DEEP FLOW HYDROPONICS - PAST, PRESENT AND FUTURE

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Abstract: In 1976, a method of growing lettuce and other leafy vegetables on a floating raft of expanded plastic was developed independently by researchers at the University of Arizona and the University of Pisa in Italy. Today facilities exist in a number of countries including the United States, Japan and Canada. Termed "Deep Flow Hydroponics," the system consists of horizontal, rectangular shaped tanks lined with plastic and filled with nutrient solutions. Those developed in Arizona measured 4 m x 70 m, and 30 cm deep. This method of hydroponics continues to grow in popularity due to the ability to control root temperatures, either by heating the nutrient solutions or chilling the solutions to reduce bolting, especially important in tropical and desert regions of the world. Concurrent with the development of the production system, were harvesting and packaging experiments. Packaging individual heads in air-sealed plastic bags extended the shelf-life up to three weeks, plus provided protection during transportation. Today, with the introduction of new specialty, leafy vegetables as those common in *Mesclun* (a variety of tender leafy salad greens) a renewed interest has been created in deep flow hydroponics.

Keywords: Hydroponics, leafy vegetables, *Mesclun*

Introduction

It has been 25 years since the University of Arizona developed a hydroponic lettuce system in which seedlings are planted into Styrofoam rafts with their roots dipping into aerated nutrient solution. The nutrient raceways serve as near-frictionless conveyor belts to facilitate planting and harvest. As a crop of several floats was harvested from one end, new floats with transplants were introduced at the other end.

This system of hydroponics was named Deep Flow Hydroponics (Jensen and Collins, 1985) and today exists in many countries throughout the world, namely the United States, Japan and Canada. Many of the results coming from the experiments in establishing the Deep Flow Hydroponic system were never reported. The following are highlights of these early studies which are as applicable today as 25 years ago.

Production System

Growing Raceways. The production system designed by the author consisted of horizontal, rectangular shaped tanks often termed raceways. Lined with plastic, each raceway measured 4 m x 70 m, and 30 cm deep. The nutrient solution was monitored, replenished, recirculated and aerated.

Each raceway had a 1.5 hp pump to enable recirculation of the nutrient solution. Along the inside of the tank, a 3 in. PVC pipe was laid the length of the tank. Air was introduced to the raceway through venturis spaced at 3.5 m intervals down the PVC pipe. With this design, dissolved oxygen levels could be maintained at 5-6 ppm in the nutrient solution. It is important to note that it is increasingly difficult to maintain oxygen levels in the solution as the solution temperature increases.

Floating rafts, approximately 60 x 60 cm and 2.5 cm in thickness, should be made of extruded polystyrene (Styrofoam) rather than compressed polystyrene beads which can become water-logged in a short time. This isn't the case with the extruded Styrofoam. While the rectangular raceways can be any dimension, it is important to introduce ample amounts of oxygen to the nutrient solution.

Seeding and Germinating. In the Arizona cultivar trials, four commercial cultivars were selected for the hydroponic lettuce trials: a short-day leafy type *Waldemann's Green,* and three cultivars of summer butterhead, *Ostinata, Salina* and *Summer Bibb*. In comparing these cultivars to similar types grown under open field conditions, these cultivars exhibited the best tolerance to bolting, tip-burn and bitterness, common physiological disorders in warmer climates.

The seeds were sown both by hand and by automatic seeding equipment. Both raw and pelleted seeds were tested. During the hot summer months, pelleted seed did not germinate as fast. One week after seeding, the raw seed had 100% germination and the pelleted seed 25%. By the end of two weeks, germination of both groups was 100%. The reason for the slower germination was attributed to oxygen deficiency.

