Proceedings of the Iowa Academy of Science

Volume 58 | Annual Issue | Article 19

1951

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In recent years it has been shown, through the use of commercial ion-exchange material, that plants are able to utilize nitrate ions incorporated in soil or nutrient culture in an adsorbed state (Schlenkler, 1940, 1942; Converse, Gammon and Sayre, 1943; Graham and Albrecht, 1943; Jenny, 1946; Arnon and Grossenbacher, 1947; Hunter, 1948). In view of the apparent adsorptive power of pumice (Veller and Arutyunyan, 1933), it was of interest to determine whether this material could be utilized in plant nutrition studies to supply nitrogen as adsorbed nitrate. Although preliminary experimentation showed that the nitrate fixing capacity of pumice was very low, it did not indicate what portion of this nitrate was available for plant absorption. It was for this reason that this investigation was undertaken.

METHODS

The pumice used in this experiment had the same particle size and chemical composition as that previously employed (McIlrath, 1950). Preparation of the pumice for the adsorption of the nitrate ions consisted of leaching with agitation for 24 hours in 1N NaOH followed by thorough washing with distilled water. The pumice was then soaked in 0.5N HNO_3 for 48 hours and then washed in distilled water. Uniform quantities, 3900 grams dry weight, were placed in glazed jars and leached for an additional two weeks in distilled water. At this time one jar of the substrate was treated with 1N NaOH and the amount of nitrogen in the leachate determined (Table I).

Table I.

Comparison of initial milliequivalent quantity of adsorbed nitrate per jar of pumice (3900 gm. dry weight) and that remaining at the plant developmental stages of flowering and fruiting.

Initial quantity (0 weeks)	At flower stage (7th week)	At fruiting stage (12th week)
m.e.	m.e.	m.e.
57.14	2.55	0.28

Two series were established, one an inert quartz gravel culture in which all nutrient elements were supplied in a soluble form and the second a pumice series in which nitrate was supplied in the adsorbed state and all other ions in soluble form. These cultures will hereafter be referred to as the gravel and pumice series, respectively. The salts and their concentrations utilized in the nutrient solutions are indicated in Table II. The jars were drained weekly and renewed with two liters of solution at the concentrations indicated. All solutions were adjusted to pH 6.4 with NaOH before addition to the jars.

Table II.

Millimolar concentration of salts in nutrient solution added to gravel and pumice substrates.*

			First to fourth weeks					
Gravel	0.703	KNO_3	0.522	KH_2PO_4	0.591	$MgSO_4$	1.726	$Ca(NO_3)_2$
Pumice	0.708	KCl	0.522	KH_2PO_4	0.591	$MgSO_4$	1.769	$CaCl_2$
			Fifth to twelfth weeks					
Gravel	1.406	KNO_3	1.044	KH_2PO_4	1.182	$MgSO_4$	3.452	$Ca(NO_3)_2$
Pumice	1.416	KCl	1.044	KH_2PO_4	1.182	$MgSO_4$	3.538	$CaCl_2$

*Both series also received traces of boron, copper, iron, manganese and zinc in nutrient solutions.

Seeds of Pan America variety of tomato were germinated in flats of sand and at 24 days of age were transplanted into jars containing the gravel and pumice substrates. All records were initiated at this date. Plants were harvested for chemical analyses at five developmental stages, namely: (1) stem elongation, (2) flower bud primordia, (3) flowering (anthesis), (4) early fruit enlargement and (5) mid-fruiting, as described in an earlier publication (McIlrath, 1950). Sampling techniques and analytical procedures were the same as those previously employed (McIlrath, 1950).

Data and Discussion

Nutrient solution residues.—Analysis of the nutrient solution residues of the pumice series during the first four weeks indicated that a large percentage of the adsorbed nitrate was leached from the substrate during this time (Table III). Jenny (1946) observed that if an amberlite-nitrate system was added to a nutrient solution, substantial amounts of nitrate were liberated by hydrolysis and anion exchange. Similarly Arnon and Grossenbacher (1947) reported a considerable release of nitrate in a system in which all ions were adsorbed on amberlites. They suggested that this release was probably due, at least in part, to NaCl contamination. It is un-

Table III.
Milligram quantities of various elements in the nutrient solution residues of gravel and pumice substrates at the end of each week.

