Advances in Fluid Drilling

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Additional index words crop establishment, fluid sowing, gel seeding, plant growth regulators, seed germination, seed hydration, seed pregermination, seed priming

Summary. Seed treatments, gels, and planters associated with fluid drilling are reviewed in detail. The future of fluid drilling likely lies predominantly in the sowing of primed seeds rather than germinated seeds in the carrier gel. The primed seeds may be hydrated before fluid drilling to enhance germination and seedling emergence. The gel can carry a variety of chemical or biological additives appropriate for the crop and seedbed conditions. The positional advantage resulting from additive incorporation in the fluid-drilling gel represents a more efficient, cost-effective, and environmentally sound application method than others such as binding or spraying.

Efficient production of high yields of field-grown vegetable crops requires the rapid establishment of a full stand of seedlings. This goal often is not achieved, however, because of poor drill performance (e.g., seed damage, improper depth of planting), inadequate seed quality, and/or the difficulty of preparing and maintaining a good seedbed environment (Salter, 1985). Fluid drilling (also referred to as fluid sowing or gel seeding) is the sowing of seeds that have been germinated, using a gel to suspend and transfer them to the seedbed. This crop establishment technique has the potential to overcome some of the problems associated with conventional dry-seed sowing (Gray, 1981, 1984). Because seeds are

germinated under ideal conditions, the effects of the seedbed environment on this phase of crop establishment is avoided so that seedling emergence can be more rapid, more synchronous, and can reach higher levels than with conventional dry-seed sowing. Faster seedling emergence should lessen the likelihood of soil crust development or pathogen attack before the seedlings emerge. Comprehensive reviews of the historical background, technological development, and benefits of fluid drilling have been presented elsewhere (Gray, 1981, 1984; Salter, 1978).

The National Vegetable Research Station (now Horticulture Research International, Wellesbourne, U.K.) began research on fluid drilling in 1972. Researchers there developed techniques for germinating vegetable seeds in bulk, and then for coldstoring them. They also developed prototype fluid-drilling planters, and examined >50 possible carrier gels. This work established fluid drilling as an integrated system involving a) germination of seeds before sowing, b) separation of the germinated from the nongerminated seeds, c) storage of the germinated seeds, d) preparation of the gel for suspending the seeds, and e) drilling of the germinated seeds (Gray, 1981). Figures 1-4 show seed germinators, the mixing of seeds in gel, and germinated seeds (chits) suspended in gel.

Fluid drilling can give a) earlier, greater, and more-uniform seedling emergence; b) earlier and greater yields; and c) in some crops, more uniform maturity than conventional methods of sowing dry seeds, as summarized by Gray (1984). Some higher yields for fluid-drilled compared to dry-seeded crops include carrot (22%), celery (36%), parsley (107%), and tomato (12%) (Gray, 1984).

While usage statistics for fluid drilling are elusive, some examples include the production of early spring carrots in the United Kingdom, parsley and celery in Florida, celery in Wisconsin and Ohio, and tobacco in North Carolina. Some greenhouse operations sow pregerminated seeds into modular containers using a nursery seeder (Fluid Drilling Ltd., Stratford-on-Avon, Warwick, U.K.). This company has exported fluid drilling planters to 26 countries. During the past decade, however, the use of fluid drilling has declined so that, at

present, it is confined to a few niche situations in which the vegetable or other crop species are difficult to germinate, or in situations where earliness is a prime requirement. The reasons for the decline in commercial use of fluid drilling include a) increased use of either module-grown (plug) transplants or primed seeds with improved germination and seedling emergence; b) the need for specialized planting equipment, extra time, and equipment necessary to prepare the germinated seeds; and c) the variable responses achieved with fluid drilling of non-germinated and germinated seeds in a seed batch.

While its popularity has waned, much continues to be learned about fluid drilling. Fluid drilling in many forms for various crops under specific conditions will likely become useful for crop establishment. As more is learned about seed treatments, gels, and gel additives, seed-gel-seedbed interactions, and planting equipment in successful fluid-drilling systems, the use of fluid drilling will increase.

