Technology & Product Reports

A Solid-matrix, Liquid Hybrid Hydroponic System for Establishing Small-seeded Crop Species

Jonathan M. Frantz,¹ Jay Frick,² and Cary A. Mitchell^{1,3}

ADDITIONAL INDEX WORDS. *Brassica napus*, controlled-environment agriculture, seedling establishment, soilless culture

SUMMARY. A solid-matrix-over-liquid (hybrid) growth system was developed for direct sowing of small-seeded crop species into hydroponic culture and compared for performance with a standard solid-matrix, capillary-wick hydroponic system. Seeds were sown directly onto a 3-cm (1.2-inch) deep soilless seed bed occupying 0.147 m² (1.582 ft²) within a tray. The planted seed bed was moistened by wicking up nutrient solution through polyester

wicking material from a 7.0-L (6.6-qt) reservoir just below the matrix seed bed. The hybrid system successfully grew dense [435 plants/m² (40.4 plants/ft²)], uniform canopies of dwarf *Brassica napus* L. in a controlled-environment growth room. Seed yield using the hybrid system was twice that achieved with the matrix-based system. Both systems eliminated the labor needed to transplant many small seedlings from a separate nurse bed into a standard bulk liquid hydroponic system. Root-zone pH extremes caused by ion uptake and exchange between roots and unrinsed soilless media were avoided for the hybrid system by the short dwell time of roots in the thin matrix before they grew through the matrix and an intervening headspace into the bulk solution below, where pH was easily managed. Once roots grew into the bulk solution, its level was lowered, thereby cutting off further capillary wicking action and drying out the upper medium. Beyond early seedling establishment, water and nutrients were provided to the crop stand only by the bulk nutrient solution. This hybrid hydroponic system serves as a prototype for larger-scale soilless growth systems that could be developed for production of small-seeded crops in greenhouses or controlled environments.

Two major types of hydroponic systems are used widely in horticulture. These are recirculating liquid systems (deep batch or nutrient film) (Molyneux, 1988; Resh, 1991) and soilless, matrix-based systems wetted either by capillary action or by direct contact of the root system with flowing or transiently flooding nutrient solution (Resh, 1991). Both types of system usually require individual handling of seedlings or cuttings for optimum stand establishment.

Transplanting into bulk liquid hydroponic production systems is undesirable for small-seeded and/or small-stature crop species since it involves much labor, handling, and possible mechanical damage to small transplants. Fine media typically are used as a seedbed for small-seeded species. Capillary wick material placed either within the medium or in contact with the bottom of the medium, with the other end extending into a nutrient solution, is used to create a matrix-based hydroponic system, thereby eliminating the need to irrigate manually. Unfortunately, seedling-establishment problems may arise with capillary-wick nutrient delivery into solid-matrix systems as surface evaporation causes salts to accumulate around young seedlings, even if nutrient solution is delivered only periodically. Seedlings that have been salt damaged do not develop properly, leading to uneven stand establishment. Additionally, yield-limiting pH extremes can occur in the root zone of solid-matrix hydroponic systems, especially if the matrix has low buffer capacity and is never rinsed or drained (Frick and Mitchell, 1993). pH excursions occur as roots exchange H⁺ and/or HCO₃⁻ for cations and anions, respectively, to maintain electrochemical balance across root membranes (Schon, 1992). This undesirable situation results in pH extremes near root surfaces and adversely affects the availability of mineral nutrients, leading to slower growth and reduced crop productivity.

A hydroponic system that minimizes stress to roots is necessary both for research and for commercial application in which yield optimization and stand uniformity are of high priority. The objective of the present study was to develop and test such a system that would include the benefits of existing hydroponic systems, but would prevent common root-zone stresses found in matrix-based systems, such as pH extremes, hypoxia, and/or salt accumulation due to capillary wicking without rinsing. By combining several seedling-management practices, a novel hydroponic system was developed to grow small-seeded, low-stature crop stands without transplanting seedlings. In addition to minimizing root-zone stresses, other goals included designing a system that is easy to build, simple to maintain, and which can be fabricated from readily available, low-cost materials. The hybrid hydroponic system described here

Purdue University Agricultural Research Project 15883. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked advertisement solely to indicate this fact.

¹Department of Horticulture and Landscape Architecture, Purdue University, West Lafayette, IN 47907-1165.

²Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, NC 27695.

³To whom reprint requests should be addressed.

meets these criteria and was evaluated by growing a dwarf, rapid-cycling brassica crop from seed to seed.

Materials and methods

HYBRID SYSTEM CONSTRUCTION. The hybrid hydroponic system combined characteristics from both bulk liquid and matrix-based, capillary-fed hydroponic systems (Fig. 1). All components were made from inert plastic materials to avoid potentially corrosive effects of salt on metallic components in prolonged contact with nutrient solutions and to prevent heavy-metal contamination of plant nutrient solutions.