During periods of high temperatures, such as those experienced in Tucson, Arizona from June - September, germination can be a problem with thermodormancy of some lettuce cultivars due to heating of the growing media above 30^{o} C in direct sunlight. Shading of the greenhouses did help but once air temperatures were 28^{o} C or more, germination was still poor. It is clear from the literature that there are considerable varietal differences for germination. Most cultivars do not germinate well above $22\text{-}25^{o}$ C. It was found that thermodormancy can be interrupted by a cold treatment, (Berrie, 1966) with germination occurring without inhibition when the seeded trays are placed back under high temperature. Simply pre-incubating the seeds under cold conditions does not work. Thermodormancy is reversed by exposing the trays to warm temperatures for 3-6 hours after sowing, then chilling them for 24 hours at 2^{o} C. When placed on the nursery bench after this treatment, germination was high even when air temperatures exceeded 30^{o} C. The germination trays were fitted with reusable molded inserts that had indentations for 50 growing cups. The cups were white molded plastic, designed to encourage root growth into the nutrient solution. The cups were filled with a growing mix of peat and vermiculite, which cost about 0.3 cents per plants. Alternative growing media would be rockwool cubes or cubes made by Oasis.

Flood tables proved to be the best germinating system. Seedlings raised on flood tables were consistently heavier and more uniform in size then those raised on mist benches (Table 1). The tables were flooded twice a day to the top of the transplant cubes then drained. The mist benches were irrigated as needed to keep the growing media wet, approximately 5-10 times per day. Both methods used nutrient solutions as the water source.

Seedlings were ready to transplant when they reached the three leaf stage, weighing 1.0 - 1.5 g. fresh wt./plant, which required from 14 to 21 days according to the season.

Table 1. Transplant production: flood versus overhead mist.

Trial No	Treatment	Cultivar/age	3wk wts (g)	Harvest wts (g)
1	Mist	Ostinata/7wks	0.84	206
	Flood		2.26	250
	Mist	Summer Bibb/7wks	1.09	175
	Flood		2.09	190
2	Mist	Summer Bibb/7wks	1.18	127
	Flood		2.16	166
3	Mist	Summer Bibb/6 wks	0.80	87
	Flood		0.80	109
4	Mist	Ostinata/6 wks	1.10	139
	Flood		2.50	164

It appears that when lettuce plants are transplanted at two weeks of age, they are heavier in weight at 45 days than those of the same age when transplanted to the raceways when three weeks old (Table 2).

Table 2. Weight of seven week old plants when transplanted to raceways 14 & 21 days after seeding.

Days after Seeding	2 wk old Transplants (g)	3 wk old Transplants (g)
14	0.05	0.04
26	3.90	0.76
28	5.00	2.30
37	66.60	16.70
40	100.50	39.20
42	107.90	45.40
44	142.40	60.70
47	- - -	100.50
48	170.90	112.20
49	186.70	113.60

Transplants at three weeks of age are probably more rootbound therefore initial plant growth after transplanting is slow versus a two-week old plant that is less rootbound.

Supplemental artificial lighting increased the weight of seedlings during winter, and the percentage of increase carried through to harvest (Table 3).

Three types of light sources-fluorescent, metal halide and high pressure sodium, were adjusted to deliver 150 Φmol s^{-1} m^{-2} over the plant canopy. The lights were on from 6:00 - 7:00 a.m. and 3:00 - 9:00 p.m. daily. In the growout stage (days 22-49), lights were on only three hours per day, 6:00 - 9:00 p.m. There were no significant differences between light sources or cultivars tested. Due to the high density of plants in the nursery stage, supplemental lighting appeared to be economical only during the low-light months (December - February).

Table 3. Lettuce weights at transplant and harvest using no supplemental light, lighting in nursery, and lighting in the growout stage.

	fresh weight/head (g)	
Treatment	**21 day**	**49 day**
Control (No lights)	0.67	117.90
Light in Nursery Only	1.15 **	152.9 **
Lights in Growout Only	0.67	147.5 **

** Significant difference from control at .01 significance level.

Transplanting. The raceway stage is the longest growing stage and required the most space per plant. Therefore, it is extremely important that raceways are always filled with plants. Transplants are planted into raceways in space vacated by the harvest of a previous crop. In theory, the closer together in time the harvest and transplant, the more efficient the space utilization. If there was a lag between harvest and planting, raceway space was not fully utilized.

Head weights of Waldemann's and Ostinata increased with hole spacing up to 20 cm whereas the more compact Summer Bibb increased only up to 18 cm. Plants grown on square spacings outweighed staggered spaced plants with the same distance between by an average of 16.5% for all varieties. Since the staggered spacing allows 16% more plants than the square spacing, there was no difference in total biomass production per unit area. For the systems at Arizona, a 17.5 cm staggered spacing between holes was optional for producing lettuce heads weighing 120 grams.