Seed treatments

Much of the variable response to fluid drilling can be attributed to the low proportion of germinated seeds in a seed batch at time of sowing (Finch-Savage, 1987). In fact, seedling emergence from a fluid-drilled crop can extend over a longer period than from one that is dry-seeded when only a small proportion of the seeds are germinated at the time of sowing, and when fluid drilling increases the emergence percentage of a seed lot. The proportion of germinated seeds at the time of fluid drilling was increased by

Fig. 1. Commercial seed germinator.

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Fig. 2. Seeds being germinated in an acrylic cylinder using temperature-controlled aerated water.

Fig. 3. Seeds, germinated or not, being mixed in gel.

Fig. 4. Germinated seeds (chits) suspended in fluid-drilling gel.

subjecting imbibed seeds to a cold treatment (1C for 6 to 12 days) before transfer to 20C for germination (Finch-Savage and Cox, 1982a). Separating germinated seeds from nongerminated seeds using a flotation technique based on density differences (Taylor and Kenny, 1985) likewise can increase the proportion of germinated seeds at time of fluid drilling. Seed leachate removal and inclusion of phthalimide growth regulator in the priming osmoticum increased the percentage of germinated carrot seeds to > 90% at time of fluid drilling (Pill and Finch-Savage, 1988). Synchronization of carrot seed germination

can also be achieved by soaking them in abscisic acid solution (Finch-Savage, 1989).

For very small seeds, such as petunia (Pill and Mucha, 1984) or tobacco (Csinos and Gbate, 1982), fluid drilling of pregerminated seeds increased the rate and percentage of seedling emergence. At least part of this beneficial response may be attributed to the gels keeping the seeds near the growth medium surface, preventing some of them from settling deeply, as can occur with conventional dry-seed sowing.

It must be possible to store germinated seeds for extended periods

with minimal radicle extension and without loss of viability if adverse weather or equipment failure prevents fluid drilling on a specific date. Germinated seeds can be stored in cold aerated water or in cold humid air (Finch-Savage, 1981), in plastic bags packaged either in vacuum or nitrogen at 7C (Gbate and Chinnam, 1987), or in cold hydroxyethyl cellulose fluid-drilling gels (Pill and Fieldhouse, 1982).

Germinated seeds react strongly with the seedbed environment (Finch-Savage, 1987; Finch-Savage and Pill, 1990). Seedbed conditions for germinated or germinating seeds that are fluid-drilled must be conducive to

continued seed growth because most germinated seeds become desiccation-intolerant (Finch-Savage, 1987). Pre-germinated seeds usually are transferred immediately from the ideal environment of the seed germinator to the more-adverse conditions of the seedbed. For example, fluid drilling of germinated seeds gave inferior stands of fall-harvested broccoli and cauliflower crops (Kahn and Motes, 1988, 1989) compared to conventional dry-sown seeds when air temperature at and following planting exceeded 30°C. The pregerminated seeds likely succumbed to heat and desiccation. Techniques to improve the hardiness of pregerminated seeds would be useful, particularly under harsh seedbed conditions.

Recent work showed that germinated seeds of *Brassica* spp. (Finch-Savage and McKee, 1990) that were dried under controlled conditions to 11% to 16% moisture could remain viable for prolonged periods. Since germination rate and subsequent seedling performance are correlated (Finch-Savage, 1986), pregerminated seeds selected for high vigor could be sown as dry pregerminated seeds or they could be rehydrated just before being fluid-drilled.

One successful approach to modification of the seedbed and fluid-drilling technique is that of gel mix in planting bell peppers in Florida (Schultheis et al., 1988a, 1988b). Pre-germinated seeds are mixed in peat-lite media containing a hydrophilic polymer. This gel mix then is planted at 60 ml/hill. The advantages of fluid drilling are enhanced by the peat-lite, which provides not only a high-moisture environment, but also anticrustant properties.

