Seed Res., Vol. 42(1): 1-24 June 2014

An overview of seed enhancement technologies for sustainable agricultural production

SHIV K. YADAV*, S. K. LAL, SANGITA YADAV AND VILAS A. TONAPI[1]
Division of Seed Science and Technology, IARI, New Delhi-110012.
skysst@gmail.com

ABSTRACT Seed is regarded as a dynamite for change and carrier of new technologies. Hence, it needs to be protected and preserved so that it can act as an effective and efficient vehicle for the delivery of such technologies. Various treatments have been used in many crops for a variety of purposes since ages. Treatments that control seed borne pathogens using conventional crop protection chemicals are considered as 'seed treatments', whereas 'seed enhancement' is the term used in scientific literature and seed industry to describe the range of beneficial techniques performed on the seeds after harvest, but prior to sowing through manipulation of physiological status for better planting value, improved germination and uniform seedling growth. Sorting on the basis of size, colour, chlorophyll content and X-ray analysis of internal structures or buoyant density in solvents offer the ability to remove weak or dead seeds, resulting in up-gradation of quality seed lots. Seed enhancement includes priming, steeping, hardening, pre-germination, pelleting, encrusting, film-coating etc. Hydration is perhaps one of the primitive methods to manipulate vigour or physiological status of seed, while enhancements like pelleting, coating and encrusting improve seed handling and precision planting. Both priming and coating technologies can also deliver beneficial microorganisms through seed. Some treatments enhance nutrient availability or provide inoculants (other than pesticides) required to improve germination and seedling establishment. *Rhizobium* inoculation of legume seeds is an efficient and convenient way of introducing effective rhizobia to the soil and subsequently into the rhizosphere. Other treatments may include the use of chemicals that trigger systemic acquired resistance or help to tolerate stress. Organic farming market standards are stimulating the evaluation and optimization of methods to produce healthy planting material and new seed sanitation treatments as alternatives to fungicides or conventional hot water or bleach treatment while retaining seed viability in storage. The advancement in technologies for improving planting value of seed will continue to usher in enhanced agricultural production. This paper tries to review the uses of range of 'seed enhancement technologies' that could be adapted as a cultural package, including latest techniques and approaches that may aid in commercial application and utility to boost early seedling vigour abetting per unit higher productivity.

Keywords: Seed priming, coating, pelleting, encrusting, sorting, drying, seed quality, agricultural production

The debate fuelled by the turbulence of world agricultural markets on relations among agriculture, food security, natural resources, population growth and economic development has been revamped over the last few years [1]. Now, it is well recognized that there is no further opportunity for expansion of the area under cultivation. Thus, sustainable agricultural production and regional food security can be ensured primarily through enhancing crop yields. Despite the all-good research efforts, availability of improved seeds in adequate quantities during the growing season is a major constraint for realizing the potential crop yields in many parts of the world. Seed is a 'Miracle of Life', a dime's worth of power that no man can create and dime's worth of mystery, destiny and fate. The importance of seed in agriculture and breeding programs cannot be over-emphasized. Quality seed is one of the cheapest and a most vital input for crop production, which has contributed towards remarkable progress in increasing agricultural production and productivity since mid-sixties and has the potential to improve the productivity to the tune of 20-25 percent under all farming systems, ranging from rainfed to irrigated. Hence, availability of quality seed of improved varieties will

*Corresponding author
[1]ICAR- Directorate of Sorghum Research, Rajendranagar, Hyderabad 500 030 (AP)

Received: January 2013 Revised: January 2014 Accepted: April 2014

consequently result in increased production and thereby provide household food security and cash income for the rural and urban population. The seed quality at the time of sowing is primarily the reflection of proper processing/conditioning and storage conditions. Generally, mechanical removal of contaminants present in a seed lot is termed as seed conditioning or seed processing. The most important consideration for storage is to avoid storing seeds at high moisture content and temperature regimes which leads to development of heat, increased/infection by storage micro-organisms and insects. A common thumb rule for satisfactory seed storage is that the total value of temperature (in Fahrenheit) plus the relative humidity in the air (in percent) should not exceed the value of 100 [2].

The success in stand establishment of a good crop is limited by abiotic and biotic stresses, which serve together to reduce germination and seedling establishment in many crops. When a seed is planted during an environmental stress like heat or drought, chemical reactions in the seed may not go as smoothly as when the seed is under little or no stress. The crops are liable to face varying degree of water stress, especially at the crucial stages of germination and seedling establishment. The early sown varieties of various crops face the problem of heat stress at early vegetative stages. Moreover, there is uncertainty regarding the physiological response of crops to enhanced atmospheric temperature due to global warming. Any significant change in climate on a global scale directly affects crop production and then would impact local agriculture. The problem of climate change compounded by the fundamental complexities of productivity loss, pest and disease patterns, natural agricultural systems and socio-economic conditions in various parts of the world has started posing threat to food supply [3]. Hence, successful stand establishment under diverse conditions is the key to assured production. The number of plants established from a given weight of seed depends on the percentage of those seeds that are viable and the vigor of the seeds that successfully establishes into a healthy plant. The evaluation of different vigour tests for predicting planting value of seed is important in providing better results for ranking the seed lot in terms of quality, rather than the standard germination test [4-5]. Many research workers have reported correlation between germination, vigour, and seedling emergence, which varies according to species, vigor test methods and field conditions, but there are also reports of inconsistencies and difficulties with the prediction of field emergence.

Addressing the challenge of assured plant stand under critical global warming conditions of tropical and sub-tropical regions would involve the necessary adjustments for modifying field operations such as tillage or pest control and developing easy and cost effective techniques for enhancing the planting value of seed. Various seed treatments have been used in many crops for a variety of purposes since ages. Seed enhancement treatments have the potential to alleviate stress effects and improve plant stand, the efficacy of which depends on the extent of stress experienced. Seed enhancement includes priming, steeping, hardening, pre-germination, pelleting, encrusting, film-coating and tagging. There are specific problems/conditions in the crops which need to be addressed through incorporation of specific treatments. The interventions with hormones, nutrients, pesticides and polymers for increasing heat stress tolerance and to serve the interests may provide an effective strategy for farmers and other stake holders. Hydration is perhaps one of the primitive methods to manipulate vigour or physiological status of seed, while enhancements like pelleting, coating and encrusting improve seed handling and precision planting. Both priming and coating technologies can be used for delivery of beneficial microorganisms

through seed. Other treatments may include the use of chemicals that trigger systemic acquired resistance or help to tolerate stress. Moreover, it is important for successful plant establishment either of increase water use efficiency or to enhance the water holding capacity around the developing root zone for a specific period/ a particular growth stage [6]. This could be possible through priming and/ or coating with the polymers or encapsulating with hydrophilic gels [7]. Nutritional management by increasing N_2 fixation through nitrogen fixing inoculants can cut down the cost of cultivation as well as improve the soil health [8]. Limited longevity is a long standing problem in many crops with high oil and protein content hence the improvement in their storability by any such seed treatments is always welcome. Simple seed separation by its bounce was a serious idea developed in an Israeli business incubator about 10 years ago. They developed a machine that separated the seed according to how high it would bounce and was intended to be used in conjunction with conventional seed cleaning separation techniques. It was based on the principal of seed elasticity. The creators claimed that seed with more elasticity (bounces higher) is most likely to germinate with highest vigour [9]. Sorting on the basis of size, color, chlorophyll content and X-ray analysis of internal structures or buoyant density in solvents offer the ability to remove weak or dead seeds, and hence upgrade the quality of seed lots. It is believed that the planting value of seed lots can be improved by the techniques, which range from simple conditioning to sophisticated methods like chlorophyll fluorescence based sorting [10].

Quality seed and agricultural production system

The food grain production fluctuates much but overall has also resulted in plateau in recent years. Various reasons have been assigned for the low productivity of crops viz., poor seed vigour, low and uncertain availability of water and severe losses due to pests and diseases [11]. A viable seed with high vigour and free from infection or seed transmitted diseases, forms the basis of a successful crop production in the overall agricultural economy [12]. Likewise, high-quality healthy planting material yields a healthy crop, leading to financial security for all stakeholders, particularly the poor farmers. Seeds and plants appearing perfectly normal at first sight may show quality deficiencies or carry harmful viruses, bacteria, fungi or other organisms, resulting in poor plant stand [13-14]. The seeds, which are free from seed-borne diseases, help in raising disease free crop as well as checking further spread of the diseases. Seed infested with insect-pests and diseases tend to lose viability rapidly during storage and become unfit for planting within a very short period. Seed is considered as a *'microcosm of microbes'* and known to carry fungi, bacteria, and viruses inside the seed, on the seed coat or along with the seed (admixture), some of which cause plant diseases. Soil, unless fumigated or sterilized, also contains fungi and other organisms that attack seed and seedlings. Similarly, insects can damage seed during storage or after planting. Hence, stored seed need to be protected from insect-pests until it can be planted. However, soil insects can be extremely destructive to seed and seedlings once planted, particularly when soil conditions are unfavorable, resulting in poor germination and emergence. Finally, birds and mammals may dig up and eat newly planted seed. Thus seed treatments can be effective for successful plant stand establishment, where insect-pests and diseases pose a serious threat at germination and early vegetative stages and under rainfed cropping systems. Fungicidal and bio-control seed treatments alone or in combination with other seed enhancement treatments could be effective for the management of seed-borne diseases [15]. Further, application of pesticidal

coatings or pelleting on seed also has enormous scope for initial plant protection in seed production systems. There are many other seed treatment technologies that have the potential of improving the planting value of the seed and shaping the future of the global agricultural and food economy. The advancement in technologies for improving planting value of seed will continue to usher in enhanced agricultural production. We have tried to review the uses of range of 'seed enhancement technologies' that could be adapted as a cultural package, including latest techniques and approaches are may aid in commercial application and utility to boost early seedling vigour abetting in per unit higher productivity.