Weeks	Gravel					Pumice				
	Ca	K	Mg	N	P	Ca	K	Mg	N	P
2	63.9	68.0	25.5	110.2	25.5	153.1	33.5	25.5	212.5	37.5
3	99.9	39.4	33.4	97.8	20.7	132.0	28.8	33.0	163.7	12.8
4	86.4	14.3	26.8	81.2	33.5	101.7	22.6	19.0	57.7	12.8
5	43.3	10.2	8.9	30.0	10.5	29.9	7.0	6.3	4.5	6.1
6	14.5	0.0	1.7	5.3	1.8	25.8	3.6	3.6	0.8	3.1
7	39.4	3.2	1.1	6.8	0.5	86.1	17.4	13.0	1.4	8.8
8	36.0	0.0	4.7	2.9	T*	101.9	22.1	18.5	0.5	11.5
9	13.5	0.0	3.3	0.6	0.5	90.7	21.5	15.4	T*	14.2
10	12.8	0.0	6.6	1.4	T*	68.1	54.4	10.7	1.1	1.7
11	16.3	0.0	5.6	2.7	0.8	43.9	45.0	11.1	1.2	2.6
12	42.4	2.1	11.8	5.4	1.8	54.9	49.5	14.4	1.0	0.7

*T represents trace present.

known, however, whether the response observed with pumice is comparable to that of nitrate release from amberlite.

After the fourth week only small amounts of nitrogen were found in the solution residues of the pumice cultures indicating a great reduction in the rate of nitrate leaching (Table III). Although at a reduced rate, the leaching continued during the remainder of the experiment. By the twelfth week only a very small quantity of nitrogen remained on the pumice substrate (Table I). The pH of the nutrient solution residues of the pumice series was always lower than that of the original nutrient solution added (varied between pH 4.8 and pH 5.4). In contrast to this the pH of the nutrient residues of the gravel cultures was higher than that of the added solution (pH 6.8 to pH 7.4). Jenny (1946) noted a reduced pH value when working with carbonate free amberlite-nitrate systems with a high degree of saturation. With a low-degree of saturation, however, the supernatant liquids were distinctly alkaline. In the case of pumice no increase in pH was observed as the amount of adsorbed nitrate decreased. Since little is known as to the mechanism of nitrate adsorption by pumice any explanation of the leaching of this ion from the substrate and the pH changes of the nutrient solution is a matter of conjecture.

Plant growth.—During the first four weeks, when analyses of the nutrient solution residues indicated large amounts of soluble nitrogen, the plants on the pumice substrate were normal in their growth. They were, however, slightly shorter in stem height, had a smaller number of leaves, less total leaf area and less total shoot weight than

Table IV.

Mean stem height, number of leaves and total leaf area of plants of gravel and pumice series.

Weeks	Stem height, mm.		Number of leaves*		Total leaf area, sq. cm.	
	Gravel	Pumice	Gravel	Pumice	Gravel	Pumice
2	70.0	60.0	5.7	4.3	....	....
3	126.9	105.0	7.5	6.5	39.0	19.7
4	168.1	136.3	9.5	8.3	66.2	45.8
5	268.7	220.8	12.5	10.5	....	....
6	371.7	295.0	14.7	12.0	....	....
7	475.0	366.7	16.4	13.0 (10.7)	181.4	111.9
8	572.0	450.0	18.0	13.8 (10.8)	....	....
9	690.0	540.0	20.8	15.6 (12.6)	292.2	100.8+
10	752.5	555.0	22.3	16.4 (11.3)	....	....
11	810.0	570.0	24.0 (22.5)	17.3 (13.0)	....	....
12	872.5	580.0	26.0 (24.5)	17.8 (12.8)	318.8	74.9+

*Values within parentheses are mean values excluding leaves that had abscised.
+Less than value above due to leaf abscission.

plants grown on gravel (Tables IV and V). This smaller size of the plants on pumice may have been due in part to the less favorable pH of these cultures. In spite of the smaller size of the shoot as indicated by the growth measurement given above, the plants on pumice at the end of the fourth week (flower bud primordia stage) had a greater total fresh and dry weight (Table V). The predominant factor accounting for this was their more extensive root systems. A large root system in relation to shoot size (small T/R ratio) has been previously shown to be characteristic of plants grown on a pumice substrate (McIlrath, 1948, 1950). In this experiment, however, this relationship has been intensified by the limited nitrogen supply (Tables III and VI).

At the end of the fifth week, by which time the soluble nitrogen in the jar residues had fallen to a very low level, nitrogen deficiency symptoms were noted in plants of the pumice series. By the end of the sixth week this deficiency had become extreme (Fig. 1). Concurrent with the onset of extreme nitrogen deficiency determination of the residual nitrate on the substrate showed that it was at a very low level (Table I).

With the appearance of nitrogen deficiency symptoms plant growth was greatly retarded. From the seventh to the twelfth week the plants of the pumice series initiated only about one-half as many new leaves as the plants on gravel (Table IV). During the seventh week the lower leaves began to abscise from plants of the pumice series, with abscission continuing during the remaining five weeks

Table V.