Radiation Requirements. Early in our research program, we found that average fresh weight of lettuce heads increased proportionately with the average daily radiation up to the maximum radiation we could get under a new clear plastic bubble. In greenhouse trials under an older fiberglass cover which had incoming light reduced by 38%, lettuce plants were grown year-around with no shade over the plants and compared to those with 35% and 70% shade. The results are shown in Figure 1.

This very detailed trial supported our early results that maximum light is most important in producing the greatest yields. In June and July, it is possible that the plants under no shade did not show the yield response to high light due to growth inhibition caused by higher nutrient solution temperatures.

Growth rates of all cultivars correlated positively with levels of available light. This correlation held to the highest levels measured, even though radiation levels in the Arizona desert are two to three times that of more temperate climates (Glenn, 1984). This finding was surprising, since OFA lettuce is saturated by relatively low levels of light, and growth is inhibited as radiation increases. In addition, in other regions greenhouse lettuce is usually regarded as a cool-season crop.

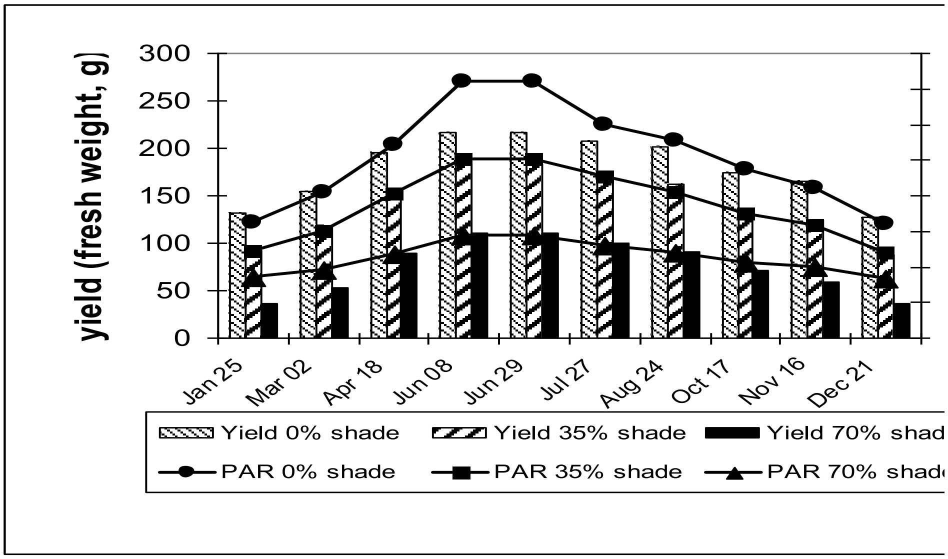

Figure 1. Influence of light on lettuce yields (8 week old lettuce plants).

A further finding was that crops grown during autumn, when daylight hours are decreasing, used available light two to three times more efficiently than winter or spring crops. Daytime air temperatures also correlated positively with growth; therefore, fall crops grown under higher temperatures were more efficient than spring crops. (However, during the summer monsoon season when evaporative cooling systems are ineffective, the combination of high-temperature and high light levels caused lettuce to bolt. As discussed later in this paper, chilling the nutrient solution reduced bolting.) The best predictor of lettuce growth in the prototype raceway system was the product of daytime temperature and the log of radiation (Glenn, 1984).

In 1983, a comparison was made between Tucson, Arizona and Columbus, Ohio in regard to the days to harvest, heat requirements and heating cost (Table 4). Undoubtedly higher light and temperatures in southern latitudes provided a real advantage to regions located further north.

Table 4. Days to harvest, heat requirements, and heating cost for greenhouse lettuce in Tucson, Arizona and Columbus, Ohio.