In the recent past, the advances in biological and engineering sciences and their merger on a common seed platform has led to the invention and application of new approaches for improving quality of the seed lots. Such new trends with the conventional techniques are also discussed in this review.

A. Conventional technologies

With most conventional upgrading techniques, the seed quality is derived from external characteristics like size and color. Seed lots are cleaned to remove inert matter and other seed mixtures, including weed seeds. The differences between seeds in shape, width, length, color, weight, etc, make it possible to separate a seed lot into desirable or undesirable fractions. The techniques that are based on density have a more direct relation with the interior of the seed. The most advanced technique available till date is the fluid density separation.

I. Seed conditioning

Seed from harvesting machines or hand collections include a mix of stems, leaves, chaff, appendages, empty glumes, and seeds of various sizes. The process of cleaning the harvested seed is known as conditioning or processing. It includes the rapid removal of excessive, extraneous materials by scalpers, hammer mills, or debearders prior to basic cleaning with air-screen separators called as Pre-cleaning. The extraneous materials must be removed to ensure seed quality and to allow uniform dispensing through seeding equipment. The air-screen separator, properly adjusted, can supply a finished product for many grasses, herbs, and shrubs. However, finishing machines are also available to separate seed by density, length, width, thickness, and shape. These include specific gravity separators, pneumatic separators, velvet rolls, spiral and indent cylinders, indent disks, magnetic separators, electrostatic separators, vibrator separators, stoners and others. The moisture content may be high in freshly harvested seed and hence drying may be required prior to cleaning. The journey of seed harvested from the field to a clean, uniform seed lot with good vigour and germination characteristics can be a long trip but effective for improving the planting value of seed [16]. The processed seed may remain viable for long, if stored in a clean facility where temperature and humidity are kept at low to optimum levels.

II. Liquid Density Separation (LDS)

Seed separation in this method is done by addition of a non-phytotoxic salt or other tiny particle to water that won't damage the seed so as the density of this mixture becomes heavier than that of the seed being separated. All seeds dropped into the mixture will float. As the liquid is diluted, the heaviest seed starts to sink. The seeds with a specific seed density can be collected at the bottom of the vessel, with each addition of water, and very precisely separate seed by its density. The density separation of the seeds can be carried out using hexane and chloroform [17]. This type of separation is not recommended for high volume, relatively low cost seed. When seed is worth thousands of dollars per pound, this type of procedure can certainly pay rich

dividends. Also, certain species like tomato or pepper seed, where seed that matures inside a wet fruit, seem to respond better to such procedures.

III. Thermotherapy

Thermotherapy or hot water seed treatments when properly used can kill most bacterial disease-causing organisms on or within seed. Hot water treatments of about 50°C for 10-30 minutes can be used along with exact pre-warming and post-treatment cooling and drying steps [18]. However, the seeds of cucurbits can be severely damaged when subjected to hot water treatment. It was reported that the germination of intact annatto seeds collected at 70, 77, and 84 days after anthesis (DAA) was 51, 53, and 16%, respectively, and thermotherapy was the only treatment that significantly altered it. Although hindering the germination of seeds collected at 70 DAA, thermotherapy for 1 and 3 minutes enhanced germination in seeds collected at 84th day DAA (62 and 55%, respectively) [19].

IV. Heat shock methods

Heat shock methods include keeping seeds under a mild water and/or temperature stress for several hours (tomato) or days (*Impatiens*) before drying. For example, pansy seeds are hydroprimed to a seed moisture content of 38%, followed by transferring them to a rotating drum for 3-4 days at 20°C. At the end of imbibition, the seeds are desiccated rapidly using forced air at 20°C and 40% relative humidity. Seed moisture contents may decrease 5-10% per hour in this 'fast drying' treatment. Alternatively, slow drying using static air of 20°C and 75% relative humidity for 3 days reduces seed moisture content at the rate of 0.1 to 0.3% per hour. At the end of this slow drying treatment, these seeds are transferred to 'fast drying' conditions to complete desiccation, that may result in better field performance as well as the storability [20].

V. Seed Treatment

Increase in agricultural production is the key to all-over economic growth. The need to increase world food production can only be met by proper management and use of high quality seed of higher-yielding cultivars. Seed is the starting point for all plant production. Seed constitutes the main propagule for plant growth and, at the same time, one of the main vehicles for the dissemination of plant pests. It was reported that seed treatments have positive impact on crop stand establishment [21]. Seed treatment refers to the application of fungicide, insecticide, or a combination of both, to seeds so as to disinfect them from seed-borne or soil-borne pathogenic organisms and storage insects. It also refers to the subjecting of seeds to solar energy exposure, immersion in conditioned water, etc. Throughout history, mankind has been striving for the development of new plant varieties that are ever more sophisticated, with higher potential for yield, resistance to pests and pathogens, and suitability for specific uses or areas of cultivation. Since the seed contains all the genetic information needed to realize the inherent potential of these efforts, its protection has always been crucial for plant breeders, seed producers, farmers and those involved in crop and/or seed production. By consensus, conventional crop protection chemical treatments (e.g. fungicides, insecticides) are considered to be separate than those in the seed enhancement category.

B. Seed enhancement technologies

Ensuring food and livelihood security to the ever increasing Indian population is a major challenge in context of global warming. For sustainable agriculture, following are the crucial inputs; 1. Seed with high germination potential and vigour to assure optimum plant stand under uncertain/less favorable environmental conditions 2. Precise and effective input delivery system and 3. Effective and need based seed treatments

resulting in maximum plant population with least environmental/ residual pollution. Seed enhancement treatments have the potential to alleviate the ill effects of biotic and abiotic stresses and thus, improving the planting value of the seed. Hence, the application of suitable seed enhancement methods to improve the planting value of seed can provide better plant stand in the farmers' fields thereby increasing the productivity per unit input. The term seed enhancement encompasses many pre-sowing, 'value-added' techniques including priming, seed coatings and pre-germination [16]. These methods are not mutually exclusive and many techniques can be combined to obtain additive effects. Seed enhancement is a broad term to describe the range of practical beneficial treatment techniques performed on seeds (after harvesting and conditioning) to improve their physical or physiological performance [22]. Manipulating the vigour of seed can be accomplished using (i) various hydration treatments, (ii) chemicals to trigger SAR (systemic acquired resistance), or incorporation/induction of seed antioxidants [15]. Other types of seed enhancements facilitate the handling and planting of seeds, through various methods of pelleting, coating or encrusting [18]. Seed enhancements can also deliver materials (e.g. nutrient inoculants, beneficial microorganisms) needed at the time of sowing. These treatments can also be designed to remove weak or dead seeds from a seed lot using upgraded, non-traditional conditioning treatments such as color sorting or X-rays. Tagging seeds with visible markers for identity preservation and traceability programs is another recent type of seed enhancement. The enhancement treatments are used most extensively in high-value, horticultural crops such as vegetables and flowers [23]. Many agronomic species are now film coated to provide better delivery of high-value crop protection chemicals and higher cost, stacked genetic traits seed. The use of various seed coatings is also well established for small-seeded legumes and some turf grass species. As seed value increases, commercial seed enhancements are more commonly available and requested. The development of seed invigoration treatments started with seed priming and improvements in the rate and uniformity of germination have been achieved in a range of species through many methods. Seed enhancement technologies have expanded over the last 20 years due to the vegetable industry's demand for strong and uniform stand establishment. Precision seeding reduces seed cost per acre and seed enhancement increases production flexibility and harvest pack-out. Since many of the leafy vegetables and cole crops mature in 60-90 days and flower-plug production requires even less time, plant uniformity in stand establishment has become a critical production consideration. The various techniques used for enhancing the planting value of seed have been discussed below.

I. Priming

Seed priming describes a broad group of hydration techniques employed to enhance seed performance in the field or in controlled environment production systems. The term, seed priming, is also used to describe the biological processes and changes that occur during seed hydration (and drying) treatments. Priming is of interest to seed researchers as a tool for understanding the germination process, and is of considerable interest to the seed industry as a vehicle for improved seed performance and quality. Seeds are primed (imbibed) to a water content and/or time period less than that required for complete germination and then (usually) dried [24]. Primed seeds are essentially held in phase II of germination by these restrictions in water potential, or because of insufficient time [25]. Phase III water uptake and seed germination is achieved upon subsequent sowing and rehydration. In addition to the improvements in germination speed and/or uniformity common with primed seed lots,

primed seed often contributes to improved seedling establishment under sub-optimal conditions at sowing (e.g. temperature extremes, or excess moisture). Primed seed is also valuable for increasing the level of useable seedlings produced in greenhouse environments.

