

DOCTORAL DISSERTATION SERIES

TITLE AVAILABILITY TO PLANTS OF IRON
AND MANGANESE IN GLASSY FRITS

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UNIVERSITY MICHIGAN STATE COLL. DATE 1951

DEGREE Ph. D. PUBLICATION NO. 4503



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AVAILABILITY TO PLANTS OF IRON AND MANGANESE
IN GLASSY FRITS

by

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A THESIS

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Botany and Plant Pathology

1951

Acknowledgement

It is a pleasure to express my appreciation to Dr. F. L. Wynd under whose continuous encouragement and helpfull suggestions this work has been carried out, and to whom the results are herewith dedicated.

I also deeply appreciate the financial support of the Ferro-Enamel Corporation of Cleveland, Ohio, and the scholarship provided by Michigan State College for the past two years which made it possible for me to carry out these investigations.

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May, 1951

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Final examination, May 18, 1951, 10:00 A.M., Room 450, Natural Science Building

Dissertation: Availability to Plants of Iron and Manganese in Glassy Frits

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I. INTRODUCTION

The results of many experiments have demonstrated the importance of minor elements in plant nutrition. Two of these elements, iron and manganese, have been given broad consideration because they in so many instances have been found to be limiting nutritional factors in crop production. Both elements are common in soils, and since they are needed by plants in minute quantities, they are usually present in the soil in adequate amounts for plant growth. The reason for the occurrence of deficiencies of these elements is to be found in chemical and physiological processes which render them unavailable to the plants or make them inactive in their physiological functions within the plant.

An example of a disturbance in the iron nutrition of plants is the so-called lime induced chlorosis which is the limiting factor in the production of certain tree fruits in several parts of the world. Bennett (1927) and Wallace (1929) have demonstrated that this type of chlorosis can be eliminated by sprays or by injections of iron salts. Lime induced chlorosis has been thought to be due to a high calcium carbonate content of the soil which will raise the pH value of the soil to such an extent that iron is precipitated and made unavailable to the plants.

It has, however, been observed by Lindner and Harley (1944), Wallace (1928) and other workers that the concentration of iron in the dry matter of chlorotic leaves is not significantly different from that in comparable green leaves. Thorne and Wallace (1944), on

the other hand, have found significantly higher concentrations of iron in healthy leaves than in comparable chlorotic leaves, when the data are expressed on the basis of leaf area. The physiological disturbance causing the chlorosis is far from being fully understood, but it may be pointed out, as concluded by Wallace and Hewitt (1946), that the evidence suggests that the mobility of iron, both in the external medium and within the plant, plays a role in the disease.

Although lime induced chlorosis no doubt is the most important cause of iron deficiency, other causes of iron deficiency may also be of importance under certain conditions. Olsen (1935) has demonstrated in solution cultures at a neutral or alkaline reaction an interrelationship between phosphorus and iron resulting in iron deficiency. Chandler and Scarseth (1941) found that the application of phosphate to a slightly alkaline and to a highly calcareous clay, in both cases, produced iron chlorosis in peanuts. Similar results are reported by Sideris and Kraus (1933).

McGeorge (1923), Johnson (1924), Rippel (1923), and Somers and Shive (1942) have shown that a high manganese level in soils or in nutrient solutions will induce chlorosis in plants and that this chlorosis can be overcome by increasing the iron concentration in the nutrient solution or by sprays of iron salts. The interrelationship thus found to exist between manganese and iron is of considerable importance on certain soils, rich in manganese, in the Hawaiian Islands, and a continuous application of iron to the plants is necessary in order to avoid chlorosis.

While iron chlorosis may be due to a number of factors, the occurrence of manganese deficiencies is, as pointed out by Conner (1932) and Willis (1932), mainly due to oxidation and precipitation of the manganese in the soil, the oxidized form being unavailable to the plants.