A rectangular, open-topped polyethylene compartment 52 cm long $\times$ 42 cm wide $\times$ 11 cm deep (20.5 $\times$ 16.5 $\times$ 4.3 inches) made up the outer shell of the system (Fig. 1). Wall thickness of the outer compartment was 0.6 cm (0.24 inch). Its exterior was painted silver to prevent light transmission and algal growth, and to prevent rhizosphere heating in a lighted environment. The reservoir was fitted with drain and refill

ports so that nutrient solutions could be changed quickly and to facilitate pH adjustments.

A standard photographic developing tray [45 $\times$ 37 $\times$ 7 cm (17.7 $\times$ 14.6 $\times$ 2.8 inches)] was adapted as a seed-bed container and positioned within the outer compartment and above the nutrient solution (Fig. 1). The seed bed was supported on a pedestal made from plastic lamp grating and sections of polyvinyl chloride (PVC) pipe. It was elevated to a height of 3.5 cm (1.4 inch) such that the top of the seed bed was flush with the upper surface of the outer compartment. Flexible aquarium aeration tubing was threaded through holes drilled through the PVC sections and wound in a spiral fashion on the floor of the outer compartment (Fig. 1). In this manner, nutrient solution in the reservoir was continuously aerated and mixed with air forced from a small aquarium pump. The pump was the only electrical component of the system and required 1 W of electrical power.

The seed-bed container was partially filled with a 3.0 cm (1.2 inch) deep layer of solid medium (2 vermiculite : 1 perlite, by volume). For the first 2 weeks of cultivation, quarter-strength Hoagland's no. 1 nutrient solution (Hoagland and Arnon, 1950) was used (pH = 5.6), and then was replaced with half-strength solution containing quarter-strength nitrate nitrogen (3.75 mM) for the duration of the cropping cycle. Nutrient solution was supplied to the substrate by capillary action through 6.5-cm (2.6-inch) wide polyester wicks

inserted through seven slits cut in the bottom of the tray. The 2-mm (0.008-inch) wide slits were parallel to one another, separated by 4.5 cm (1.8 inch), and ran the entire width of the inner tray. Once inserted through the slits, the wicking material was folded under the seed-bed container such that the lower end of the wick rested at the contact point between the bottom of the seed-bed container and the upper surface of the lamp grating platform. The nutrient solution level was just high enough initially to moisten the lower end of the polyester wicking material, thereby allowing solution to be wicked up into the seed bed. Once the roots had grown through the slits, however, the solution level was lowered below the top of the grating to prevent further wicking of solution into the seed bed. The volume of the lowered solution was 5.5 L (5.2 qt).

Aluminum foil was used to cover gaps between the seed bed and outer compartment, effectively eliminating light from entering the nutrient solution reservoir. Upon complete assembly, the hybrid system had a growing area of 0.147 m² (1.582 ft²).

SOLID-MATRIX SYSTEM CONSTRUCTION. The matrix-based hydroponic system was constructed with materials identical to those of the hybrid system (Fig. 2). However, the seed-bed container did not have slits in its base to allow roots to escape to the lower solution reservoir. Instead, polyester wicking material lining the bottom of the seed bed was draped up and over two ends of the tray and down into the outer reservoir to allow solution to be wicked from the reservoir into the growth medium (Fig. 2). Foil covered the wick where it draped over the edge of the seed-bed tray to prevent evaporation and algae growth. The volume of the solid-matrix seed bed was the same as that of the final solution in the hybrid system [5.5 L (5.2 qt)].

SYSTEM TESTING. Dwarf, rapid-cycling Brassica (*Brassica napus* L. CrGC 5-2, Genome: Acaacc, Wisconsin Fast Plants) seeds were sown directly into the solid substrate layer at a depth of $\approx$ 1 cm (0.39 inch) with the aid of a planting template to ensure equal seed spacing. Four replicate systems were constructed for each treatment. Sixty-four seeds were planted into each system, producing an equivalent planting density of 435 plants/m² (40.4 plants/ft²). A single layer of transparent plastic wrap was placed loosely over the growing surface

Fig. 1. Schematic side views of the hybrid hydroponic system design at seedling stage (upper diagram) and at maturity (lower diagram). (A) is the tygon tubing, (B) is the vermiculite-perlite matrix, (C) is the air pump, (D) is the wicking material, (E) is the PVC support, (F) is the aeration hose, (G) is the light-grate support, (H) is the nutrient solution reservoir, and (I) is the solution level. At maturity (lower diagram), roots had grown through the solid substrate and into the nutrient solution reservoir.