Because of the variability in response from one seed lot to another, the optimum priming protocols used in commercial seed enhancement operations are often determined on a case-by-case basis. This can be accomplished by conducting 'pilot' priming runs on small samples and testing the germination responses. Optimal priming procedures and the resulting improvement in uniformity of emergence are especially valuable for high-value crops, where multiple harvests are expensive or impractical (e.g. lettuce). Among vegetables, priming increased germination as well as speed of emergence in radish [26]. Seed priming is most extensively commercialized in the field seeding or plug transplant production of tomato, pepper, onion, carrots, leek and the production of ornamental plants including begonia, *Viola*, cyclamen, primrose and many herbs. Priming is also commonly used with seeds of sugar beet, some turf species and has been used for decades to circumvent seed thermo-dormancy in lettuce and other species.

Priming leads to better germination in a wider range of temperatures. For example, primed tomato seeds germinate to higher percentages at 35^{0}C than unprimed seeds and are able to germinate well at 10^{0}C, whereas unprimed seeds do not germinate. Similar results have been observe in primed leek seeds even though leek is a cool season crop. The understanding of the biochemical, physiological and cytological processes involved in seed priming could be developed from studies on (i) germination kinetics and modeling using hydro time (and hydrothermal time) concepts, (ii) DNA replication and cell division plus cell cycle changes in seeds and (iii) endosperm weakening by hydrolysis in species, where the embryo is mechanically restrained from expanding. Hydro time and hydrothermal time are concepts which involve modelling of water potential and temperature in combination. The base temperature for radical emergence may differ from species to species and the base water potential for a species or seed lot is that value, which just prevents germination. Hydro (thermal) time can be adopted to explain the influence of external factors on germination, and to describe the basis and design of priming protocols. An accumulated hydro time effect on priming effectiveness generally reaches a peak, followed by potential 'over priming'. For example, highest germination rate for broccoli seeds occurred after 218 MPa h; however, accumulation of hydropriming time greater than 252 MPa h may reduce the germination rate.

When priming occurs at suboptimal temperatures, it is useful to add thermal time to the model. An ultimate goal of hydro time modeling is to efficiently predict optimal priming protocols and minimize the need for small scale pilot testing of seed lot samples. These models should also be useful in predicting seedling emergence in a wide range of agro-ecological environments. Several methods have been proposed to regulate water availability (as a liquid or in the vapor phase) to seeds. Three basic systems used to deliver and restrict water supply adequate amounts of O_2 to seeds are (i) osmopriming, (ii) matrix priming and (iii) hydropriming.

i. Osmopriming / osmoconditioning

Osmopriming refers to the process in which seeds are incubated with aerated solutions of low water potential. Seeds are then rinsed off after completion of the priming step. Osmoconditioning improved the performance of tomato [27] and pepper seed lots [28]. Various inorganic salts like; KNO_3, KCl, Ca $(NO_3)_2$ have been used as osmotica,

but their small molecular size permits uptake and potential seed damage. Compounds like NaCl, KNO_3, K_3PO_4, KH_2PO_4, K_2HPO_4, $MgSO_4$, glycerol, mannitol, peg, Leondardite shale, diatomaceous silica, vermiculate and expanded clay are commonly used for priming treatments [29]. High molecular weight polyethylene-glycol (PEG 6,000 to 8,000) is a preferred osmoticum, since its large molecular size prevents seed uptake. Continuous aeration is important in any osmo-priming system. For small quantities of seeds, they are either placed on the surface of blotter paper moistened with osmopriming solutions or immersed in aerated columns of solution. A new variation 'membrane priming' uses a rotating tube with an outer jacket, where the seed is separated from the osmoticum by a selectively permeable membrane. Pre-soaking of seed in growth regulators (GA_3, ABA, and IAA) showed marked improvement in germination, its rate, growth and uniformity under sub-optimal and high temperature conditions [30-31]. Similar results were obtained with sodium and potassium salt solutions [32-33].

ii. Matrix-priming/ matriconditioning

Solid or dry matrix priming involves the soaking of seeds in a matrix of water and insoluble matrix particles, such as vermiculite, diatomaceous earth, clay beads in pre-determined proportions. The seeds during matrix priming imbibe waters slowly, reaching an equilibrium hydration level determined by the reduced matrix water potential adsorbed on the particle surfaces [34]. After equilibrium is achieved, the moist matrix material is removed by screening or can be partially incorporated into the seed coating. Solid particulate systems can be used to increase seed moisture across a wide range of species and seed sizes and are generally compatible with the addition of biological controls. Early studies with matrix-priming (or 'moisturized' seed) and hydropriming (or 'hardened' seed) of sweet corn seed substantially improved early emergence and uniformity of stand in two field plantings. Osmopriming with PEG 8000 did not perform well in these experiments, which reinforces the need for pilot runs to optimize priming protocols in commercial operations. Matrix priming mimics the natural process of water uptake by seeds from soil particles or components of greenhouse soilless mixes. Matric potentials in this type of priming generally range from -0.4 to -1.5 MPa at 15-20°C for 1 to 14 days. This technique has been successfully used in the priming of species including carrot, celery, fescue, lettuce, onion, pepper, tomato, purple coneflower, common bean, soybean and sweet corn.

iii. Hydropriming

Hydropriming can be used both in the sense of steeping, imbibition in water for a short time and in the sense of the continuous or staged addition of a limited amount of water, with or without subsequent incubation in humid air. Slow imbibition through hydropriming is also the basis of drum priming techniques. Water availability is not limited in the simplest hydropriming (or steeping) methods and some seeds will eventually complete germination, unless the process is time limited to prevent the onset of phase III water uptake and radicle emergence [35]. Hydropriming is also used to infiltrate water soluble crop protection chemicals to control seed-borne diseases. These treatments usually immerse or percolate seeds at up to 30°C for several hours, followed by drying to near the original seed moisture content.

a. Steeping

Steeping has been employed as an agricultural practice over many centuries. Overnight seed steeping without drying (clarify) is still advocated in many parts of the world as a pragmatic, low cost and low risk on-farm priming method for improved seedling establishment of many crops.

Steeping can also be designed to remove water-soluble germination inhibitors from the seed coats of many Apiaceae species (e.g. parsley, celery) and sugar beets.

b. Drum priming

Drum priming is used commercially to hydrate seeds evenly and slowly to the desired moisture content, typically 25-30% on a fresh weight basis, by precise misting or dribbling with water [36]. The duration of this hydropriming method depends on the absorptive characteristics of the species and seed lot and the target seed moisture content. In European models, the priming drum sits on a scale which determines seed weight increases. Seed lots are tumbled in the drum for uniform hydration, aeration and temperature control. Another experimental drum priming system controls seed hydration by time interval and volume of water applied. A preset water volume is injected during each cycle as regulated by a timer attached to a solenoid. Dividing the total water volume required by the preset water injection volume establishes the number of cycles. Seed absorptive patterns of a species and cultivar must also be known to minimize the amount of free water remaining after a given cycle. Once the seeds obtain the desired water content, they can be incubated for time periods which ensure uniform seed hydration and give optimal germination results.

iv. Bio-priming

These techniques involve the addition of beneficial rhizosphere microorganisms in the priming process, either as a method for efficient delivery to the crop or to control pathogen proliferation during priming itself [37]. Matrix priming, osmopriming and hydropriming methods have all been employed to increase beneficial microbial populations on the seed. Compatibility of these microbes with chemical seed treatments, inoculants, and other additives may vary. Microbial formulations, quality control, delivery systems and costs of registration have slowed commercial use of biopriming to date. However, biological control organisms continue to present, a unique approach as an alternative control of soil pathogens and managing soil borne diseases.

v. Pre-germination

Pre-germination technologies allow seeds to germinate prior to sowing for optimum and uniform seed performance [38]. Fluid drilling (also known as fluid sowing or gel seeding) starts with the selection of germinated seeds using density separation. The sprouted seeds are then suspended in a viscous gel and sown by extrusion into the soil. Pre-germination techniques permit the separation of germinable seeds from dormant seeds and can be used to salvage high-value seeds from within a seed lot, where deterioration has occurred [39]. In a more recent type of pre-germination process, fully imbibed seeds are germinated to the point of radicle protrusion, sorted (by machine vision, floatation etc.) to remove ungerminated seeds and gradually dried to induce desiccation tolerance. Capron *et al.* [40] reported the temperature and oxygen dependence of priming efficiency closely paralleled that for germination of the untreated seeds, reinforcing the finding that the beneficial effect of priming corresponded to the advancement of germination *sensu stricto* (i.e. phase II of the germination process). For priming times longer than 2 d, particularly for osmopriming, there was a very dramatic decrease in germination of the treated seeds. For instance, following a 14 d osmopriming at 25°C as much as 60% of the pre-treated seed population failed to germinate when transferred to water. This loss in germination performance quite closely paralleled degradation of LEA (late embryogenesis abundant) proteins, notably a heat-stable seed-specific protein of about 60 kDa and a seed-specific biotinylated LEA protein.