The future of fluid drilling in the field may rest primarily in the use of primed seeds, thereby avoiding the need to pregerminate seeds and assure a high proportion of germinated seeds at time of fluid drilling. Although asparagus seedling emergence rate and synchrony were significantly increased by fluid-drilling germinated seeds rather than primed seeds, this benefit was insufficiently great to warrant seed pregermination (Evans and Pill, 1989). Seedling emergence from primed parsley seeds was more rapid when the seeds were fluid-drilled than when they were dry-sown (Pill, 1986). Thus, priming and fluid drill-

ing should be considered as complementary processes. Seed priming and other preplant physiological seed conditioning treatments have been reviewed by Khan (1991).

Primed seeds are available as enhanced or invigorated seeds under a variety of trade names from numerous seed companies. Such seeds have been exposed to a low external water potential, enabling sufficient hydration for pregerminative physiological and biochemical activity but insufficient for protrusion of the radicle (Khan et al., 1978). Results obtained from priming different crops have been reviewed (Bradford, 1986). Seedling emergence from primed seeds compared to control seeds is generally earlier and more synchronous, especially with adverse seedbed conditions such as low temperature (Pill and Finch-Savage, 1988; Szafirowska et al., 1981), high temperature (Globerson and Feder, 1987), reduced water availability (Akers et al., 1987), or salinity (Wiebe and Muhyaddin, 1987).

Many variables affect germination responses to priming, including a) the seed species and seed lot; b) the duration, water potential, and temperature of the priming treatment; and c) the post-priming seed storage conditions. The agent inducing the low external water potential also can affect subsequent germinative response. The low external water potential can be induced either osmotically (with various inorganic salts or with high-molecular-weight organic compounds such as polyethylene glycol) or matrixally using solid matrices (Taylor et al., 1988). Solid Matrix Priming (SMP, Kamterter Products, Inc., Lincoln, Neb.) uses the physico-chemical characteristics of solid matrix materials to facilitate inhibitor removal and seed enhancement additions (chemicals and beneficial microorganisms) while priming. A drum-priming technique that involves controlled hydration of seeds using sophisticated machinery and controls was developed by Horticulture Research International. The British Technology Group has applied for a patent on the process.

Hydrating the primed seeds before fluid drilling (prehydration) may be accomplished by incorporating them in the gel for extended periods before sowing. However, the moisture content of the seed at drilling will be critical, because when radicle exten-

sion begins at the end of the lag phase of water uptake, water again is rapidly taken up for growth. As the radicle extends, the seeds progressively lose desiccation tolerance (Finch-Savage, 1990). Thus, as the seed moisture content increases at time of fluid drilling, so does the importance of adequacy of soil moisture. Primed seeds of relatively low moisture content when fluid-drilled into a dry seedbed may be able to survive until conditions become amenable for germination and seedling emergence, whereas pregerminated seeds might perish. The interaction between the moisture content of primed seeds at time of fluid drilling and seedbed conditions requires research.

Gels

Gels generally fall into one of five chemical classes: synthetic mineral clays, starch-polyacrylonitrile polymers, cellulose polymers, polyacrylamide polymers, and copolymers of potassium acrylate and acrylamide (Orzolek, 1987), although natural gels such as potato or maniac starches can be used effectively (Pill and Bojas, 1987). Some of the essential characteristics of a desirable gel carrier were reported by Darby (1980), as follows. The gel should suspend seeds of various sizes for at least 24 h, and yet be pumped easily through delivery tubing. It should be nonphytotoxic and should be mixed easily with water of different pH, mineral content, and hardness. It should be relatively inexpensive, should not dry to form a skin, but should break down readily in the soil.

While the gels are usually 1% to 3% solids at time of fluid drilling, the water supplied with the gel at a normal extrusion rate (20 to 30 ml/m of row) is inadequate to sustain seedling growth in a dry seedbed (Pill and Rojas, 1987). The protective gel, in addition to carrying seeds to the seedbed, can carry additives such as fertilizer salts, plant growth regulators, pesticides, and microorganisms, thereby creating a packaged environment for the seed and seedling (Salter, 1978). However, addition of the beneficial additives must not affect the gel rheology adversely, and, in turn, the gel must not counter the efficacy of the additive. Since seedlings can interact only with the small volume of soil occupied by their roots, inclusion of additives in the gel represents an efficient, low-input option

with obvious cost and environmental benefits.

