NUTRIENT SOLUTIONS FOR WHEAT

W. E. Tottingham and E. J. Rankin[1]

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The following brief notes relate to collaborative work of the writers upon a project outlined by a special committee of the National Research Council (17). Publication in the present rather fragmentary condition is ventured in the hope that our observations may be of aid to others operating in the same field. Acknowledgment is hereby made of a grant from the research funds of the University of Wisconsin in support of this investigation.

Of the six possible three-salt combinations which can supply the six essential elements of a nutrient solution, exclusive of iron, as arranged in the plan for collaborators, Type VI was chosen for the present investigation. This type is composed of KH_2PO_4, $CaSO_4$, and $Mg(NO_3)_2$. Cultures of wheat were conducted in duplicate in the series of solutions of this type, following the prescribed plan. The results appear to justify no further statement here than that the agreement between duplicate cultures was generally very poor. It seemed probable that this condition was due in part to the very poor root development of the seedlings employed. The roots were short, and usually curved and discolored where they came in contact with the nutrient solution.

Shive's nutrient solution R5C2 (15) diluted to 0.1 the usual concentration is the medium prescribed for germination in this work. The pH of this nutrient solution, at the concentration commonly employed, is approximately 4.7 (16). It appeared possible that the poor root growth observed here was due partly to the acidity of this solution. With this possibility in mind, the following tests were undertaken. The seed used throughout was wheat of the Marquis variety, provided for collaborators by the committee in charge of the project. In tests other than the comparison of continuous with intermittent renewal of the solution, ferric citrate was used instead of ferric phosphate, as a source of iron.

pH in Relation to Germination

The best solution of the series tested by Livingston and Tottingham (9), R8C1, is unfavorable for the germination of wheat when continuously renewed at 0.001 the usual concentration of 1.75 atm. osmotic value. This solution is still decidedly acid, however, as indicated by the data of table 1, obtained by the use of Clark and Lubs' method (2):

[1] Published with permission of the director of the Wisconsin Experiment Station.

TABLE 1. *Change of pH Values of Solution R8C1, Type III, Three-Salt Solution*

Conc.	pH
Usual (1.75 atm.)	4.1
0.5 usual	4.3
0.1 usual	5.3
0.01 usual	5.4
0.001 usual	5.5

The same solution diluted to 0.1 its usual concentration was adjusted to pH values of 6.4 and 7.5 by the addition of KOH. When used as a medium for germination, including preliminary soaking of the seeds and suspension on netting upon the flowing solution, this nutrient solution at pH 6.4 gave root systems but little superior to those obtained at pH 5.3. At pH 7.5, however, the roots elongated in a satisfactory manner, so that the seedlings were employed in a test described later.

These results hardly agree with those of Hixon (4), who found pH values both below and above 6.0 favorable for elongation of roots in the germination of wheat. It should be noted, however, that his solutions were not renewed. Salter and McIlvaine (14), employing the method of intermittent renewal of nutrient solutions, reach conclusions directly opposed to ours, namely:

> Germination of the seed was found less sensitive to an acid reaction . . . . than was the subsequent growth of the seedling.

Their criterion of growth, however, was green weight of seedlings. Their photographs of wheat seedlings show best root development at pH 7.7. Inasmuch as wheat grows well at much lower pH values than 6.4, as shown by Duggar (3), and appears to be independent of hydrogen-ion concentration in yield of dry matter, at least in intermittently renewed solutions, as observed by Meir and Halsted (12) and by McCall and Haig (10), it seems possible that its peculiar sensitiveness to pH values during germination may be related to some factor inherent in the seed, such as the isoelectric points of its proteins.

The adjustment here developed seems to offer a means of providing more uniform seedlings for different collaborators, by use of a common solution for germination, should it seem advisable to continue such practice.

Comparison of Continuous with Intermittent Renewal of the Nutrient Solution

One of the fundamental desiderata of investigations with nutrient solutions is the avoidance of disturbing effects of the absorbing plant upon the concentrations and proportions of nutrients available to it. This point was stressed long ago by Nobbe (13) and has been re-emphasized by Hoagland (6).