I.a. Factors affecting priming

The outcome of priming depends upon many factors, some of the major factors affecting seed performance after priming are mentioned below.

i. *Aeration*

Proper aeration of the osmotic solution is essential to the living seeds and helped synchronize seed germination [41]. However, later reports showed that the response to aeration during priming varied according to the species. Moreover, aeration of the solution modified the optimal duration of priming. Regardless of the osmoticum or temperature used during lettuce seed priming, aeration of the priming solution lessened soaking time to achieve greater germination percentage at 35^{0}C [42].

ii. *Light*

The beneficial effects of seed priming could be modified by light quality during treatment. When seeds of endive were primed in KNO_3 solution under continuous red light, they had a greater germination percentage and more uniform germination than seeds primed in the dark [43]. However, seed priming in K_3PO_4 solution improved germination of 'Valmaine' lettuce at high temperature regardless of light conditions.

iii. *Duration of the priming process*

The ideal duration of the priming process varies according to the type of osmoticum, osmotic potential of the solution, temperature during the treatment and species. If radicle protrusion occurs during seed priming, irreversible embryo damage could be expected during dehydration after priming.

iv. *Temperature*

Duration of seed priming depends on the species and seed quality. However, temperature during treatment and osmotic potential of the solution affect the length of the soaking period. If the soak temperature is maintained below the optimum range for rapid germination, radicle growth during priming could be restricted. The temperature during treatment also appears to be related to the type and concentration of osmotic and length of the treatment period.

v. *Osmotic potential*

Osmotic potential of the solution is another factor affecting the length and effectiveness of the priming period. Seed priming in high osmotic potential solutions may allow rapid seed germination and radicle growth because seed water content becomes too great. Decreasing the osmotic potential from -0.5 to -1.0 MPa prevented the germination of carrot seeds in the priming solution [44] suggesting that a small change in the osmotic potential of the solution may affect the effectiveness of the treatment.

vi. *Seed quality*

A differential response to seed priming among seed lots of the same species has been reported by numerous authors [25, 45]. Perkins-Veazie and Cantliffe [46] demonstrated that seed vigour is another factor influencing the response to seed priming. They reported that priming did not alleviate thermo dormancy of artificially aged seeds of 'Great lakes' and 'Montello' lettuce, but was effective for non aged seeds.

vii. *Dehydration after priming*

To achieve the maximum potential of priming, strict control of all the factors previously discussed is required. However, following priming, dehydration and subsequent seed storage become crucial components for the commercial application of this technology. To facilitate handling and storage, the seeds should be

dried to an acceptable moisture level for long term storage after the priming treatment. Water uptake during priming is influenced by the osmotic potential of the solution, type of osmoticum, duration of treatment and the physical and chemical characteristics of the seeds. Thus, dehydration after priming may involve removal of a large quantity of moisture from the seed.

viii. *Seed Storage*

After seed priming and dehydration, seeds are usually stored before planting. The conditions and duration of storage may alter the advantages achieved from priming. An interaction between the osmotic used during treatment and the ability of the seed to store well has been reported. Seeds of tomato primed in KNO_3 solution had a lower capacity to tolerate high-temperature storage (30^{0}C) than seeds primed in PEG solution [24]. The effects of storage conditions after priming have been studied; however, more information about seed dehydration conditions after priming and their potential effects on seed behavior are required.

I.b. Molecular and physiological aspects of seed priming

The physiological and biochemical effects of seed priming during or after the treatment are not understood completely. Several reports related seed priming treatment to changes in nucleic acids. In a pioneer report, it was demonstrated that synthesis of RNA, proteins and low levels of DNA occurred as a normal germination process during hydration of rye embryos [47]. However, they observed that numerous metabolites were stable after dehydration and accounted for the ability of the embryo to synthesize proteins and RNAs rapidly after rehydration. Coolbear and Gierson [48] concluded that high levels of nucleic acids in primed tomato seeds may account for their rapid germination. They observed that increase in nucleic acid amount was due to rRNA synthesis during and after priming treatment.

Physiological studies have indicated increased rates of metabolic processes involved in germination when primed seeds are rehydrated. After rehydration, respiration and ATP production were higher in primed seeds of spinach, kohlrabi, pepper and eggplant than in non primed seeds [49]. Dehydration of primed seeds reduced ATP levels, but not below those of non- primed seeds. It is apparent that seed priming initiates germination potentially up to the point of cell division. After dehydration and subsequent re-imbibition, germination process resumes essentially where they were stopped.

The effects of priming are then evidenced as rapid radicle growth and seedling emergence. The ability of the seed to germinate and emerge under stressful environmental conditions probably is the result of bringing the germination processes of the seed to the brink of radicle protrusion, thus negating the effects of stress on germination.

I.c. Effect of seed priming on seedling growth and development

Seed priming treatments modify embryonic axis growth and subsequent seedling development. The response varies according to the species and priming conditions. Embryo volume and cell number per embryo of leek and onion were not modified by priming [50]. In the same experiment and under the same conditions, the carrot embryo volume increased almost 50% and the number increased by twofold. Progressive rupture of the endosperm after 9h of priming was one of the potential factors leading to increased germination of 'Minetto' lettuce seeds at high temperature [51].

The differences in root and shoot growth between primed seeds and non primed seeds is more evident under stressful conditions. Root growth from perennial ryegrass seeds germinated at low temperature ($5^0 - 15^0$) was greater in primed seeds than in non-primed seeds, but no differences were observed at 25°C [52]. Shoot dry weight was higher for primed tomato seeds germinated at stressful temperature conditions than for non-primed seeds [53]. Generally, the major effects of seed priming on growth has been observed as earlier and more uniform emergence and not accelerated growth, *per se*, of the species.

I.d. Effect of seed priming on yield and harvest quality

Synchronization and rapid seed emergence are the commonly reported benefits of seed priming. Particular advantages of seed priming are augmented under adverse conditions [54]. However, the effects of priming on yield and plant quality characters were more elusive. Seed priming promoted early growth of egg plant, pepper, cucumber and muskmelon plants, but no differences were detected in early and final yield, fruit size between primed and non-primed seeds [55]. Early seedling growth of tomato was improved by seed priming, but priming increased markedly yield only under more stressful conditions [55]. Beneficial effects of priming on yield and quality in a similar fashion to seedling growth and development have been reported only in crops growing under stressful environmental conditions.

II. Seed pelleting

Seed pelleting is the process of adding inert materials to change seed size and shape for improved plantability [56]. These enhancements improve the performance of planter by making seeds rounder or larger and can be used as a carrier for various seed additives such as nutrients, growth regulators and crop protection materials. Pellets are made to precise size tolerances and are very useful in combination with precision seeding equipments. Therefore, singulation of seed in the field is easier. For crops like onion, precise seed placement is of great advantage as uniform bulb development is assured with equal distance planting. There are two components to a seed pellet: bulking (or coating) material and binder. The bulking material can be either a mixture of several different mineral and/or organic substances or a single component. The coating material is the "work-horse" of the duet. The coating material changes the size, shape and weight of the seed. Desirable characteristics of a good coating material include: uniformity of particle size distribution, availability of material and lack of phytotoxicity. The second component, the binder, holds the coating material together. The concentration of binder is critical because too much binder will delay germination and too little binder will cause chipping and cracking of pellets in the planter box, which can cause skips and/or wide gaps in the plant rows. Many different compounds have been used as binders such as various starches, sugars, gum arabic, clay, cellulose, vinyl polymers and even water.

Seeds for pelleting are first placed in revolving pans or drums of various designs and sizes and blends of powdered materials, hydrophilic or hydrophobic additives and binders are progressively added in a layering process along with water until the desired seed pellet weight or size increase is achieved. The wet coated seeds are then dried with heated air in a separate step. Although automated for some species and products, many pelleting processes involve skilled manual inputs. Batch size can range from about 250 g up to 100 kg of seed per batch. Seeds of various sizes are commercially pelleted, from relatively large seeds like onion and tomato to very small seeds like *Begonia* sp. In summary, chemical loading of pellet provides a means to treat the seed directly. When possible, application of active

ingredients to the seed is considered better than other applications such as in-furrow, foliar or broadcast because of precise placement on the target, minimum toxicant used minimum environmental impact and minimum wildlife and beneficial organism exposure.