Small quantities of phosphorus in gels have increased seedling weight of fluid-drilled carrot (Finch-Savage and Cox, 1982b), lettuce and onion (Finch-Savage and Cox, 1983), tomato (Espinosa and Pill, 1987), and collard seeds (Pill, 1990b), even in soils that have received traditional rates of N-P-K fertilizer. Commercially available biostimulants, such as Agro-Lig, Enersol (humic acids), and Ergostim (folic acid), in magnesium silicate gel increased carrot seedling vigor and percentage emergence compared to fluid-drilled seeds without stimulants (Sanders et al., 1990). Plant growth regulators mixed in fluid-drilling gels have been evaluated on tomato seedling emergence and growth (Pyzik and Orzolek, 1986). Fungicide incorporation into fluid-drilling gels effectively controlled damping-off caused by *Pythium aphanidermatum* (Giammichele and Pill, 1984; Ohepetal., 1984). Incorporation of the insecticide chlorfenvinphos in fluid-drilling gels was effective in protecting carrots against the carrot fly (Thompson et al., 1982).

Activated charcoal incorporated into gels protected fluid-drilled lettuce from herbicides (Taylor and Warholc, 1987). The lowest level of crop injury occurred when the charcoal was incorporated in hydroxyethyl cellulose (HEC) gel rather than in magnesium silicate or polyacrylamide gels, because HEC had greater mobility in the seedbed. This greater mobility of HEC gel in the seedbed also may reduce the likelihood of water stress due to osmotically active additives (e.g., fertilizer salts) in the gel (Espinosa and Pill, 1987).

Various biological materials can be delivered to the seedbed in the fluid-drilling gel. Jawson et al. (1989) noted that for *Bradyrhizobium japonicum*, both adhesive and carrier properties are combined in the fluid-drilling gel. Hayman et al. (1981) reported that fluid drilling had the advantages over other methods of greatly reducing the amount of vesicular-arbuscular mycorrhiza inoculum needed to cause a given level of host infection, and of readily combining seeds and inoculum in a single carrier. Conway (1986) noted that delivery of *Laetisaria arvalis* sclerotia in HEC gels increased plant stands and decreased the incidence of damping-off. Another biological con-

trol agent (*Trichoderma*) was most effective in reducing damage to fluid-drilled peas in *Pythium*-infested soil when incorporated in HEC gel.

As a polysaccharide, HEC seems especially suitable as a fluid-drilling carrier for biological (microorganism) additives. The properties of N-Gel, an HEC gel developed specifically for fluid drilling, have been described in detail (Banyai, 1987). In addition to the desirable properties of a fluid-drilling gel listed by Darby (1980), HEC seems to possess superior gas exchange properties, since viability of germinated seed subsequent to storage at low temperatures for up to 20 days was greater in HEC than in other gels (Pill and Fieldhouse, 1982). Other important characteristics of HEC include its transparency, which allows the suspended seeds to be seen easily, and its nonionic nature, which avoids the complexing (deactivation) of additives. The fact that HEC quickly moves away from the seed in the seedbed, leading to a modified environment stretching several centimeters from the seed, seems to be beneficial. I hypothesize that, as a consequence of this, HEC provides greater seed-to-soil contact, thereby increasing water supply to the seed. The HEC also may reduce mechanical impedance against seedling emergence, since HEC was found to be the most effective anticrustant of several materials applied to the soil surface (Page and Quick, 1979).

Fluid-drilling planters

A developmental history of fluid-drilling planters is provided by Eddington and Shaw (1987). Fluid Drilling Ltd. offers planters based on the prototype design (Fig. 5, Elliott, 1966) that use peristaltic pumps to extrude either a single continuous stream of gel, or triple continuous streams of gel within the width of the drill. In addition, they offer a clumper that deposits blobs of gel at precise intervals along a row, and a clumper puncher that deposits the blobs of gel through holes punched in plastic mulch. Sumitomo Chemical Company (Osaka, Japan) markets a small-volume continuous-stream (Fig. 6) and a clump fluid driller that use peristaltic pumps. Ghatte et al. (1986) developed a fluid-drilling planter in which seeds and gel were extruded from a sealed tank using compressed air. This system has the advantage of eliminating the mechanical damage that may occur when seeds travel through a pump.