Fig. 2. Schematic side views of the matrix-based hydroponic system design at seedling stage (upper diagram) and at maturity (lower diagram). (A) is the tygon tubing, (B) is the vermiculite-perlite matrix, (C) is the air pump, (D) is the wicking material, (E) is the PVC support, (F) is the aeration hose, (G) is the light-grate support, (H) is the nutrient solution reservoir, and (I) is the solution level. At maturity (lower diagram), roots remained within the solid substrate.

to provide a high humidity microenvironment for seedling emergence. Additionally, 30% shade cloth was placed above each system for 48 h to prevent overheating below the plastic wrap and drying of the matrix surface before seedling establishment. The seeded systems were arranged within a controlled-environment growth room in a completely randomized design and the following environmental conditions were established: Photosynthetic photon flux was $250 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ supplied by metal halide, high pressure sodium, and incandescent lamps; photoperiod was 20 h; relative humidity averaged 50%; diurnal temperature was 23°C (73°F) during the light period and 20°C (68°F) during the dark period. After 24 h, the plastic wrap was removed, and after 48 h, the shade cloth also was removed.

The only routine maintenance required during the cropping cycle included daily pH adjustment of the nutrient solution, maintaining pH within a range of 5.5 to 6.5, and addition of fresh solution to maintain solution volume. The nutrient solution was com-

pletely refreshed at 5-d intervals, and the drained reservoirs were refilled immediately either with 7.0 or 5.5 L (6.6 or 5.2 qt) of fresh, half-strength Hoagland's no. 1 nutrient solution for the matrix-based and hybrid systems, respectively. After a 60-d growth cycle, the systems were drained and plants were left to dry for 14 d before harvest (Frick and Mitchell, 1993). At harvest, shoot biomass was separated into siliques, seeds, leaves, and stems. Root biomass could not be separated from the growth medium and wicking material, so its weight was not measurable. Siliques, leaves, and stems were further dried in a forced-air oven for 72 h and then weighed.

Following harvest, the hybrid systems were completely disassembled and sanitized with 1% (vol/vol) bleach (final concentration of 0.0525% sodium

hypochlorite). System performance was evaluated with respect to the following criteria: 1) final seed yield and other harvest parameters, 2) observed progress in canopy development, 3) visual stand uniformity, and 4) status of the hydroponic systems themselves, including a durability assessment.

Results and discussion

Plants adapted well to the hybrid hydroponic system, without any visual indications of environmental or cultural stress. The direct-seeded crop stand was uniform and produced a closed canopy 2 weeks after seeding (Fig. 3A). In comparison, seedling-establishment problems were observed for the solid-matrix hydroponic system. For example, some seedlings developed slowly and remained chlorotic after 4 weeks (Fig. 3B). These differences likely occurred in part due to a rise in substrate pH from 7.0 to >9.0 by 4 weeks following seedling establishment in the matrix-based system, whereas roots within the hybrid system developed within the pH-adjusted nutrient solution. It also is likely that border plants (adjacent to areas where solution was being wicked) preferentially absorbed water and nutrients, leading to uneven stands.

By 3 to 5 d after seeding, the main root system of plants in the hybrid system already had grown through the slits, along the capillary wicking mate-

Fig. 3. Overhead view of *B. napus* canopies in the hybrid hydroponic system (A) and in the matrix-based hydroponic system (B) after 2 weeks of growth.

Table 1. Mean yield parameters of four replications in each system for *Brassica napus* grown for 60 d using the hybrid hydroponic system and the matrix-based hydroponic system.

System	Wt (g·m ⁻²) ^z			SHI ^y
	Seed	Silique	Shoot	
Hybrid	226.3	342.7	821.3	16.3
Matrix	112.9	178.6	377.8	17.4
P value ^x	0.0009	0.0038	0.0031	0.5424

^zMultiply values by 3.28×10^{-3} to convert to oz./ft².

^yShoot harvest index = g dry weight seed/g dry weight total shoot biomass.

^xP value determined from *t* test of means between systems.

rial, and into the nutrient solution below the seed bed. This was important because the solution level then could be lowered, thereby cutting off further wicking, drying out the upper seed bed, and also eliminating the potential for salt accumulation on the surface and pH extremes within the feeding root zone. Once the roots had reached the nutrient solution, daily root-zone pH adjustment was possible, thereby allowing the root-zone environment to be managed within a pH range of 5.5 to 6.5. The hybrid system more than doubled the seed yield and shoot biomass of the matrix-based system, yet both systems had similar shoot harvest indices (Table 1).

At the end of the test period, structural components of the hybrid system indicated no evidence of physical deterioration. Except for the flexible aeration tube and polyester wicks, all components were cleaned and reassembled with minimal effort. Roots grew directly through the inexpensive aeration tubing, requiring replacement before the system could be reused. Other hydroponic systems developed previously did not use active aeration, yet still achieved yields comparable to growth in soil (Kratky, 1993). Aeration other than that occurring through recirculation may not be necessary for crops with a short cropping cycle (e.g., lettuce), but may prove beneficial for crops with longer crop cycles (>4 weeks) due to gradual O₂ depletion in the root zone as stands mature and root development becomes extensive (Chun and Takakura, 1993). In a float-bed hydroponic system, leaf epinasty was observed for a variety of horticultural crops when aeration was not provided, which reduced the quality of the plants (Frantz and Welbaum, 1998).