Schreiner and Dawson (1927), Skinner and Ruorecht (1930), and others have observed manganese deficiency in various crops grown on calcareous soils. Zimmerley (1926) and Gilbert, McLean and Hardin (1926) observed the same deficiency symptoms in crops grown on heavily limed soil.

The most prominent case of manganese deficiency in crops is perhaps the so-called "gray speck" disease of oats which is common in several parts of Europe and Australia. The Australian workers Samuel and Piper (1928) have proved that the disease was identical with manganese deficiency. Manganese deficiency on oats has been reported by Willis (1928) and Alberts (1934) to occur on the eastern coastal plains in the United States and by Sherman and Harner (1941) to occur in alkaline organic soils of Michigan. It is now generally accepted that manganese deficiencies may occur when the soil is limed above $\text{pH} = 6.5$ and when the soil has strong oxidizing tendencies.

The importance of iron and manganese deficiencies lies in the difficulty with which they are controlled. Soil treatments with salts of these elements, or with sulfur to make the soil more acid, are generally unsatisfactory and of limited application, since the

conditions in the soil causing the original deficiencies still exist.

Skinner and Ruprecht (1930) concluded from their experiments with truck crops on calcareous soil that much of the manganese added to the soil became insoluble within three months. Gilbert (1934) concludes that it seems necessary to apply manganese before each crop under alkaline soil conditions. Wallace and Ogelvie (1941) found that manganese sulfate and manganese chloride used as fertilizers at a rate equivalent to 100 pounds of manganese sulfate per acre, were effective in combating manganese deficiency in Globe beets only during the early stages of their growth. Vain, Silk and Wills (1943) treated soils in the laboratory and in the field with solutions of manganese sulfate and then examined at intervals the amounts of manganese which could be extracted with neutral 1 N ammonium acetate. They found in an experiment with a highly calcareous soil that the extractable manganese down to a depth of 12 inches fell to its original level only seven days after treatment.

To avoid the influence of the disturbing soil factors, resort has been made to spraying and injection of iron and manganese salts. The latter of these two alternatives can only be applied to trees, and although effective on some trees, may give rise to gumming of stone fruits (Wallace, 1929), besides being tedious to carry out. Sprays are cumbersome, and sometimes unsatisfactory since they are often damaging at effective concentrations. In case of lime induced chlorosis several applications must be made during a single season to keep the

plants sufficiently well supplied with iron, because the iron in such instances is relatively immobile.

In lieu of the difficulties thus encountered in maintaining a sufficient supply of available iron and manganese, the possibility of supplying the elements by adding slowly available compounds or artificially prepared physical complexes to the soil presents an intriguing approach to the problem.

The material should ideally have the following properties: (1) The solubility in water should be relatively small in order to prevent the elements from leaching, and also to prevent them from being rendered unavailable to the plants through chemical reactions in the soil. The absorption by the plant root would, therefore, necessarily have to take place directly by contact between the plant root and the material. (2) The material should be nontoxic to plants in high concentrations so that large amounts could be applied at once to furnish an ample supply of the nutrient over a long period. (3) The rate of release of the nutrients from the material should be adequate for plant growth, but must not attain a toxic magnitude.

The implication of a contact absorption does not present any serious objection to the development of such a material. An active role played by the absorbing root surfaces in releasing nutrient elements from the solid phase of the soil has already been recognized, and a mechanism of this absorption has been suggested by Jenny (1938). According to Jenny, colloiddally adsorbed nutrients may be absorbed

directly by the plant roots without the intervention of water solubility when there is a contact between the colloidal particles and the absorbing surface of the plant root. The reaction taking place is described as being merely an exchange of adsorbed ions.