Research on fluid-drilling planters continues. A minimum-tillage fluid-drilling planter has been developed (Ghatte and Phatak, 1983). Eddington and Shaw (1987) developed a fluid-planter mechanism that can singulate seeds in water based on pressure differentials before injecting the seeds into a stream of gel or water. Kamterter Products Inc. has introduced a fluid planter that is capable of delivering

Fig. 5. An early fluid drilling planter from Elliott's (1966) patent.

Fig. 6. Small-volume continuous-stream fluid drill.

and singulating a full range of seed sizes using a lower gel-to-seed ratio than used by other planters. This planter is part of a crop establishment system that includes seed enhancement through Solid Matrix Priming (SMP) and the delivery of beneficial micro-organisms.

Fluid drilling is one of several handling systems that can facilitate

delivery of somatic embryos. Conversion of carrot somatic embryos into plants in the glasshouse occurred when the embryos were incubated for 1 to 2 weeks in HEC fluid-drilling gel containing Murashige and Skoog salts and vitamins and 2% (w/v) sucrose (Kitto et al., 1991). This embryo conversion was improved further if the fluid-drilling gel contained truban or chitosan

glutamate (Seacure, Protan Co., Redmond, Wash.). The development of fluid-drilling planters that can singulate true seeds parallels the development of a hydro-pneumatic seeder (Gautz et al., 1989) that can singulate and meter synthetic seeds formed from somatic embryos that have been encapsulated in alginate gel.

Growers will likely continue to develop their own fluid-drilling machinery. One such grower in Maryland has constructed a 12-row planter (Fig. 7), with which he successfully fluid-drills collard, kale, and spinach (Pill, 1990a). This planter has the gel mixer and two 100-gal (380-liter) water storage tanks mounted on top. While the 45-gal (170-liter) hopper delivers the gel-seed mixture to the 12 rows, another batch of gel is mixing. Without returning for more water, this planter can fluid-drill 10 acres (4 ha) of small-seeded vegetables.

Conclusions

The use of pregerminated seeds probably will be reserved for the production of bedding plants or transplants where water will be the predominant carrier fluid. However, delivery of

Fig. 7. A 12-row fluid drill constructed by a vegetable grower.

pregerminated seeds to the seedbed in a gel is particularly useful in increasing percent emergence of very small seeds (e.g., tobacco or petunia).

The sowing of untreated dry seeds (collard and kale) in streams of fluid-drilling gel has improved stands compared to conventional dry-seed sowing. The reasons for the beneficial effect of the gel may include increased seed hydration, improved seed-soil contact, and increased antirustant effect. The future of fluid drilling lies predominantly in the use of primed seeds. The primed seeds may be hydrated before fluid drilling (prehydrated) to enhance germination and seedling emergence responses. The interaction between moisture content of the primed seed at time of fluid drilling and that of the seedbed requires research. The gel will carry a variety of chemical or biological additives specific for the crop and seedbed conditions. The positional advantage resulting from additive incorporation in the fluid-drilling gel represent a more efficient, cost-effective, and environmentally sound application method than others such as banding or spraying.

Literature Cited

Akers, S.W., G.A. Berkowitz, and J. Rabin. 1987. Germination of parsley seed primed in aerated solutions of polyethylene glycol. *HortScience* 22:250-252.

Banyai, B.E. 1987. N-Gel™ polymers for agricultural fluid drilling. *Acta Hort.* 198:111-120.

Bradford, K.J. 1986. Manipulation of seed water relations via osmotic priming to improve germination under stress conditions. *HortScience* 21:1105-1112.

Conway, K.E. 1986. Use of fluid-drilling gels to deliver biological control agents to soil. *Plant Dis.* 70:835-839.

Csinos, A.S. and S.R. Ghate. 1982. Fluid sowing of pregerminated tobacco seed. *Tob. Sci.* XXVI:32-34.