	Day to harvest		**Heat requirements ($BTU\ head^{-1}$)**		**Heat cost (¢ $head^{-1}$)**	
	Tucson	**Columbus**	**Tucson**	**Columbus**	**Tucson**	**Columbus**
Fall (Sept - Nov)	39	62	497	3540	0.33	2.41
Winter (Dec - Feb)	57	96	3433	15562	2.33	10.58
Spring (Mar - May)	40	55	778	3922	0.52	2.67

Nutrient Solution. The nutrient solution used in these early studies contained the following (mg 1^{-1}); 139 N, 38 P, 257 K, 90 Ca, 15 mg, 2.3 Fe plus micro-elements. In commercial production today, the nitrogen, phosphorous and potassium are higher at 200 ppm, 69 ppm and 360 ppm respectively.

Chilling Nutrient Solutions. In 1977, studies by the author showed that cooling the nutrient solution would stop the bolting (going to seed) of lettuce (Table 5), as well as reduce the incidence of tipburn.

Table 5. Chilled versus non-chilled nutrient solutions.

	Non-Chilled	**Chilled**
Fresh top wt.	44.70 g.	66.20 g
Fresh root wt.	19.50 g.	12.80 g.
Stem elongation	7.68 cm.	3.52 cm.
Water used/1 gram of fresh top	8.57 g.	4.78 g.

Non-Chilled: Air temperature 35° C, root temperature 32 - 38° C
Chilled: Air temperature 35° C, root temp 18° C

The study was conducted in growth chambers and repeated with similar results in regard to the reduction of stem elongation. Several years later the concept was used in raceways in a greenhouse where solution temperatures would commonly reach 27° C. In comparing the plant response to those growing in solutions of 27° C versus 22-24.5, the plants growing in the cooled solution were heavier with less bolting and tipburn (Table 6.).

Table 6. Weights and quality of Ostinata lettuce grown in chilled and non-chilled nutrient solution during August in Tucson, Arizona.

	Non-chilled (27° C)	**Chilled (22 - 24.5° C)**
Ave. Fresh wt/hd.*	147.80	169.60
% retail	60.70	87.30
% undersized	39.30	12.70
% bolted	5.40	0.0
% tipburn	1.80	0.0
Sample size	56 plts	55 plts
Average H_20 Temp	27.20 °C	23.30 °C

* Lettuce head plus peat pellet

Studies were also done in the raceways comparing plant quality in nutrient solutions of 15.6° C and 23.3° C. Plants did not differ in weight or quality at harvest. It was concluded that root temperatures in the range of 15.6 - 23.3° C (60 - 75° F) were optimal but temperatures exceeding 27.2° C (80° F) harmed growth and quality.

Harvesting and Packing. The greatest expense in producing lettuce is in the harvesting and packing operations which can account for two-thirds of the total cost. Most of the expense was in labor. In the 1982 studies, the cost of production was as low as 21.3 cents per retail head while the unit cost of packaging can be as high as 26 cents per head.

Packaging individual heads in air-sealed plastic bags extended shelf-life up to three weeks and provided protection during transportation. This procedure has also been effective in Norway (Lawson, 1982). Sealing the heads in a CO_2 atmosphere had no apparent beneficial effect. The lettuce was also sealed with the roots intact, as researchers at General Mills (Mermelstein, 1980) had reported, such packaging keeps plants alive and unwilted for extended periods. This procedure has also been used by ICI in England (Shakesshaft, 1981). In the Arizona experiments, however, the roots-on package did not appear to increase shelf-life, tripled the cost of preparation and packing, increased product volume and weight for transportation, and was not particularly popular with wholesalers or retailers.

Conclusion

Deep flow hydroponics for lettuce production is technically sound but in most cases uneconomical in the United States, because lettuce can be grown year round in the open field at less cost per unit. Such a system may be better suited to tropical or certain desert regions where local open field production does not occur during the warmer months.

Also, production in northern latitudes, located long distances from southern production areas, appear to have economic potential. In these areas, such production systems deserve consideration, especially if automation begins to replace high labor cost in a time when consumers are beginning to demand new speciality high quality leafy vegetables.

Acknowledgments

The author would like to acknowledge Dr. Ed Glenn, Ms. Paula Cardran and Ms. Barbara Furer for their technical contribution to the lettuce research program. Paper # P-125933-12-01. CEAC, the Controlled Environment Agriculture Center, College of Agriculture and Life Sciences, The University of Arizona. (Deep Flow Hydroponics.doc)

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