Fresh weight per plant in grams, percentage dry weight and top/root ratio at various developmental stages.

Stage		Gravel				Pumice			
		Roots	Stems	Leaves	Fruits	Roots	Stems	Leaves	Fruits
Elongation	Fresh wt.	0.8	1.8	4.6	....	0.8	0.8	1.9	....
	% dry wt.	5.9	4.2	7.5	....	9.8	4.4	8.5	....
	T/R ratio*	7.6—8.2				3.4—2.4			
Flower Bud Primordia	Fresh wt.	1.6	4.9	13.2	....	8.3	4.3	11.2	....
	% dry wt.	7.6	5.2	9.0	....	7.6	6.0	11.4	....
	T/R ratio*	11.3—7.3				1.9—2.2			
Flowering	Fresh wt.	41.9	36.1	124.2	....	38.0	25.4	52.7	....
	% dry wt.	10.6	10.0	1.08	....	12.7	16.0	14.3	....
	T/R ratio*	3.8—3.9				2.1—2.4			
Fruit Enlargement	Fresh wt.	89.2	87.2	263.7	....	31.6	23.0	38.5	....
	% dry wt.	8.8	13.4	12.5	....	11.5	19.1	13.9	....
	T/R ratio*	3.9—5.7				2.0—2.7			
Mid-fruiting	Fresh wt.	101.1	104.2	326.7	676.3	42.8	29.7	43.7	31.9
	% dry wt.	9.1	16.8	14.2	6.2	11.0	11.2	15.2	7.5
	T/R ratio*	11.0—11.5				2.5—3.3			

*First figure represents ratio on fresh weight basis; second on dry weight basis.

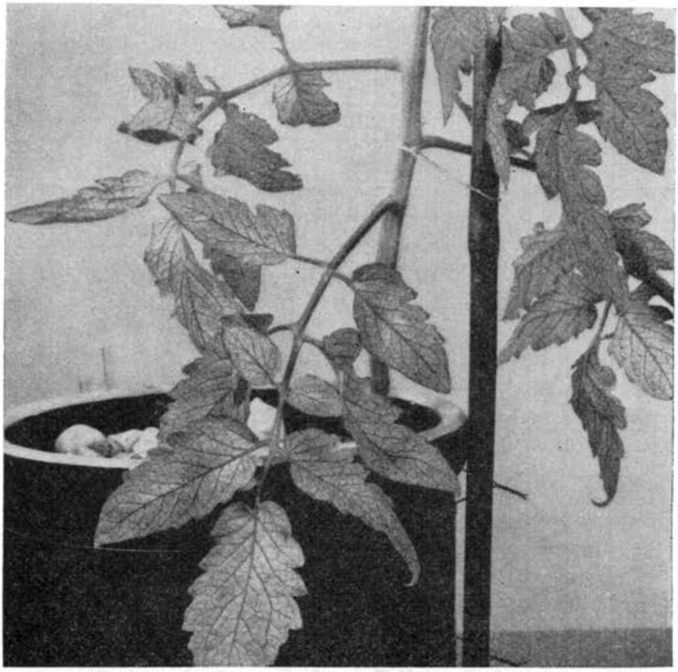

Figure 1. Plant from the pumice series at the end of sixth week showing high degree of vein pigmentation, a manifestation of extreme nitrogen deficiency.

of the experiment. At the end of the twelfth week 28.1 percent of the leaves of the plants of the pumice series had abscised as compared to 5.8 percent for the plants grown on gravel.

Total fruit yield of the pumice grown plants was less than 10 percent of the plants on gravel. Fruit set occurred only on the first inflorescence of the pumice grown plants, all other flowers abscising (Fig. 2). The fruit that did develop was extremely small in comparison to that produced at the first inflorescence of plants of the gravel cultures (Fig. 2). The percentage dry weight of all organs, with the exception of roots at flower primordia and stems at mid-fruiting, was greatest for the pumice grown plants (Table V). This fact is undoubtedly correlated with low nitrogen supply in the pumice cultures (Janssen, Bartholomew and Watts, 1934).

Plant analyses.—At the stem elongation and flower bud primordia stages the percentage composition of the various elements was slightly less in the plants of the pumice series. The total quantity of the various individual elements at the elongation stage was significantly less (Fig. 3). At the formation of floral primordia although the percentage of the various elements was less in plants of the pumice series, as compared to those grown on gravel, the total

Figure 2. Plants of the pumice (left) and gravel (right) series at mid-fruiting stage.