This mechanism will, of course, not explain a possible release to the plant roots of nutrient elements held in a crystalline or amorphous matrix. There exists, however, good evidence that plant roots have the ability to break down such structures to a limited extent and to obtain nutrients during the process. In recent years, it has been observed that the highly insoluble mineral magnetite may serve as a source of iron for plants in hydroponic cultures. Eaton (1936) claims that 0.1 percent of magnetite mixed with quartz sand makes unnecessary the use of soluble iron in the culture solutions maintained on the acid side of neutrality, and that a number of crop plants obtain sufficient amounts of iron from magnetite even when the pH value is as high as 8. Chapman (1939) reported that Citrus seedlings grow successfully in quartz gravel containing 0.1 gram of magnetite per 100 grams of gravel flooded with a nutrient solution at pH value from 5.8 to 7.0. He found that the addition of calcium carbonate to the gravel resulted in chlorosis unless the amount of magnetite was correspondingly increased. This experiment indicates that there must be a sufficient area of contact between the magnetite and the plant roots in order to prevent chlorosis.

Guest (1944) used bentonite and magnetite incorporated into quartz sand as a solid-phase source of certain nutrients in hydroponic cultures. He found that even at alkaline reactions of the nutrient solution, chlorosis did not appear in Citrus seedlings as long as the magnetite was finely ground in order to present a large surface area. Incorporation of finely ground dolomite in the sand induced chlorosis which he assumed was due to interference of solid dolomite particles with the contact between the roots and the magnetite particles.

The present study was carried out in order to investigate the possibility of compounding relatively insoluble glassy frits in such a manner that certain plant nutrients would be held in a relatively insoluble form, but would be released to the absorbing root surface when a contact is established between the root and the frit particle.

The material which has been studied is a product of the porcelain enamel industry. It has an amorphous structure, and its physical and chemical properties can be varied within wide limits by changing the raw composition and the manufacturing procedure.

The technical problem involved in the study is, therefore, to prepare frits in which plant nutrients are held in the amorphous matrix with sufficient forces to prevent their dissolution in water, but which are not strong enough to prevent their release and subsequent absorption by plant roots acting on the matrix.

Badger and Bray (1945) were the first ones to describe the possibility of using especially compounded glasses as a source of plant nutrients. These authors attempted to prepare glasses of such a high

solubility that the rate of disintegration in water would be sufficient to support plant growth. Studies were made on the effect of melting temperature on the solubility of the products manufactured from mixtures of rock phosphate, potash and silica, and it was found that glasses may be prepared which are surprisingly soluble with respect to phosphorus and potassium. The work was not extended to include other elements, nor were any nutrition experiments carried out. There is reason to believe that their material would have a strong tendency to raise the pH value of the medium in which it was dissolved. No pH measurements, however, were reported.

The purpose of the present study was to explore the value of glassy frits as a source of iron and manganese for plants, and especially to determine the importance of the pH value of the medium on the release of iron and manganese to the plant and on the release of these nutrients by aqueous solubility of the frit material.

II. EXPERIMENTAL METHODS AND MATERIALS

The availability of iron and manganese in frits was studied in greenhouse experiments in which wheat seedlings were grown in hydroponic pot cultures using the frit in place of gravel. A quartz culture served as control to each individual frit culture, by being flooded repeatedly with identical nutrient solution, in a manner to be described below. The difference in growth and chemical composition of the plants in the two cultures could be taken as a measure of the relative importance of contact absorption and absorption based on the aqueous solubility of the frit constituents.

A. Mechanical arrangement of the cultures

The culture pots were one-gallon, glazed earthenware pots. A hole three-quarters of an inch in diameter was located near the base of the wall of the pot. Through this hole the nutrient solution was introduced at regular intervals by an automatic subirrigation system. The details of the automatic system employed are shown in figure 1. The carboy C contained 16 liters of nutrient solution. At intervals of four hours an electric time clock turned on an electrically driven air pump for seven minutes. The air from the pump entered the main air line (D) running underneath the greenhouse table and forced the nutrient solution upwards flooding the pots A and B simultaneously. Culture pot A contained the experimental frit, while pot B contained quartz gravel equal in particle size to that of the frit. A hydrostatic

water column (E) was connected to the end of the main air pressure line. The maximum pressure in the line could thus be regulated by altering the height of the column. Since the volume of the nutrient solution in the carboy greatly exceeded the volume needed to fill the two culture pots, A and B which it supplied, an accurate regulation of the air pressure was necessary in order to prevent the excess nutrient solution from being forced over the rim of the culture pots. The end of the glass tubing leading the nutrient solution into the pot, was inserted into a six-inch test tube (F), the opening of which was covered with a thin layer of glass wool. Thus the material in the pot was prevented from entering the glass tube and the nutrient solution in the carboy.