The tumbling action of seeds, water and the pelleting materials distributes and uniformly moulds the mixture to the desired size distribution. Tumbling in the rotating pans or drums also minimizes the formation of empty pellets, or seeds/pellets sticking together. If desired, special techniques can be employed to create multi-seeded pellets. Seed pelleting protocols can be designed to increase seed weight by about 2-fold up to 50-fold or more (in tobacco seed pellets, for example). This compares to increases of only 0.1 to 2X for coatings or encrusting and less than 0.1X weight increase with film coating. For onion, the seed can increase in weight 6-fold due to pelleting; there are approximately 230 raw seed per gram, and after pelleting the diameter may be 13.5/64th of an inch (0.54cm). The volume for 1000 propagules is 3.7 cm^3 for raw seed compared to 18.0 cm^3 after pelleting. As the demand for pelleted seeds increased, so did the number of companies producing pelleted seeds. Increased competition in the pelleted seed market has fostered the development of more effective pellets with greater capabilities and wider planting characteristics. Pellet improvements over the last 15 years includes; increased oxygen penetration/availability, wider pellet density range, pellet loading and better field visibility. It was reported that the seeds pelleted with *Albizia amara* leaf powder + DAP + Micro nutrient mixture + *Azospirillum* improved the seed yield and quality [57].

III. Encrusting/Minipelleting

Seed encrusting is similar to coating wherein, it usually doesn't change the shape of the seed much, but add quite a bit of weight to the seed. This may be the best way to maximize planters' ability to precisely place each seed in the row [58]. Encrusted seed can usually be planted at a faster tractor speed than a light density seed without encrustment. It not only add weight to the seed, but also fill in the relatively large depressions in the seed, making a smoother seed surface which is more easily handled by most planters. The result is usually more evenly spaced plants, with less skips and doubles.

IV. Coating/Encapsulation

Coating has gained popularity as a seed-coating method over the last several years, because of worker safety considerations. Film coating is often used on seed species that do not require pelleting (e.g. *Brassica* sp.) for precision planting, but the seed requires some encapsulation due to plant protectant application [59]. Encapsulation of plant protectants by film-coating ensures the uniformity of application and is superior to slurry application. Once plant protectants are sealed to the seed, dispersal to the environment prior to planting is minimized. All the dosages originally applied to the seed will be available against the pests in the target environment and workers exposure to harmful dusts are minimized. Other advantages of film coating include; increased flowability in the planter caused by better "slippage" between individual seeds, increased visibility of seed in the soil and seed treatment identification by using different colorants. There are some disadvantages of film coating as well *viz.* plant protectants that inhibit germination may not be used because of inadequate separation between the seed and the active chemical; seed size and shape and weight are not altered sufficiently to make a dramatic difference in plantability; and polymers and plasticizers in the film coating may be toxic or inhibitory to the seed species, seeds of different species can have different sensitivities to the same film coating chemical. It was reported that the seed coating improved stand establishment in rice [60].

Many of the advanced film coating seed products rely on the sprouted bed and side-vented pan coater systems to maximize the advantages. Typical seed capacities in these devices range from less than 1 kg up to 25 kg and 250 kg of seed. Film coating is also widely used to apply insecticides, fungicides and pigments to dry pelleted seed.

For more advanced pelleting and coating options, enhancement modifications allow tailored performance to fit the season of crop production. Lettuce seed pellets, for example, can be modified to rapidly disintegrate or split in two to expose the seed to adequate soil oxygen after initial water uptake. Water attracting materials added to seed coats and pellets can aid in imbibition and seed soil contact under low water conditions. Temperature-sensitive polymers and oxygen-generating materials can also be added to seed coats/pellets for better seed performance in specific cropping systems or environments.

C. Recent approaches

I. *Drying*

Seed storage can be a major problem because the majority of the world's poor countries are located in the tropics, where the combination of high temperature and relative humidity causes rapid deterioration of seed quality. In India, seeds harvested before or during the monsoon season need to be dried and stored until the next planting season. Seeds absorb water from the ambient air when they are stored in humid environments and lose water when stored at low relative humidity. Generally speaking, seed longevity is reduced by approximately half for every 1% increase in seed moisture content (water content as a percent of fresh weight) or 5°C increase in temperature, and the effects are additive [2]. Because of this fact, 'seed moisture content' has been included as one of the essential components of seed quality under Indian Minimum Seed Certification Standards (IMSCS). The principle implies that seed storage life can be enhanced considerably by lowering both moisture and temperature. Under conditions of high atmospheric relative humidity (RH), bringing down the moisture content (MC) of the seed to the required level is difficult even by prolonged sun drying in high humidity areas. So, the use of forced heated and dehumidified air through layers of seeds (Bin drying/Batch drying) is recommended. However, the temperature of the air needs to be controlled precisely, so that it is below the threshold and does not turn out deleterious to seeds. Moreover, rapid drying for bringing the seed MC to 3-5% in a limited period of time is a difficult task in sub-tropical conditions like India. Moreover, the problem of resources and particularly the power supply is a big constraint to reduce the seed moisture content to the levels low enough to assure long-term viability.

These problems can be overcome by drying seeds to low moisture contents (even to below 5%) in a comparatively short time by using inexpensive hermetic containers and zeolite drying beads, a recently developed desiccant technology. These drying beads have pore spaces of 1A°, which selectively absorbs only water molecules from the atmosphere and hence reduces the RH without raising the temperature. For this, drying beads and seeds are kept together in an airtight container and left for a pre-determined period of time, depending on the required seed MC to be attained. As the drying beads (DB) create a negative water potential inside the container, the hygroscopic seeds lose moisture till it reaches equilibrium moisture content (EMC) and attains the required MC. Using drying beads, seeds can be quickly and efficiently dried to safe storage moisture contents and storing seeds in hermetic containers not only maintains low moisture contents also prevents losses to rodents, insects and molds. The drying beads have advantage that it can be recharged,

reused and could attain the required MC in humid climates. The chemically inert dry beads offers enormous potential in making seed drying effective and economical [61]. In addition, the beads can also be used to dry herbs, vegetables, fruits, nuts, medicinal plants, or other horticultural products.

II. *Seed separation by Color*

It is the practice of providing an exogenous colour coating to the seeds in order to improve its marketability, brand identity and help farmers in easy identification of crops. Earlier, seed colouring was considered as 'unrealistic and uneconomical'. However, colouring of seeds along with pelleting or film coating has been adopted by private companies in the United States, Canada and Europe as these enable the seeds to be sown in defined patterns as well as modification of germination in many crops. Seed colouring has various merits; enable brand identification of the selling company, prevent inadvertent mixing of high value seeds with other seeds of the same crop, facilitate addition of desirable ingredients along with colouring so as to offer protection to the seeds, helps to seal the cracks on seed coat and improves the physical appearance of the seeds, provide smooth and even surface for easy sowing or planting, provides a distinct and attractive look to the seed, thus enhancing the market value and promotes environmental safety as well as workers' safety in the field.

Rapid discoloration and micro-organism contamination during production and storage is the main cause of seed discoloration. The color sorter uses an electronic eye that can pick up different colors according to the way the machine is adjusted. As seed falls down a shoot, it passes through the electric eye. If the color of the seed is different than the desired color, the electric eye will activate a sudden burst of air that pushes that seed into a reject bin while the rest of the seed passes through to another bin. This technique was successfully used for separation of quality seeds of anardana [61].

Both natural and synthetic dyes are used for colouring seeds. The seeds of tomato when coated with fresh extracts of different plant dyes improve the physical appearance and make them attractive. When fresh extracts were applied on tomato seeds, the seeds turned out to be a lump. However, singling of seeds was not so difficult when they are shade or sun dried. The colour produced was attractive and seeds were uniform and smooth. The colors produced by different plant dyes were identified using the Munsell colour chart. The identified active principle for seed colouring and pH of the dye solutions have been furnished in Table 1. The seed colouring with natural dyes from botanicals did not influence the speed of germination, shoot length, root length and vigour index. Seed colouring with turmeric rhizome powder excelled over other botanical dyes tested in this study. From this, it could be deduced that seed colouring with chemical dyes did not improve the germination, but increased the shoot length, root length and vigour index. Seed colouring with Bromocresol green, Pink CM and congo red at 0.5 percent concentration was found to enhance the seedling growth and vigour. However, direct chenbaga and Turquoise blue were found to be detrimental to seed quality.

Tomato seeds when colored with different synthetic chemical dyes make the seed very attractive. Unlike the plant dyes, seed colouring with synthetic dyes did not result in lumping of seeds. The seeds were found to be uniform and smooth when dyes were applied. However, seed colouring with different concentrations of copper sulphate produce abnormal seedlings and hence this treatment was discontinued. The colors produced by the different synthetic chemical dyes were identified using the Munsell colour chart. The identified pH of the dyes solutions have been furnished in Table 2.

