, as well as to upgrade the seed quality and appearance. Satisfactory conditioning requires a specific sequence through several operations. Raw seed is initially conditioned by pre-cleaner to remove impurities such as crop debris and soil particles. It also removes bigger and smaller sized seeds to large extent. Later, pre-cleaned seed is conditioned through air-screen machine (seed grader) and quality upgradation is done through machines viz. indented cylinder separator, gravity separator, fractioning aspirator, roll mill, spiral separator, buckhorn machine and inclined belt separator. Specialized machineries such as huller-scarifiers (to scarify hard seeds) and debearders (to remove seed appendages like awns, beards or glumes) are also employed. The choice of operation and machinery depends on the kind of seed, the nature and type of contaminants in seed lot and quality standard need to be achieved after seed conditioning and upgradation (see chapters 'Seed Processing for Quality Upgradation' and 'Seed Quality Enhancement' for more).

5.3.6 Seed Treatment

Seed treatment promotes the planting value mainly by ensuring good seedling establishment and control of seed and soil-borne pathogens. The application of seed treatment is a specialized operation and last step in the conditioning of seed before the bagging. Range of contact and systemic fungicides, and insecticides are available for the purpose. Choice of chemicals depends upon the nature of protection needed. Treated seed should be clearly distinguishable and seed container properly labelled by the statement indicating that seed is treated and these are not suitable for food, feed and oil (see chapters 'Seed Health: Testing and Management' and 'Seed Quality Enhancement' for more).

5.3.7 Seed Packaging and Storage

After seed processing and treatment, seeds are ready for packaging into the containers of specified weight based on seed rate per unit area in various crops. The packaging materials should protect quality of seed and should have sufficient tensile strength, bursting strength and tearing resistance to withstand the handling stresses (Walters 2007). Such materials may not always protect the seeds against either insect pests or moisture regain. Based on the nature, seed packaging materials are classified as moisture vapour permeable container (freely permeable to water vapour and gases, e.g., jute bag, cloth bag, paper bag, multiwall paper bag), moisture vapour resistant container (materials resistant to the passage of moisture but, over a long period of time, there will be a slow passage of water vapour tending to equilibrate the relative humidity inside with surrounding environment, e.g., jute bag laminated with thin polythene film) and moisture vapour proof container (material is completely moisture and vapour impermeable and hence, seeds should be dried to low moisture levels before packaging and they can be hermetically sealed with altered gaseous content inside the package, e.g., tin can, polythene bags, aluminium foil pouches, glass bottles). Two simple rules say that for every 1% decrease in moisture content, storage life of the seed is doubled and for every 5 °C decrease in storage temperature, storage life is also doubled. The ideal temperature range for insect and fungal activity is 21 °C to 27 °C. Seed storage godown should be well ventilated and has provision for prevention of entry of rodents. Stored seeds need to be monitored at regular intervals for insect infestation and fumigation may be done if need arises. The stacks of bags should not be made directly on the floor. These should be arranged on the wooden platform in dry, cool, clean and rat proof godown (see chapter 'Seed Storage and Packaging' for more).

5.3.8 Seed Certification

Seed certification is a legally sanctioned system for quality assurance of seed multiplication and production. Certification programme is necessary (or sometimes obligatory) for the seed trade. OECD seed schemes are globally accepted seed certification system, whereas AOCSA system is widely followed in North America. In India, the state seed certification agency is the legally authorized body to manage and monitor the seed quality during multiplication. Seeds which are certified under the certification schemes have to meet both general and crop-specific field and seed standards. Producing high-quality seeds of the crop varieties and making them available to the farmers are the prime aim of any seed certification system (see chapter 'Role of Seed Certification in Seed Quality Assurance' for more).

5.3.9 Seed Certification Procedures

Application

Seed producer needs to submit an application along with the requisite fee to the designated seed certification authority, requesting for certification. The fee is for one season for a single variety and for an area as specified for one seed plot, which is mostly up to ten hectares. The official tag of the source seed should also be submitted (e.g., breeder seed tag in case of foundation seed production; and foundation seed tag in case of certified seed production) along with the application.