For the present purpose Shive's solution R5C2 was employed. The seedlings were reared in flowing tap water tempered to about 25 degrees C. This water is drawn from Lake Mendota and has the following composition in p. p. m.:[2] K 2.2, Ca 19.8, Mg 21.6, P undetermined, S 5.0, N 1.1, pH approximately 7.5. It supports excellent growth of wheat seedlings, especially as regards the root systems. Three duplicate cultures of 5 plants each were mounted in wide-mouthed jars of about 480 cc. capacity (Mason pint jars) through which the nutrient solution flowed continuously at the rate of about 4 liters per jar daily. The nutrient solutions of three other similar cultures were renewed every third day. Finally, three duplicate cultures were grown in jars of about 240-cc. capacity and received fresh solution every third day. These cultures grew from February 14 to March 1, 1921. No climatic records were taken in the greenhouse during this period. The data of yields are assembled in table 2.

TABLE 2. *Influence on Growth of Proportion of Plants to Nutrient Solution*

Form of Renewal	Capacity of Culture Vessel	Average Length		Average Dry Weight	
		Roots	Tops	Roots	Tops
	Cc.	Mm.	Mm.	Mg.	Mg.
Continuous..........	480	121 (5)*	Not measured	114 (11)	232 (13)
3-day................	480	150 (8)		130 (16)	338 (23)
3-day................	240	121 (5)		140 (12)	353 (45)

* Average departure from mean.

On the basis of dry weight of plants produced, the method of intermittent renewal was superior to that of continuous replacement. These results are not in agreement with those of Trelease and Free (20), but the rates of continuous renewal, and probably also the climatic complex, differed in the two tests.

Conditions generally associated with injury from acid, such as darkening and withering of leaf tips, were apparent in all the cultures at the time of harvesting. They appeared earliest and most severely, however, in the cultures whose solutions were continuously renewed. We interpret this difference as due to the ability of the plants to reduce the hydrogen-ion concentration when the solutions were renewed at intervals, as demonstrated by Hoagland (7, p. 101), Toole and Tottingham (19) and Duggar (3, pp. 11, 15, 19). It may be noted that growth was most uniform in the cultures whose nutrient supply was continuously renewed. These results support the assumed importance of continuous renewal of nutrient solutions, or equivalent treatment, so that the plant may be subjected continuously to a constant composition of the nutrient medium.

[2] Compiled from data of the Wisconsin Geological and Natural History Survey and of the State Hygienic Laboratory.

Comparison of Different Concentrations and Renewal Rates of Solutions

Wheat seedlings reared on flowing tap water were mounted in groups of 5 in each 480-cc. jar. Three jars received Livingston and Tottingham's solution R8C1 diluted to 0.1 the usual concentration and renewed continuously, approximately at the rate of 2 liters per jar in 24 hours. A second group of three jars received 0.01 the usual concentration of the same solution at the rate of 4 liters per jar in 24 hours. Finally, a third set of jars received the solution at 0.001 the usual concentration at the rate of 8 liters per jar in 24 hours. It will be noted that the rates of renewal were not increased in proportion to the dilution of the nutrient solution. The proportions used were dictated largely by practical considerations of time and apparatus available.

The young plants were grown under these conditions from May 3 to May 16, 1921. During this period the atmospheric conditions of the greenhouse, as measured by atmometers (Livingston, 8), were as follows:

Mean daily evaporation from standard spherical white atmometer, 20.4 cc.
Mean daily evaporation from standard spherical black atmometer, 25.6 cc.
Ratio of black to white instrument, 1.25.

The cultures at 0.001 the usual concentration were discontinued on May 7, when the plants showed decided signs of withering, with little growth. At the time of discontinuing the series, the plants grown in 0.01 the usual concentration of solution were decidedly withered and had apparently ceased to grow, while the leaves of cultures grown in 0.1 the usual concentration of solution were beginning to turn yellow. The yields are presented in table 3.

Table 3. *Influence upon Growth of Concentration and Rate of Renewal of the Nutrient Solution*

Concentration of Solution	Rate of Supply	Average Length		Average Dry Weight	
		Tops	Roots	Tops	Roots
		Mm.	Mm.	Mg.	Mg.
0.1 usual	2 l. in 24 hr.	225 (38)*	84 (3)	201 (9)	117 (10)
0.01 "	4 " " " "	144 (19)	72 (3)	92 (27)	70 (3)
0.001 "	8 " " " "	Practically no growth			

* Average departure from mean.

From these data it appears that, for these rates of renewal, 0.01 the usual concentration of this nutrient solution was not nearly sufficient for maximum growth. The limits of practicability in rate of supply and degree of dilution of the solution for maximum growth are important points for further investigation.