Table 1. Botanical dyes and their properties

Botanical Dyes	Colour appearance after seed treatment	Active principle	pH
Annatto	Dawn glow	Bixin	4.35
Basella	Leaf brown	Not known	5.20
Beetroot	Teak	Betanin	6.20
Henna	Sandstone	Not known	4.30
Hibiscus	Sandstone	Cyaniding diglycoside	5.49
Jamun (with seed)	Sandstone	Jamboline	6.75
Jamun (without seed)	Brandy	Jamboline	6.75
Marigold	Golden brown	Alpha terthienyl	4.35
Opuntia	Red	Not known	3.00
Turmeric	Lemon yellow	Curcumin	2.88

Table 2. Synthetic dyes and their properties

Synthetic chemical dyes	Colour appearance after seed treatment	pH
Bromocresol green	Bus green	10.15
Congo red	Red	10.25
Direct chenbaga	Golden brown	9.36
Jade green	Deep green	9.93
Pink CM	Rose	9.99
Sky blue	Phiroza	9.38
Turquoise Blue	Azure blue	7.87

III. *Seed separation by chlorophyll fluorescence*

Harvesting seed that is totally and uniformly mature is quite rare. The seeds within a lot that have not reached full maturity will most likely be less vigorous and with impaired germination capabilities. Many times these fully developed but not quite mature seeds are impossible to separate using normal density, size or shape separations. Chlorophyll fluorescence (CF) measures the amount of green chlorophyll present in each seed. The more the amount of chlorophyll in the seed, the more immature and less vigorous will be the seed [10]. Commercial separation would occur much like a normal color sorter, with the seed individually passing through a chlorophyll sensing beam of light. When the seed chlorophyll levels are too high, a burst of air would separate the immature seed from the rest. The prototypes are currently being developed for commercial application.

IV. *Seed separation by near-infrared (NIR)*

Near-infrared light shoots through the seed and gives off a signal that is linked to the internal components of the seed, which are related to seed vigour and germination [62]. So, we can separate low vigour and dead seed according to the type of NIR signal that is given off. In addition, seed that is contaminated with fungal pathogens will give

off a unique NIR signal and can be used to separate seed with fungal contamination. NIR signals have also been used to separate hybrid watermelon seed from inbred seed and as a method to determine the length of time needed to primed seed for optimal results. This technology is currently available to the seed and its industry commercial utility is being explored.

V. *Molecular impulse response (MIR)*

Biochemical reactions in the seed may not go as smoothly as desired when the seed is planted under abiotic stress environments like heat, drought or flooding. Under stress, the cell may produce "free radicals" that are electrically charged in a way that enables them to pull apart or breakdown compounds that are needed for normal plant growth. Higher the activity of free radicals, higher the damage caused to the seeds. MIR is a process in which seed is placed between an anode and a cathode. However, there is no flashy electrical arc, and in fact, the current is usually only a fraction of a micro-amp (a very, very small amount of electricity). This small amount of electricity does travel from one electrode to the other going through the seed [63]. The inventors of this process claim that doing this at the correct electrical strength and for the correct amount of time will set into motion reactions inside the seed that result in the production of anti-oxidants, which deactivate those harmful free radicals that want to break things down in the seed and plant. The MIR treatment only puts in motion the reactions needed to produce anti-oxidants. The seed needs to be kept for about 30 days after the treatment for these reactions to be complete enough to obtain noticeably improved seed performance, especially under stress conditions.

VI. *Genes switches*

Genes contain the "instructions" that determine the structure and function of all living tissues. Each gene or combinations of genes produce proteins that form tissues, which carry out these specific functions. Not all genes continuously produce their proteins. Promoters can enhance the production of certain proteins, and promoters can be programmed to promote protein production by regulator genes at a particular time Regulator genes, in their most simplistic form, may be thought of as gene switches that can turn genes 'on' and 'off', and in some cases, turn genes 'on' and 'off' by external stimuli [64-65].

VII. *Systemic acquired resistance (SAR)*

When a pathogen attacks a plant, the plant reacts to survive against it. Gene switches are turned 'on' to produce proteins that in some way help the plant to defend itself against the attack. In other words, the plant turns on a defense mechanism. When a plant turns on its defense mechanism in every part of the plant in response to a chemical or pathogen, it's known as a systemic acquired resistance by the plant or SAR. There are several commercial chemical sprays that will turn 'on' genes in a plant, producing a systemic acquired resistance to disease. One of these chemicals is a product put out by syngenta crop protection called 'Actigard'. Actigard does not directly affect disease causing organisms; it only activates defense mechanisms in the plant that can help to resist attack by these organisms.

VIII. *Induced systemic resistance (ISR)*

When plant defense mechanisms are induced by a microorganism that does not cause disease, it is referred to an induced systemic resistance or ISR. Bayer crop science puts out an ISR seed treatment called 'Yield Shield'. Yield Shield is a bacterial seed treatment (*Bacillus pumilus* GB34) that, again, does not directly attack disease causing organisms. It turns on gene switches in the plant, which provides stimuli for initiating plants defense mechanisms, and helps the plants to resist the attack.

IX. *Adding modifier genes*

Generally speaking the problem for corn growers is that, the better the eating quality of the corn; the harder it is to grow in the field conditions. Hence, the discovery of a naturally occurring mutation of dent corn that happened to produce kernels consisting mostly of sugar, rather than starch changed the expectations of all who like to eat corn with their meal. There are genes called "modifier genes" that can be added to each sweet corn type to improve eating quality. The addition of these "modifier genes" and whether one or both of the parents have the best eating quality traits are two ways to develop distinct varieties within each sweet corn type. Seed physiologists are also working on the application of "artificial seed coat" to help solve the problem of plantability and stand establishment of some of the high quality sweet corn varieties.

D. Harvesting the benefits of seed enhancement

Priming has also been shown to change the development of free space in tomato seeds. Dehydration prior to seed priming is required for this phenomenon to occur. The increased percentage of free space in primed tomato seeds may speed up germination by reducing endosperm restraint to radicle emergence or by facilitating water uptake and availability. Drying followed by priming can be accomplished using forced air, ambient conditions or controlled atmosphere of specific relative humidity. The drying methods and rates of drying are important to subsequent seed performance. Slow drying at moderate temperatures is generally preferred. Controlled seed moisture loss after priming can extend longevity by 10% or more in studies with hydroprimed tomato seed lots. Heat shock treatments are also used to improve the longevity of primed seeds. The benefits of seed priming can also be combined with enhanced germination effects from plant growth regulators or hormones, especially gibberellins and ethylene. Seed treatments or priming with growth retardants such as paclobutrazol, a GA inhibitor, can effectively dwarf the bedding plant transplants, producing stocky and high-quality seedlings. The treated seedlings are also greener, more uniform with thicker stems and have a higher root: shoot ratio compared to control.

Seed fortification with Zn, Mo and Mn significantly increased the field emergence in black gram and cowpea [66]. The enrichment of cowpea seeds with zinc and manganese sulphate and sodium molybdate along with DAP increased seed yield by 25%. Similarly, fortification of wheat seed with a mixture of 1 g each of KH_2PO_4, Urea and ammonium nitrate/100 g seed gave higher grain yield than seeds without fortification. Seed fortification also increased grain N and P contents [67-68]. In maize seeds, fortification with IAA and ascorbic acid increased dry matter accumulation and leaf area [68]. Seed treatment with phosphon-D (chlorphonium) increased the hypocotyl and radicle growth during germination under moisture stress conditions in Indian mustard [31]. Seed treatment with GA_3, NAA or IAA for 14 h improved germination of onion seeds [30]. Amongst various fortification techniques employed, seeds of okra treated with 50 ppm GA_3 produced highest germination, seedling establishment, total dry matter, harvest index and fruit yield [69]. Hydropriming followed by seed treatment with fungicide captan improved field emergence and crop performance in the parental lines (CM-135 and CM-136) of Pusa hybrid Makka-1 [70].

CONCLUSION

Delivering improved seeds to smallholder farmers in the developing world is an efficient and sustainable method of increasing crop yields and quality. Unlike fertilizers, pesticides and equipment, seeds can be produced locally for distribution to the farmers or self-saved. Furthermore, improved varieties of horticultural crops often reduce

dependence on synthetic pesticides, ensure food safety, reduce pre and post-harvest losses and fetch higher prices in the market. However, the benefits that developing world farmers accrue from improved varieties may depend on their local systems for seed drying and storage. Without proper storage conditions, seeds can rapidly lose viability, resulting in poor crop establishment, lack of uniformity, reduced yields and poor marketability. Farmers' experience, with poor seed performance lowers their incentive to invest in genetically improved seeds and systematic development of breeding and seed marketing systems for more productive horticultural varieties. On the other hand, farmer confidence in the quality of purchased seeds and in their ability to store them safely will strengthen local seed markets and increase yields and incomes. Assured plant stand is must for secured production and seed enhancement is an important aspect of modern agriculture for boosting crop yields. The positive effect of such enhancements could be observed on seedling vigour [71] that may enable the seeds to overcome stresses and can be recommended as a pre-sowing treatment.