A total of 44 pairs of pots were arranged on two parallel, adjacent greenhouse tables, as shown on plates I, II, and III. One air pressure system controlled simultaneously the entry of nutrient solution in all of the cultures.

When the electric time clock shut off the motor driven air pump, the solution in the culture pots drained back into the carboys. It is apparent that pot A and B were supplied with an identical nutrient solution. Any soluble material released from the frit in pot A would become equally distributed between pot A and its corresponding quartz control culture B. If the experimental frit released soluble nutrients, both cultures would profit equally. If, on the other hand, the plants growing in the frit were able to obtain nutrients by contact

absorption, the plants growing in the corresponding quartz culture would be expected to be inferior to those growing in the frit, providing the nutrient solution was deficient in one or more of the nutrients furnished by the frit.

All frits were studied in duplicate, and each frit culture was coupled with its individual corresponding quartz culture.

B. Nutrient Solutions

As the purpose of this study was to determine the availability of iron and manganese in frits, two types of frits were used, one containing iron but no manganese, and one containing both iron and manganese. Consequently, the nutrient solution which flooded the pots containing the iron frit was complete except that no iron was added, while the nutrient solution flooding the iron-manganese frit was complete except that neither iron nor manganese was added.

A three-salt solution, similar to that of Shive (1915), was used, and its final composition was as follows:

Salt	Grams per liter
$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	3.70
$\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$	1.23
KH_2PO_4	2.76

Concentrated stock solutions of each salt were made up separately with the following concentrations:

Salt	Grams per liter
$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	296
$\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$	98
KH_2PO_4	221

Each carboy, containing 15 liters of distilled water, received 200 milliliters of each of these stock solutions, and then distilled water was added to bring the total volume to 16 liters.

Micro-nutrients were supplied by adding 16 milliliters to each carboy of a stock solution having the following composition:

Salt	Grams per liter
HBO_3	2.860
$\text{MnSO}_4 \cdot 7\text{H}_2\text{O}$	0.220
MoO_3	0.007
$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$	0.080

The final concentration of the micro-nutrients in the culture solutions was as follows:

Element	Parts per million
Boron	0.50
Zinc	0.05
Molybdenum	0.05
Copper	0.02

To the culture solutions flooding the frits containing iron but no manganese, 16 milliliters of a stock solution containing 1.538 grams of $\text{MnSO}_4 \cdot \text{H}_2\text{O}$ per liter were added per carboy. The final concentration of manganese in the solution was approximately 0.5 parts per million.

Absolute control cultures with quartz gravel in pot A as well as in pot B (figure 1) were arranged in the same manner as described above. Iron and manganese were added to the nutrient solutions according to the following table:

Absolute control culture	Micro-nutrients	Parts per million of Fe	Mn
1	Iron and manganese	4.0	0.5
2	Manganese only	0	0.5
3	Iron only	4.0	0
4	No iron and no manganese	0	0

Each culture was run in triplicate. Iron was supplied by adding ten milliliters of a stock solution made up as follows: 6.40 grams of electrolytic iron was dissolved in 12 milliliters of concentrated sulphuric acid. The solution was transferred to a 1000 milliliters volumetric flask half filled with distilled water. After cooling the solution was brought to volume with distilled water.