Another potential benefit that active aeration provides, especially in low root-volume systems, is to mix the nutrient solution. In systems where neither aeration nor recirculation are

provided, nutrient gradients can occur leading to symptoms of severe salinity stress or nutrient deficiency (Kratky et al., 1988). Root-zone aeration is a simple method for the grower or researcher to use to avoid such problems.

The need for slight modifications that would further improve future hybrid hydroponic systems became apparent during the system test. These include the use of larger solution reservoirs to reduce the frequency of solution replenishment and to allow for more precise management of pH. Manual pH adjustment could be eliminated and pH maintained more tightly with an electronic pH controller. However, this modification would increase the complexity and cost of the system, tradeoffs that may not be necessary or justifiable for certain hydroponic applications. A finer matrix may be required to accommodate such small-seeded species as *Arabidopsis thaliana* (L.) Heynh. (Gilbeaut et al., 1997). Additionally, the thickness of the matrix layer of the seed bed may need to be further decreased to allow more convenient access to the root zone of very young seedlings (Mackowiak et al., 1998).

The most innovative aspect of the hybrid hydroponic system described lies in combining the practice of direct seeding into a thin, solid matrix with a cutoff of fresh nutrient solution delivery to that matrix once seedling roots have grown through slits in the bottom of the tray and into the solution reservoir positioned just below the tray. Important root-zone parameters then can be easily managed in the aerated nutrient solution while the original seed bed dries out and is no longer a factor in crop development. Nutrient solution pH, conductivity, and content cannot be closely controlled in unrinsed solid-matrix hydroponic culture, especially if wetted only by unidirectional capillary action. The hybrid hydroponic system eliminates the need for transplantation altogether, yet combines the advan-

tages of establishing small seedlings in a solid seed bed with close management of root-zone parameters in solution culture of established seedlings. Thus, the hybrid system avoids the pH extremes that limit crop growth and productivity in solid-matrix hydroponic systems of limited ion-exchange capacity, allows for better root-zone management, and minimizes labor for establishment of dense crop stands. Since the system is of modular design, it can be expanded readily without additional support equipment. This simplicity allows for more complete utilization of available growth area for cultivation of closed canopies and better control over plant growth and development. The principles of this direct-seed hybrid hydroponics technology should be readily transferable from the bench-scale, proof-of-concept approach reported here to a pilot, crop-production scale for many different kinds of horticultural crops.

Literature cited

- Chun, C. and T. Takakura. 1993. Control of root environment for hydroponic lettuce production rate of root respiration under various dissolved oxygen concentrations. Amer. Soc. Agr. Eng. (St. Joseph, Mich.) paper no. 934040, p. 1-7.
- Frantz, J.M. and G.E. Welbaum. 1998. Producing horticultural crops using hydroponic tobacco transplant systems. HortTechnology 8(3):392-395.
- Frick, J. and C.A. Mitchell. 1993. Stabilization of pH in solid-matrix hydroponic system. HortScience 28(10):981-984.
- Gilbeaut, D.M., J. Hulett, G.R. Cramer, and J.R. Seemann. 1997. Maximal biomass of *Arabidopsis thaliana* using a simple, low-maintenance hydroponic method and favorable environmental conditions. Plant Physiol. 115:317-319.
- Hoagland, D.R. and D.I. Arnon. 1950. The water culture method for growing plants without soil. Univ. Calif. (Berkeley) Expt. Sta. Circ. 347.
- Kratky, B.A. 1993. A capillary, noncirculating hydroponic method for leaf and semihead lettuce. HortTechnology 3(2):206-207.
- Kratky, B.A., J.E. Bowen, and H. Imai. 1988. Observations on a noncirculating hydroponic system for tomato production. HortScience 23(5):906-907.
- Mackowiak, C.L., R.M. Wheeler, G.W. Stutte, N.C. Yorio, and L.M. Ruffe. 1998. A recirculating hydroponic system for studying peanut (*Arachis hypogaea* L.). HortScience 33(4):650-651.
- Molyneux, C.J. 1988. A practical guide to NFT. 1st ed. Nutriculture Ltd., Mawdesley, Ormskirk, Lancashire.
- Resh, H.D. 1991. Hydroponic food production. 4th ed. Woodbridge, Santa Barbara, Calif.
- Schon, M. 1992. Tailoring nutrient solutions to meet the demands of your plants. Hydroponics Soc. Amer., Proc. 13th Ann Conf., Orlando, Fla., 9-12 Apr. p. 1-7.