Seed priming has been successfully employed for many crops and species where rapid, uniform and complete seedling emergence is essential. The benefits of seed priming have been well documented in various review articles [15, 29]. However, practical drawback in many species is that primed seeds can often suffer from more rapid deterioration under normal storage conditions. In summary, developing a priming protocol must address the balance between germination advancement and reduced longevity. Post treatment drying and shelf-life problems should be tackled to ensure consistent performance over a wide range of storage conditions. This warrants increased attention to drying protocols after priming and storing primed seeds in conditions where °F + % RH is equal to or less than 80 will decrease storage concerns. The drying beads offer a great potential to address storage concerns [61]. Priming protocols are required to be combined with enhanced screening with removal of weak or dead seeds to achieve near perfect seedling establishment targets. The attempts to attain the most rapid germination must be weighed against the enhanced liability of this pre-sowing treatment. Hydropriming has the economic advantage of minimal waste materials being generated as compared to osmopriming and matrix priming methods. A disadvantage of hydropriming is that seeds are sometimes not evenly hydrated which decreases the potential for uniform germination. Linking the phases of water uptake in germinating seeds and associated physiological events to priming protocols is essential for success during the priming process [72]. Controlled hydration and solid particulate systems is a convenient tool to hydrate seeds fairly precisely to a desired level from their initial seed moisture content to full imbibition. Since priming often leads to improved seed performance, it is suggested that priming reverses some of the detrimental events occurring during seed deterioration. As seeds deteriorate, a cascade of disorganization steps occurs, which ultimately leads to a complete loss of cell function. The rapid initial water uptake of phase I occurs at the time of DNA and mitochondrial repair plus protein synthesis using existing mRNA's. Seed water content increases slightly during phase II, while new processes, synthesis of mitochondria, creation of proteins from new mRNA's, completion of DNA repair are still occurring. Thus, some proposed events associated with seed deterioration during storage and seed repair potential during seed hydration that occurs in imbibition or priming require detailed and in-depth studies not only on cellular events associated with hydration, but also on dehydration phenomenon. Physiological, biochemical and biophysical markers are needed to detect seed

quality. The identification of markers for optimal priming and mystery of successful priming mechanism is yet to be solved! The success of these technologies is variable and dependent on several factors and hence suitable methodologies with respect to chemical, duration, crop etc. needs to be standardized. These markers would have practical application in quality control programmes, as tools to develop and monitor hydration events and possibly for up-gradation of seed quality.

Coatings will continue to be an important delivery system for materials required at the time of sowing. Seed coating is capable of offering a unique opportunity to use lesser amounts of plant protectants, chemical and/or biological in a way that may be more effective, economical and ecologically safer. In future, a more deliberated attempt needs to be made to resolve the complexity involved in seed coating research by developing sound principles on which to build a model of seed coatings and their interactions. Seed coating should be developed as a management tool to be an integral component to enhance seedling establishment under a wide range of environmental conditions. Limited research has been performed on the addition of hydrophobic polymers for sowing into wet soils [16], hydrophilic compounds for sowing into dry soils and temperature sensitive coatings to regulate the onset of imbibitions at a desired soil temperature [73]. Hence, specific polymer formulations are required to broaden the range of environmental conditions in which a desired stand may be established. Thus, coating improves the chances of successful germination and seedling establishment under field conditions. Moisture and temperature are the two most critical factors that control the seed deterioration process during storage. The technologies like cold plasma coating (CPC) are still in its infancy stage, wherein the seeds could be coated with different (hydrophobic/ hydrophilic) gaseous polymers under high energy and low temperature. Under such conditions, the gases attain the plasma state and get coated on the seed surface. Application of this technology has been shown to control the speed of germination in maize and soybean. However more in-depth studies are needed before commercially application of this technology for seed quality enhancement.

Seed enhancement technology is a tool to improve the efficiency of crop production, which can help in attaining food security. Conceptually, the future seems of seed enhancement technologies seem to be bright as witnessed by the above discussion. The acceptance of these new technologies will depend on how a seed perform in the field but the bottom line may just be that there will be continued interest because of the potential time saving. There are powerful methods for improving the quality and performance of seeds that can be explored, developed and exploited after the production, maintenance and conditioning procedures are exhausted. A multi-disciplinary effort from chemical and mechanical engineers, chemists, agronomists, soil scientists and biologists could combined to reduce some of the biological complexities involve in these technologies. In brief, we may say that the technologies listed are amongst the few that are indispensable in preventing major crop losses. Last but not the least, we may conclude that the day is not very far when application of above listed approaches would capture the seed industry, benefiting humanity in general and farmers in particular for attaining food security.

REFERENCES

1. CONFORTI P (2011). Looking Ahead in World Food and Agriculture. In Perspectives to 2050 (edn.) Food and Agriculture Organization of the United Nations, ISBN 978-92-5-106903-5.

2. HARRINGTON JF (1960). Thumb rules of drying seed. *Crops Soils* **13**: 16-7.

3. ROSENZWEIG C AND HILLEL D (1995). Potential Impacts of Climate Change on Agriculture and Food Supply. *Consequences* **1** (2): 1-12.

4. ANONYMOUS (1993). Association of Official Seed Analysts (AOSA). Seed Vigor Testing Handbook. Contribution No. 32 to the Handbook on Seed Testing. AOSA, Las Cruces, NM.

5. ISTA (2002). International Seed Testing Association (ISTA). International rules for seed testing. *Seed Sci Technol* (Suppl.) **37**: 54-9.

6. DUFF AA, PAULTER RE AND LOCH DS (2009). Rootzone amendments to improve soil moisture relations under newly laid sod. *TPI turf News* **33** (3): 42-5.

7. JHURRY D (1997). Agricultural Polymers. In AMAS: Food and Agricultural Research Council, Réduit, Mauritius, pp: 109-13.

8. VANCE CP (2001). Symbiotic Nitrogen Fixation and Phosphorus Acquisition. Plant Nutrition in a World of Declining Renewable Resources. *Pl Physiol* **127** (2): 390-7.

9. KUBIK K (2009). Odd but true seed enhancement techniques. In communication: Harris Moran Seed Company, Davis, USA.

10. JALINK H, VAN DER SCHOOR R, FRANDAS A, VAN PIJLEN JG AND BINO RJ (1998). Chlorophyll fluorescence of *Brassica oleracea* seeds as a non-destructive marker for seed maturity and seed performance. *Seed Sci Res* **8**: 437-43.

11. SINGH BB, EHLERS JD, SHARMA B AND FREIRE-FILHO FR (2002). Recent progress in cowpea breeding. In Proceedings, World Cowpea Conference III, Challenges and opportunities for enhancing sustainable cowpea production, IITA, Ibadan, Nigeria, pp. 22-40.

12. SINGH SP, KHANNA BM, DODAN DS, BAGGA PS, KALAPPANAVAR IK AND SINGH A (2002). Losses caused due to leaf blight in wheat in different agro climatic zones of India. *Pl Dis Res* **17** (2): 313-7.

13. EDJE OT AND BURRIS JS (1971). Effects of soybean seed vigour on field performance. *Agron J* **63**: 536-8.

14. JOHNSON RR, AND WAX LM (1978). Relationship of soybean germination and vigour tests to field performance. *Agron J* **70**: 273-8.

15. TAYLOR AG AND HARMAN GE (1990). Concepts and Technologies of Selected Seed Treatments. *Annual Rev Phytopath* **28**: 321-39.

16. TAYLOR AG, ALLEN PS, BENNETT MA, BRADFORD KJ, BURRIS JS AND MISRA MK (1998). Seed enhancements. *Seed Sci Res* **8**: 245-56.

17. TAYLOR AG, MCCARTHY AM AND CHIRCO EM (1982). Density separation of seeds with hexane and chloroform. *J Seed Technol* **7** (1): 78-83.

18. HALMER P (2008). Seed technology and seed enhancement. *Acta Hort* **771**: 17-26.

19. LOPES JC, LIMA RV AND MACEDO CMP (2008). Annatto seeds germination at different maturation stadia. *Horti Bras* **26** (1): 19-25.

20. GURUSINGHE S, POWELL A, ANN LT AND BRADFORD KJ (2002). Enhanced Expression of BiP is Associated with Treatments that Extend Storage Longevity of Primed Tomato Seeds. *J Amer Soc Hort Sci* **127** (4): 528–34.

21. BENNETT M, FRITZ VA AND CALLAN NW (1992). Impact of seed treatments on crop stand establishment. *Hort Techol* **2**: 345-9.

22. KUMAR VK, RAVI H, BIRADAR PNK, VYAKARNHAL BS (2007). Effect of seed coating with polymer, fungicide and insecticide on seed quality in cotton

during storage. *Karnataka J Agri Sci* **20** (1): 137-9.

23. COPELAND LO AND MCDONALD MB (1995). Principles of Seed Science and Technology, 3rd edn. New York, Chapman and Hall.

24. BASU RN (1976). Physio-chemical control of seed deterioration. *Seed Res* **4**: 15-23.

25. HEYDECKER W AND COOLBEAR P (1977). Seed treatments for improved performance, survey and attempted prognosis. *Seed Sci Technol* **5:** 353-425.

26. BRADFORD KJ (2004). Seed technology and enhancement. In: Seed production and quality. pp. 112–117.

27. ALVARADO, AD AND BRADFORD KJ (1988). Priming and storage of tomato (*Lycopersicon esculentum*) seeds. 1. Effects of storage temperature on germinate rate and viability. *Seed Sci Technol* **16**: 601-12.

28. FRETT JJ, PILL WG AND MORNEAU DC (1991). A comparison of priming agents for tomato and asparagus seeds. *Hort Sci* **26**: 1158-9.