Since the acidity of the nutrient solution may be a major factor determining the rate at which frit constituents are brought into solution, a constant pH value was maintained in the nutrient solutions

throughout each experiment. The pH value of the solution in each individual carboy was determined twice a week with a glass electrode and, if necessary, adjusted to the proper value by the addition of a 1 N sulphuric acid solution or a 1 N potassium hydroxide solution. The pH values of the nutrient solutions were maintained within 0.2 pH unit from the value originally decided upon for the experiment.

C. Plant Material

Forty-five seeds of wheat, variety "ILLINOIS" harvested in 1948, were planted an inch deep in the culture media. From 30 to 40 plants were obtained in each pot. No effort was made to obtain a uniform number of plants per pot since the removal of plants severely disturbed the root system of the remaining plants. The plants were harvested when they had reached the jointing stage, and each experiment lasted for about 45 days.

The roots of the plants were separated from the tops and discarded. The lower part of the stems, which had been in contact with the nutrient solution, was washed in running tap water, rinsed in distilled water, and gently wiped dry with a cheesecloth.

The plants were dried in a forced-air chamber at a temperature of 60° C.

D. Methods of chemical analysis

1. Plant material

A one gram sample of the dry and finely ground plant material

was weighed into a platinum crucible and placed in a cold electric muffle. The temperature was gradually increased until smoking began, and held constant until heavy smoke was no longer given off. The temperature was then increased to 850° C. and maintained at that level for two hours.

After cooling, the ash was wetted with one milliliter of a 1:4 sulphuric acid solution, about five milliliters of concentrated hydrofluoric acid was added, and the crucible was then placed on a hot plate at low heat. The solution was evaporated until a viscous residue was left in the crucible. About ten milliliters of a 0.1 N nitric acid solution were added while the crucible remained on the hot plate. The dissolved residue was transferred to a 50 milliliters volumetric flask. After cooling, the solution was made to volume with 0.1 N nitric acid.

Iron in the ash solution was determined colorimetrically by the o-phenanthroline method described by Hummell and Willard (1938). The detailed procedure is given in appendix 1. Manganese in the ash solution was determined colorimetrically by the periodate method described by Willard and Greathouse (1917). Detailed procedure is given in appendix 2.

2. Nutrient solutions

Samples of the nutrient solutions were collected after the completion of the individual experiments. In order to obtain a representative sample, five milliliters of concentrated sulphuric acid were added to each carboy, the acidified solution was well shaken, and the sample

collected while the carboy was emptied.

The sample was filtered, and 500 milliliters of the solution were transferred to a 600 milliliter beaker, and evaporated on a hot plate until the volume was about 50 milliliters. The concentrated solution was transferred to a 100 milliliter flask. After cooling, the solution was made to volume with distilled water.

Iron and manganese in the concentrated sample of the nutrient solution, was determined by the same method as used for the plant material (see appendix 1 and 2).

The concentrations of potassium and sodium in the nutrient solution were determined by the Perkin-Elmer flame photometer, Model No. 520, using an acetylene flame. A 2-milliliter aliquot of the concentrated nutrient solution was pipetted into a 50 milliliter volumetric flask and made to volume with distilled water. The concentration of potassium and sodium in this solution was determined according to the direct intensity method (see appendix 3).

E. Preparation of the frits

Technical grades of raw materials were used in compounding the experimental frits, such as powdered quartz, potassium carbonate, sodium carbonate, mono-calcium phosphate, etc. The well mixed components were melted in an electric smelter and held in the molten stage for 3.5 hours. The molten material was quenched by permitting it to flow into cold, running water. The material was fragmented into small pieces by the rapid cooling in the water. The moist, fragmented

material was cooled and dried in a commercial rotatory drying pan, and then the particles were graded for size in a series of screens. The material selected for the nutrition experiment was about one-eighth of an inch in diameter.

Before the frit was placed in the culture pots it was sieved through a 2 millimeter sieve in order to remove all finer particles. The material retained on the sieve was washed in tap water and finally rinsed thoroughly with distilled water after being placed in the pots. Two liters of frit were placed in each pot.