Darby, R.J. 1980. Effects of seed carriers on seedling establishment after fluid drilling. *Expt. Agr.* 16:153-160.

Eddington, D.L. and L.N. Shaw. 1987. Singulator for fluid planting of sprouted seeds. *Trans. Amer. Soc. Agr. Eng.* 30:1569-1574.

Elliott, J.G. 1966. The sowing of seeds in aqueous fluid. *Rpt. Weed Res. Org.* for 1965-1966. Oxford, England. p. 31-32.

Espinosa, W.A. and W.G. Pill. 1987. Response of tomato seeds fluid-drilled in low-

phosphorus growth media to phosphorus incorporation in the carrier gel. *Scientia Hort.* 33:37-47.

Evans, T.A. and W.G. Pill. 1989. Emergence and seedling growth from osmotically primed or pregerminated seeds of asparagus (*Asparagus officinalis* L.). *J. Hort. Sci.* 64:275-282.

Finch-Savage W.E. 1981. Effects of cold-storage of germinated vegetable seeds prior to fluid drilling on emergence and yield of field crops. *Ann. Applied Biol.* 97:345-352.

Finch-Savage, W.E. 1986. A study of the relationship between seedling characters and rate of germination within a seedlot. *Ann. Applied Biol.* 108:441-444.

Finch-Savage, W.E. 1987. Some effects of seed bed conditions on seedling establishment from fluid-drilled pre-germinated seeds. *Acta Hort.* 198:277-286.

Finch-Savage W.E. 1989. The use of abscisic acid to synchronize carrot seed germination prior to fluid drilling. *Ann. Applied Biol.* 102:213-217.

Finch-Savage, W.E. 1990. The effects of osmotic seed priming and the timing of water availability in the seed bed on the predictability of carrot seedling establishment in the field. *Acta Hort.* 267:209-216.

Finch-Savage W.E. and C.R. Cox. 1982a. A cold-treatment technique to improve the germination of vegetable seeds prior to fluid drilling. *Scientia Hort.* 16:301-311.

Finch-Savage W.E. and C.R. Cox. 1982b. Effects of adding plant nutrients to the gel carrier for fluid-drilling early carrots. *J. Agr. Sci.* 99:295-303.

Finch-Savage, W.E. and C.R. Cox. 1983. Effects of adding plant nutrients to the gel carrier used for fluid drilling lettuce and onion seeds. *Ann. Applied Biol.* 102:213-217.

Finch-Savage, W.E. and J.M.T. McKee. 1990. The influence of seed quality and pregermination treatment on cauliflower and cabbage transplant production and field growth. *Ann. Applied Biol.* 116:365-369.

Finch-Savage, W.E. and W.G. Pill. 1990. Improvement of carrot crop establishment by combining seed treatments with increased seed-bed moisture availability. *J. Agr. Sci.* 115:75-81.

Gautz, L.D., S.K. Upadhyaya, and R.E. Garrett. 1989. Hydropneumatic singulation of gel-encapsulated propagules. *Trans. Amer. Soc. Agr. Eng.* 32:791-794.

Ghate, S.R. and S.C. Chinnnan. 1987. Storage of germinated tomato and pepper seeds. *J. Amer. Soc. Hort. Sci.* 112:645-651.

Ghate, S.R. and S.C. Phatak. 1983. A minimum till fluid drill. *Amer. Soc. Agr. Eng. Paper* 83-1518.

Ghate, S.R., S.C. Phatak, and C.A. Jaworski. 1986. A new seeder for sowing germinated seed. *Acta Hort.* 187:45-52.

Giammichele, L.A. and W.G. Pill. 1984. Protection of fluid-drilled tomato seedlings against damping-off by fungicide incorporation in a gel carrier. *HortScience* 19:877-879.

Globerson, D. and Z. Feder. 1987. The effect of seed priming and fluid drilling on germination, emergence and growth of vegetables at unfavorable temperatures. *Acta Hort.* 198:15-21.

Gray, D. 1981. Fluid drilling of vegetable seeds. *Hort. Rev.* 3:1-27.