Field Inspection

The field inspections are performed by the concerned certification agency on all fields for which applications are received. The objective of the field inspection is to verify that proper care is taken to check the factors that may affect genetic purity and physical health of seeds during multiplication. A number of field inspections differ from crop to crop and certification schemes. Generally, field inspections would be carried out for a minimum of two or more times during pre-flowering, flowering, pre-harvest and harvest stages. During field inspection, isolations are verified; presence of off types, other crops, weed contaminations and diseased plants are checked and seed growers are guided to undertake necessary corrective measures, if required. The fields, which do not conform to the prescribed standards, and if there is enough evidence to prove that contamination has already occurred, shall be rejected for certification.

Seed Sampling, Testing and Tagging

The purpose of sampling is to draw a representative sample from a seed lot (of 10 t or more) of a size suitable for conducting quality testing, in which the probability of a constituent being present is same as its proportion present in the seed lot. Seed sample thus drawn by the authorized persons is sealed, labelled and submitted to the certification agency, and tested for quality parameters in an official seed testing laboratory. Seed lots which meet the prescribed seed standards (pure seed, germination, weed seeds, other crop seeds, and diseased seeds) alone will be eligible for allotment of seed certification tag. Under the OECD seed schemes, the results of seed

Table 4 Specific seed standards for chickpea, soybean and lentil under the AOSCA seed certification scheme (in North Dakota State, USA as an example)

Factor	Foundation seed	Registered seed	Certified seed
Pure seed (minimum)	98.0%	98.0%	98.0%
Total weed seed (maximum)	None	1 per pound	2 per pound
Other varieties (maximum)[a]	0.1%	0.2%	0.2%
Other crop seeds (maximum)			
Soybean and chickpea	None	1 per 2 pounds	1 per pound
Lentil	1 per 2 pounds	1 per pound	3 per pound
Inert matter	2.0%	2.0%	2.0%
Prohibited noxious weed seeds	None	None	None
Objectionable weed seeds[b]	None	None	None
Germination and hard seeds	85.0%	85.0%	85.0%

[a]Other varieties shall not include variants characteristic of the variety
[b]Objectionable weed seeds are dodder, hedge bindweed (wild morning glory), wild oats, buckhorn, hoary alyssum, quackgrass, wild vetch, giant foxtail, wild radish, nightshade species, and cocklebur
Seed label shall have the results of an *ascochyta* test performed on the harvested seeds of each seed lot

testing should, whenever possible, be given on the orange international seed lot certificate issued under the rules of the International Seed Testing Association (ISTA). Most of the agencies have adopted a two-tag system, in which seed analysis tag and certification tag are different. Certification tag is issued by the seed certification authority and seed analysis information is printed on seed label and affixed on seed containers separately (Table 4).

5.3.10 Marketing

Generally, the seed companies, both in the public and private sectors produce seed through the contract seed growers/certified seed growers, where production is taken up in the farmers' fields and raw seed is procured, processed, tested, packed and sold through the network of dealers (Chauhan et al. 2016). Public sector seed production agencies may also produce seed in their own farm and sell it through their own outlets. Effective promotion, branding, attractive packaging, product mix, established market channels, seed quality, seed price etc. play important roles in seed marketing.

6 Conclusion

Seed production is a series of well-defined specialized activities, requiring rigorous criteria to be followed by the seed producers at each of the stages to ensure that high-quality seed is produced and marketed. Continuous flow of new improved varieties with steady augmentation of variety replacement and seed replacement rates are going to be the key for future food and nutritional security of the countries. The genetic, agronomic and seed technology principles of quality seed production discussed broadly hold good for current scenario. However, with threats of climate change in future, alternate procedures may need to be adopted with respect to growing locations and agronomic practices. Seed production of high-value seeds, especially hybrid vegetables under controlled conditions of polyhouse/greenhouse/ net house, is a viable option to combat the threats of abiotic and biotic stresses.

The varietal spectrum across the cropping system is also expected to shift more towards early maturing and climate-resilient varieties in the times to come. Modified agronomic practices or growing seed crops in protected environments may take forefront for narrowing the ill effects of changing climate on seed production. Likewise, the prescribed field standards may need to be redefined in cross and often cross-pollinated species. Future researches will also need to address the management of some diseases and pests, which are of lesser economic significance today, but threaten to become major problems for seed production in the coming years.

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