Quartz gravel was sieved in the same manner as described for the frit in order to obtain a uniform and equal particle size in the two comparable cultures. The quartz gravel was further spread out in a thin layer and thoroughly treated with a strong electro-magnet to remove any iron impurities. It was then soaked for several days in a dilute sulphuric acid solution (pH 2.5), thoroughly washed in tap water and finally rinsed in distilled water.

F. Composition of the frits

The composition of the frits used in the present study were based upon results obtained in previous studies with iron-containing frits. A report on the preliminary experiments has been given by Myrd (1950, 1951), and his results are summarized as follows:

The composition of the frits used in the preliminary experiments was based arbitrarily on the data presented by Badger and Bray (1945)

and the frits thus obtained varied greatly in solubility as determined by the method given in appendix 4. The solubility of the frits was found to have a marked influence on the growth of the plants, a high solubility (above 7.0 percent) made the nutrient solutions alkaline, thus creating a toxic condition for the plants. The most successful wheat cultures, comparing favorably in growth with absolute control cultures receiving a complete nutrient solution, were obtained with frits of relatively low solubility. Chlorosis would, however, appear in the later stages of the experimental period, and in later experiments the iron content of the frits was increased from 2.0 to 5.0 percent Fe_2O_3 .

Some of the frits thus developed produced plants which were green and healthy throughout the experimental period and which were superior in size to plants grown in the absolute control cultures receiving a complete nutrient solution. In table 1, the composition and the solubility of the newer frits are listed. The table includes three groups of frits representing three different levels of silica content. Within each group a decrease in the percentage of CaO , MgO , K_2O , and Na_2O with a corresponding increase in the phosphorus content resulted in a decrease in solubility.

Of the frits listed in table 1, 6238-C and 6224-C produced the best plants as judged by the fresh weight obtained, 6238-C produced slightly higher fresh weights than did 6224-C. Based on the total amount of iron absorbed per plant however, 6224-C gave a higher value

than 6238-C. The basic formulae represented by these two frits were, therefore, selected for the present study. Since both frits had proved successful, the investigations had reached the point where it was appropriate to explore the effects of changes in the iron content. At this stage manganese was also included in the study, and the four series of frits listed in table 2, were prepared for the present study.

The 6285 and 6287 frit series in table 2 conform to the basic formula represented by 6238-C in table 1, and the 6286 and 6288 series conform to the basic formula represented by 6224-C in table 1. The variation in iron and manganese in the new frits, as shown in table 2, has been compensated for by a change in all the other constituents to avoid any appreciable deviation from the basic formula with subsequent change in solubility.

All frits listed were studied simultaneously at various pH levels of the nutrient solution. The following experiments were carried out:

Experiment No.	pH of nutrient solution	Experimental period	Total number of days
1	6.0	June 13—July 26	43
2	7.0	Sept. 10—Oct. 24	44
3	4.0	Nov. 7—Dec. 22	45
4	5.0	Dec. 28—Feb. 14	48

III. EXPERIMENTAL RESULTS

A. Visual appearance of the plants

1. At pH 4.0 of the nutrient solution. The experiment with the nutrient solutions at pH = 4.0 was carried out during the months of November and December and the plants grew relatively slowly because of the low light intensity. In spite of the slow growth, pronounced differences in the size of the plants and in the color of the leaves was observed between the plants grown in frit and those grown in quartz. In all instances, the size of the plants in the frit cultures was larger than that of the plants in the corresponding quartz cultures. In most instances, the plants which were grown in the frits exhibited a darker green color than did those grown in the corresponding quartz cultures.

It was noticeable also that the plants grown on the frits of the 6285 and the 6287 series with low SiO_2 content were larger than the plants grown on the frits of the 6286 and 6288 series with high SiO_2 content. Similar differences were observed between the plants grown in the respective quartz control cultures, the largest plants being associated with the largest frit-grown plants.

Within the cultures of each series of frits, no visible differences were apparent. This indicated that the different iron or manganese contents of the frits exerted no effect on the plants which was visibly evident.