Gray, D. 1984. The role of fluid drilling in plant establishment. *Aspects Applied Biol.* 7:153-172.

Hayman, D.S., E.J. Morris, and R.J. Page. 1981. Methods of inoculating field crops with mycorrhizal fungi. *Ann. Applied Biol.* 99:247-253.

Jawson, M.D., A.J. Franzleubbers, and R.K. Berg. 1989. *Bradyrhizobium japonicum* survival and soybean inoculation with fluid gels. *Applied & Environ. Microbiol.* 55:617-622.

Kahn, B.A. and J.E. Motes. 1988. Comparison of fluid drilling with conventional planting methods for stand establishment and yield of spring and fall broccoli crops. *J. Amer. Soc. Hort. Sci.* 113:670-674.

Kahn, B.A. and J.E. Motes. 1989. Comparison of fluid drilling with conventional planting methods for stand establishment and yield of spring and fall cauliflower crops. *J. Amer. Soc. Hort. Sci.* 114:200-204.

Khan, A.A. 1991. Preplant physiological seed conditioning. *Hort. Rev.* (In press.)

Khan, A.A., K. Tao, J.S. Knypl, B. Borkowska, and L.E. Powell. 1978. Osmotic conditioning of seeds: Physiological and biochemical changes. *Acta Hort.* 83:267-278.

Kitto, S.L., W.G. Pill, and D.M. Molloy. 1991. Fluid drilling as a delivery system for somatic embryo-derived plantlets of carrot (*Daucus carota* L.). *Scientia Hort.* (In press.)

Ohep, J., H.H. Bryan, and D.J. Cantliffe. 1984. Control of damping-off of tomatoes by incorporation of fungicides in direct-seeding gel. *Plant Dis.* 68:66-67.

Orzolek, M.D. 1987. Gel seeding update. *Amer. Veg. Grower.* 35:10-11.

Pale, E.R. and M.J. Quick. 1979. A comparison of the effectiveness of organic polymers as soil anti-crusting agents. *J. Sci. Food Agr.* 30:112-118.

Pill, W.G. 1986. Parsley emergence and seedling growth from raw, osmoconditioned and pregerminated seeds. *HortScience* 21:1134-1136.

Pill, W.G. 1990a. Gel seeding makes cole crop comeback. *Amer. Veg. Grower* 38:29, 32-33.

Pill, W.G. 1990b. Seedling emergence and yield from hydrated collard seeds fluid-drilled in high-phosphorus gel. *HortScience* 25:1589-1592.

Pill, W.G. and D.J. Fieldhouse. 1982. Emergence of pregerminated tomato seed stored in gels up to twenty days at low temperatures. *J. Amer. Soc. Hort. Sci.* 107:722-725.

Pill, W.G. and C.F. Mucha. 1984. Performance of germinated, imbibed and dry petunia seed fluid drilled in two gels with nutrient additives. *Scientia Hort.* 22:181-188.

Pill, W.G. and J.E. Rojas. 1987. Response of fluid-drilled Grand Rapids lettuce seeds to high temperature and low moisture. *J. Agr. Sci.* 109:411-414.

Pill, W.G. and W.E. Finch-Savage. 1988. Effects of combining priming and plant growth regulator treatments on the synchronisation of carrot seed germination. *Arm. Applied Biol.* 114:383-389.

Pyzik, T.P. and M.D. Orzolek. 1986. The effect of plant growth regulators and other compounds in gel on the emergence and growth of germinated tomato seeds. *J. Hort. Sci.* 60:353-357.

Salter, P.J. 1978. Fluid drilling of pregerminated seeds: Progress and possibilities. *Acta Hort.* 33:245-249.

Salter, P.J. 1985. Crop establishment: Recent research and trends in commercial practice. *Scientific Hort.* 36:32-47.

Sanders, D.C., J.A. Ricotta, and L. Hodges. 1990. Improvement of carrot stands with plant biostimulants and fluid drilling. *HortScience* 25:181-183.

Schultheis, J.R., D.J. Cantliffe, H. Bryan, and P. Stoffella. 1988a. Planting methods to improve stand establishment, uniformity, and earliness to flower in bell pepper. *J. Amer. Soc. Hort. Sci.* 113:331-335.