Comparison of Different pH Values with Continuously Renewed Solutions

On the basis of the results of the preceding experiment, 0.1 the usual concentration of Livingston and Tottingham's solution R8C1 was chosen for this test. Two cultures were arranged at each of three degrees of acidity as follows: 5.3 pH, 6.4 pH, 7.5 pH. The pH values were adjusted by adding KOH with use of the appropriate indicators used by Clark and Lubs. For this purpose, 0.9 cc. of *N*/2 KOH per liter of diluted nutrient solution was required for the highest pH value and 0.5 cc. for the intermediate one. Seedlings reared in flowing tap water were grown in these solutions of different pH values, continuously renewed at approximately the rate of 2 liters per jar per 24 hours. The growth period extended from May 20 to June 7. During this time the atmometer measurements taken adjacent to the cultures were as follows:

Mean daily evaporation from standard spherical white atmometer, 19.1 cc.
Mean daily evaporation from standard spherical black atmometer, 25.1 cc.
Ratio of black to white instrument, 1.31.

The data of yields appear in table 4.

Table 4

pH Value of Solution	Average Length		Average Dry Weight	
	Tops	Roots	Tops	Roots
	Mm.	Mm.	Mg.	Mg.
5.3	182 (18)*	106 (6)	229 (9)	108 (5)
6.4	258 (45)	245 (33)	367 (76)	198 (17)
7.5	295 (58)	300 (75)	512 (218)	230 (35)
Second Test				
6.4	178 (3)	175 (25)	170 (9)	96 (3)
7.5	188 (0)	213 (13)	141 (5)	75 (3)

* Average departure from mean.

At the end of the test the plants grown at pH 5.3 had short root systems, especially as regards secondary roots, and the leaf tips were withered. Both of these conditions are characteristic of acid injury. The growth response at the two higher pH values was irregular. Both groups of plants at pH 6.4 were superior to those grown at pH 5.3, but one culture at the former pH value was much superior to the other in appearance of roots and tops. At pH 7.5 one culture was but little superior to the poorer one at pH 6.4, while the other gave profuse elongation of roots and development of tops.

In view of these discrepancies, the comparison of pH 6.4 and 7.5 was repeated. For this purpose seedlings were available which had been reared in Livingston and Tottingham's solution R8C1 at 0.1 the usual concentration and adjusted to pH 7.5. The plants grew in the solutions from June 7 to June 14. During this period the climatic measurements were as follows:

Mean daily evaporation from standard spherical white atmometer, 16.6 cc.
Mean daily evaporation from standard spherical black atmometer, 23.3 cc.
Ratio of black to white instrument, 1.40.

The growth data of this test also appear in table 4.

When dismounted, the appearance of the tops grown in the solution having a pH value of 7.5 was superior to that of plants grown at pH 6.4. The latter were developing yellow color in the leaves. The combined tests indicate that pH 7.5 excels pH 6.4 on the basis of elongation of the plants, but that the lower pH leads to greater production of dry matter. The latter result compares favorably with previous results from solutions intermittently renewed, which also have shown a favorable effect of slight acidity of the culture solution as measured by production of dry matter. As suggested by Meir and Halsted (12), however, solutions of relatively high hydrogen-ion concentration may be efficient on account of their correspondingly high phosphate content and resulting buffer capacity, rather than because of acidity *per se*. They may also favor availability of iron, as suggested by McCall and Haig (11).

Conclusions

The optimal nutrient conditions, as regards pH values, appear to differ as between the germination phase and the later growth of wheat. Hydrogen-ion concentrations which are endured by the wheat plant in intermittently renewed solutions become unendurable when the solution is continuously renewed. Certain pH values which restrict the elongation of stem and root in wheat appear to favor the production of dry matter in these organs.

The above noted relations enhance the importance of specification of the standards by which nutrient efficiency is to be measured. They also suggest the advisability of employing the method of continuous renewal of the nutrient solution, or equivalent procedure, for more rigid control of experimental conditions. Obviously, in its relation to agricultural practice, this suggestion involves consideration of the extent to which field crops modify the composition of the soil solution. Inasmuch as changes of concentration of the water-soluble constituents have been found to follow cropping of the soil (Stewart, 18; Burd, 1), there appears to be a considerable degree of practicability in the original plan of intermittent renewal of nutrient solutions.

Department of Agricultural Chemistry,
University of Wisconsin

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