29. PASSAM HC, LAMBROPOULOS E AND KHAN EM (1997). Pepper seed longevity following production under high ambient temperature. *Seed Sci Technol* **25**: 177-85.

30. KHAN AA (1992). Pre plant physiological seed conditioning. In: Janick J. (edn). *Hort Rev* **13**: 131-81.

31. KATHALE CN, DESHMUKH AR AND DESHPANDE VB (1974). Effect of seed treatment with plant growth regulators on growth and yield on Onion (*Allium cepa* L.). *Magazine, College of Agriculture – Nagpur* **47**: 59-63.

32. SHEORAN IS AND KHAN MI (1987). Induction of drought tolerance in Indian mustard during germination by pre-sowing seed treatment with growth regulators. *Indian J Agril Sci* **57**: 54-6.

33. BHATTACHARJEE A AND BHATTACHARYA RN (1989). Prolongation of seed viability of *Oryza sativa* L. cultivar Ratna by dikegulac sodium. *Seed Sci Technol* **17**: 309-16.

34. RAI AS, CHHETRI DR AND BHATTACHARJEE A (1995). Influence of sodium–dikegulac on storage potential of selected seed species. *Seed Sci Technol* **23**: 249-52.

35. TAYLOR AG, KLEIN DE AND WHITLOW TH (1988). SMP: Solid matrix priming, *Scientia Horti* **37**: 1-11.

36. MCDONALD MB (2000). Seed priming. In: Black M, Bewley JD (edn.) Seed Technology and Its Biological Basis. Sheffield Academic Press, Sheffield, England pp. 287-325.

37. ROWSE HR (1996). Drum priming- a non-priming osmotic method of priming seeds. *Seed Sci Technol* **24**: 281-94.

38. RAO MSL, KULKARNI S, LINGARAJU S AND NADAF HL (2009). Bio-priming of seeds: a potential tool in the integrated management of Alternaria blight of sunflower. *HELIA* **32** (50): 107-14.

39. FAROOQ M, BASRA SMA AND AHMAD N (2005). Rice seed priming. *IRRN* **30** (2): 45-8.

40. CAPRON I, CORBINEAU F, DACHER F, JOB J, COME D AND JOB D (2000). Sugar beet seed priming: effects of priming conditions on germination, solubilization of 11-S globulin and accumulation of LEA proteins. *Seed Sci Res* **10**: 243-54.

41. HEYDECKER W (1975). Seed Priming - The Treatment of Future? *Grower* **27**: 554-5.

42. GUEDES AC AND CANTLIFFE DJ (1980). Germination of lettuce seeds at high temperature after seed priming. *J Amer Soc Hort Sci* **105**: 777-81.

43. BEKENDAM J, VAN PIJLEN JG AND KRAAK HL (1987). The effect of priming on the rate and uniformity of germination of endive seed. *Acta Hort* **215**: 209-18.

44. ELBALLA MM (1987). Control of growth regulators and temperatures on seed stalk development, seed yield and seed quality in carrots (*Daucus carota* L.), Ph.D. Diss *Univ of Florida, Gainesville.*

45. BRADFORD KJ, STEINER JJ AND TRAWATHA SE (1990). Seed priming influence on germination and emergence of pepper seed lots. *Crop Sci* **30**: 718-21.

46. PERKINS-VEAZIE P AND CANTLIFFE DJ (1984). Need for high-quality seed for effective priming to overcome thermo dormancy in Lettuce. J *Amer Soc Hort Sci* **109**: 368-72.

47. SEN S AND OSBORNE DJ (1974). Germination of rye embryos following hydration-dehydration treatments: enhancement of protein and RNA synthesis and earlier induction of DNA replication. *Exptl Bot* **25**: 1010-9.

48. COOLBEAR P AND GRIERSON D (1979). Studies on the change in the major nucleic acid components of tomato seeds (*Lycopersicon esculentum* Mill.) Resulting from osmotic presowing treatment. *J Exptl Bot* **30**: 1153-62.

49. MAZOR L, PERL M AND NEGBI M (1984). Changes in some ATP-dependent activities during treatment with polyethylene glycol and during the redrying process. *J Exptl Bot* **35**: 1119-27.

50. GRAY D, STECKEL JR AND HANDS LJ (1990). Responses of vegetable seeds to controlled hydration. *Ann Bot* **66**: 227-35.

51. GUEDES AC AND CANTLIFFE DJ (1980). Germination of lettuce seeds at high temperature after seed priming. *J Am Soc Hort Sci* **105**: 777-81.

52. DANNEBERGER TK, MCDONALD MB JR, GERON CA, AND KUMARI P (1992). Rate of germination and seedling growth of perennial ryegrass seed following osmoconditioning. *Hort Sci* **27**: 28–30.

53. ODELL GB, CANTLIFFE DJ, BRYAN HH, AND STOFFELLA PJ (1992a). Stand establishment of fresh market tomatoes sown at high temperatures. *Hort Sci* **27**: 793-5.

54. KNYPL JS AND KHAN AA (1981). Osmoconditioning of soybean seeds to improve performance at suboptimal temperatures. *Agron J* **73** (1): 112-6.

55. PASSAM HC, KARAVITES PI, PAPANDREOU AA, THANOS CA AND GEORGHIOU K (1989). Osmo conditioning of seeds in relation to growth and fruit yield of aubergine, pepper, cucumber and melon in unheated greenhouse cultivation. *Scientia Hort* **38**: 207-16.

56. ASHRAF M AND FOOLAD MR (2005). Pre Sowing Seed Treatment—A Shotgun Approach to Improve Germination, Plant Growth, and Crop Yield Under Saline and Non Saline Conditions. *Adv Agron* **88**: 223–71.

57. RATHINAVEL K AND DHARMALINGAM C (1999). Effect of seed pelleting on elite seedling production in cotton cv. MLU-7 (*Grossypium hirsutum* L.). *Crop Res* **18** (1): 139-41.

58. HALMER P (1988). Technical and commercial aspects of seed pelleting and film-coating. Pages 191-204 in Application to Seeds and Soil, Mono. 39, BCPC, Thornton Health, UK.

59. JAMIESON G (2008). New perspectives on seed enhancement. *Acta Hort* **782**: 143-50.

60. HALMER P (1994). The development of quality seed treatments in commercial practice objectives and achievements. In

seed treatment: Progress and Prospects Mono. 57, BCPC, Thornton Health, UK. pp. 363-74.

61. JOHAN VA AND PATCHARIN T (2009). Fast field drying as a method to maintain quality, increase shelf life and prevent post harvest infections on Cucumis sativum L. *J Food Ag-Ind* (Spl Issue) **9**: 133-7.

62. PARASHAR A, GUPTA SK AND KUMAR A (2009). Studies on separation techniques of pomegranate seeds and their effect on quality of *Anardana*. *African J Biochem Res* **3** (10): 340-3.

63. DAVID L, PAZDERNIK A, KILLAM S AND JAMES H ORF (1997). Analysis Amino and Fatty Acid Composition in Soybean Seed, Using Near Infrared Reflectance Spectroscopy. *Agron J* **89**: 679-85.

64. ANONYMOUS (2000). Method and apparatus for enhancing growth characteristics of seeds using ion-electron avalanches. US Patent No. 6023880.

65. ALBERTS B, JOHNSON A AND LEWIS J (2002). How Genetic Switches Work. In Molecular Biology of the Cell. 4th edition: Garland Science.

66. VIJAYA A AND PONNUSWAMY AS (1999). Effect of seed fortification with micronutrients on seed quality in black gram and Cowpea. *Madras Agril J* **84**: 223-5.

67. BAPAT MV, KAMAT VN AND UMALE SR (1998). Effect of fortification of seeds with nutrients on the yield and quality of wheat. *Seed Farms* **4**: 12.

68. ESHANNA MR AND KULKARNI GR (1990). Effect of seed fortification with chemicals on the growth parameters of maize. *Seed Res* **18**: 7-10.

69. VIJAYARAGHAVAN H (1999). Effect of seed treatment with plant growth regulators on Bhendi (*Abelmoschus esculentus* L.) grown under sodic soil conditions. *Madras Agril J* **86**: 247-9.

70. MAHAJAN SS (2002). Pre-storage and pre-sowing treatments for enhancing the seed quality of parental lines of maize hybrid. Ph.D. Thesis submitted to IARI, New Delhi: pp. 156.

71. SMITH RS (1992). Legume inoculant formulation and application. *Can J Microbiol* **38** (6): 485-92.

72. GHOLAMI A, SHAHSAVANI S AND NEZARAT S (2009). The Effect of Plant Growth Promoting Rhizobacteria (PGPR) on Germination, Seedling Growth and Yield of Maize. *World Acad Sci Engg Technol* **49**: 19-24.

73. NI BR (1997). Seed coating, film coating and pelleting. In: Seed Industry and Agricultural Development, Chinese Association of Agricultural Sciences, DOA, Ministry of Agriculture, Beijing, China Agriculture Press, pp. 737-47.