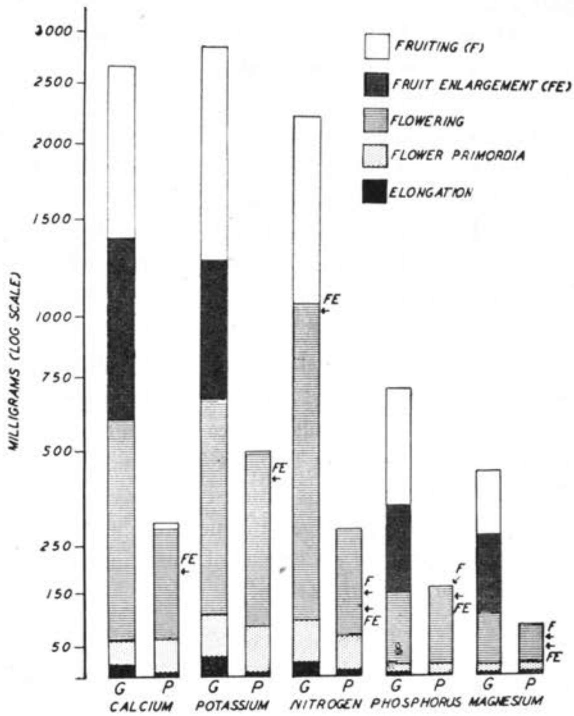

Figure 3. Total quantities of various elements in plants of gravel (G) and pumice (P) series at different developmental stages.

Table VI.
Nitrogen composition of plants on gravel and pumice substrates at various developmental stages expressed as percentage of dry weight.

Stage	Gravel				Pumice			
	Roots	Stems	Leaves	Fruits	Roots	Stems	Leaves	Fruits
Elongation (3 weeks)	2.78	2.33	5.48	......	1.99	2.33	5.21	......
Flower bud primordia (4 weeks)	3.28	2.64	6.74	......	2.36	1.45	3.75	......
Flowering (7 weeks)	3.56	3.55	5.73	......	1.68	1.29	1.99	......
Fruit enlargement (9 weeks)	2.21	1.29	2.13	......	1.15	0.49	0.96	......
Mid-fruiting (12 weeks)	1.88	0.96	1.71	2.68	0.84	0.35	0.84	1.00

amounts of calcium, magnesium and phosphorus were slightly greater (Figure 3).

With the exception of the percentage magnesium in the roots, the plants of the pumice series, as compared to gravel, at the flowering stage had a lower elemental percentage concentration and total amount of calcium, potassium, magnesium and nitrogen (Table VI). The percentage and total amount of phosphorus, however, was higher. Since severe nitrogen deficiency was evident at this developmental stage, this observation is in accord with that of McCalla and Woodford (1938). They found with wheat that when nitrogen was limiting, the effect was felt chiefly in increased phosphorus absorption.

At the stages of fruit enlargement and mid-fruiting the total quantity of all elements was significantly less in the plants of the pumice series (Figure 3). At fruit enlargement the total quantity of the various elements was less than at the preceding stage of flowering because of the onset of extensive leaf abscission. At these two latter developmental stages the percentages of potassium and phosphorus were higher in all tissues of the pumice plants with the exception of phosphorus in the fruits.

Conclusions

It is apparent from this investigation that the chief disadvantage in the use of a pumice-nitrate complex as a source of nitrogen for plant growth is pumice's extremely low nitrate adsorptive capacity.

This limits its use to studies of very short duration or the utilization of plants with a much lower nitrogen requirement than that of the tomato plant.

The results of this experiment seem to indicate that the nitrate is not strongly bound to the pumice substrate and that a major portion of that initially adsorbed becomes readily available for plant utilization. The mechanism of the release of nitrate from the substrate in this case is unknown.

The appearance of nitrogen deficiency in the plants of this experiment could have been delayed if the leachates at the end of each week had been returned to the jars, in that over 50 percent of the nitrate initially adsorbed on the pumice was lost in discard of the leachate.

Summary

1. This investigation employing tomato, variety Pan American, was undertaken to determine the availability of nitrate adsorbed on a pumice substrate for plant growth when all other essential elements were supplied in a nutrient solution.
2. Although the nitrate adsorption capacity of pumice was very low, a major portion of the nitrate became available for plant utilization under the conditions of this experiment. The mechanism of the release of nitrate from the substrate is unknown.
3. Growth of plants on the pumice substrate was normal until the available supply of nitrogen became a limiting factor.
4. One of the chief limitations of a pumice-nitrate complex in nutritional experiments appears to be the very small amount of nitrogen that can be supplied by such a complex.

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