Schultheis, J.R., D.J. Cantliffe, H. Bryan, and P. Stoffella. 1988b. Improvement of plant establishment in bell pepper with gel mix planting medium. *J. Amer. Soc. Hort. Sci.* 113:546-552.

Szafirowska, A., A.A. Khan, and N.H. Peck. 1981. Osmoconditioning of carrot seeds to improve seedling establishment and yield in cold soil. *Agron. J.* 73:845-848.

Taylor, A.G. and T.J. Kenny. 1985. Improvement of germinated seed quality by density separation. *J. Amer. Soc. Hort. Sci.* 110:347-349.

Taylor, A.G. and D.T. Warholic. 1987. Protecting fluid drilled lettuce from herbicides by incorporating activated carbon into gels. *J. Hort. Sci.* 62:31-37.

Taylor, A.G., D.E. Klein, and T.M. Whitlow. 1988. SMP: Solid matrix priming of seeds. *Scientia Hort.* 37:1-11.

Thompson, A.R., D.L. Suett, and A.L. Percival. 1982. The protection of carrots against carrot fly (*Psila rosae*) with granular and emulsifiable concentrate formulations of chlorfenvinphos incorporated in gels used for drilling pregerminated seed in a sandy loam. *Ann. Applied Biol.* 101:229-237.

Wiebe, H.J. and T. Muhyaddin. 1987. Improvement of emergence by osmotic seed treatments in soils of high salinity. *Acta Hort.* 198:91-100.

Seed Testing and Quality-Assurance

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Additional index words. seed purity, germination, seed vigor

High-quality seed is the basis for profitable and productive agriculture, be it a large commercial field operation, a small family-owned farm, or a greenhouse-based operation producing bedding plants or specialty horticultural crops. Assessing seed quality and assuring the buyer of the validity of the seed label (Fig. 1) has been an important mission of the various seed regulatory agencies of state and federal governments and service-testing provided by commercial seed-testing laboratories around the world. Based on validity of labeling, commercial sales of seed have been a profitable business to both the seed producer and the consumer.

In the United States and Canada, seed-testing rules have been developed and standardized by the Assn. of Official Seed Analysts (AOSA) and in other countries around the world by the Inter-

national Seed Testing Assn. (ISTA). The first state seed-testing laboratory in the United States was established in 1876 at the Connecticut Agricultural Experiment Station, and by 1930, 44 states had established seed-testing laboratories (Justice, 1961). In 1897, the first seed-testing rules in North America were prepared and published by the USDA in a circular entitled Rules and Apparatus for Seed Testing as unofficial guidance for seed analysts (Justice, 1961). The formation of the AOSA in 1908 and the passage of the U.S. Federal Seed Act in 1939 resulted in the formalized procedures for testing seeds that are acknowledged and used in the United States.

To meet the demands of new technology and new crops, the rules and procedures are reexamined and revised annually. For example, the development of seed-coating technology has led to changes and additions to the Rules for Testing Seeds as published by the AOSA (1988) and the International Rules for Seed Testing published by the ISTA (1985).

Assessment of seed quality includes tests for purity (physical and genetic), viability (germinable plus dormant), and vigor. Purity and germination normally are included as information on the seed label, along with a statement of the variety or cultivar. Vigor test results are not included as part of the regulatory labeling requirement. They are used extensively for in-house quality control by seed producers. A purchaser of seed may ask for vigor test results, or can obtain them from a commercial laboratory. Assurance of seed quality by a commercial producer involves continual monitoring of viability and/or vigor during all phases of harvesting, conditioning, and storage before the sale and shipping of the seed. Mechanical damage, seed contamination, and deterioration all must be avoided if high quality is to be retained.

Purity tests

The concept of seed purity includes both physical purity and genetic purity. Physical purity includes the presence or absence of soil, plant debris, weed seed, and other contaminants. Genetic purity relates to the presence of the correct cultivar and degree of contamination with other cultivars, or, in the case of hybrid seed, the presence or absence of self-pollinated inbreds or incorrect crosses.

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