The color of the absolute control plants grown without iron was

less green than the color of the plants supplied with complete nutrient solution. No deficiency symptoms were observed in those absolute control cultures from which manganese was excluded. Although the size of the iron deficient plants was not appreciably smaller than the size of the ones receiving complete nutrient solution, it was apparent, however, that the plants receiving a complete nutrient solution were smaller than the plants grown in the frits of the 6285 and 6287 series.

2. At pH 5.0 of the nutrient solution. The experiment was carried out during the months of January and February. The installation of adequate artificial light materially improved the growth of the plants.

The control plants showed signs of chlorosis early in the experimental period and the growth was markedly inhibited. All of the frit grown plants, however, were still green and healthy at the end of the experimental period.

Again it was observed that the frit series 6285 and 6287 produced larger plants than did the 6286 and 6288 frit series, and a similar difference was again noticeable between the corresponding control plants. Therefore, the control plants corresponding to the 6285 and 6287 frit series were larger than the control plants corresponding to the 6286 and 6288 frit series.

The plants grown in frit had, in most instances, started to joint at the time of harvest, while very few of the control plants had reached the jointing stage when they were harvested.

Within each frit series, no marked visible differences in the plants were associated with the differences in the iron or manganese

content of the frits. However, in case of the series 6287, the frit containing 2 percent of MnO_2 produced definitely taller plants than did the rest of the frits within this series. The corresponding control culture likewise produced definitely taller plants than did other control cultures in the series.

The absolute control cultures receiving no iron in the nutrient solution produced plants which were very chlorotic and the growth was obviously inhibited. Omission of manganese from the nutrient solution resulted in a slight chlorosis of the plants. The growth, however, seemed not to have been visibly inhibited by the chlorotic condition. The complete nutrient solution gave rise to normal healthy plants, but in no instances did the growth of these plants compare with that of the plants grown in the frits of the 6285 and 6287 series.

3. At pH 6.0 of the nutrient solution. The experiment was carried out during the months of June and July. It was, therefore, difficult to avoid high temperatures in the greenhouse on bright days and injury to the plants in the form of drying of the leaf tips was encountered in some instances.

The same general picture of the growth of the plants as described for the previous experiment also was apparent in this experiment. The control plants became chlorotic at an early stage of their development, and the size obtained by the control plants was markedly less than the size obtained by the plants grown in the corresponding frit cultures.

The plants grown on frit 6287-B (2.0 percent Fe_2O_3) reached an exceptional large size and the frits of the 6285 and 6287 series

produced plants of a size superior to that of the absolute control plants receiving complete nutrient solution (Plates IV, V, VI, and VII). Since one might expect precipitation of the iron in the nutrient solution at the high pH level used in this and the following experiment, the solutions receiving iron were thoroughly shaken once a day prior to flooding of the culture pots. Since the plants grown in the absolute control cultures receiving complete nutrient solution appeared green and healthy, this precaution was apparently sufficient to keep the plants supplied with iron. Still, the growth of these plants was inferior to the growth of the best frit grown plants (Plate VIII).

Manganese deficiency did not occur in this or in the following experiment when manganese was excluded from the nutrient solution of the absolute control cultures. Iron deficiency, on the other hand, became very prominent in the cultures not receiving iron in the nutrient solution (Plate IX).

4. At pH 7.0 of the nutrient solution. The plants in this experiment, which was carried out during the months of September and October, made a very slow growth which might be ascribed partly to low light intensity and partly to the unfavorable pH level of the nutrient solution.

The difference in growth between the plants in the frit cultures and the plants in the corresponding control cultures was here more pronounced than in any of the previous experiments. The control plants reached only about half the size obtained by the corresponding frit grown plants. The control plants were in all instances very chlorotic.

It was again easily observed that the plants grown in the frits of the 6285 and 6287 series were superior in size to the plants grown in the frits of the 6286 and 6288 series.

The development of the plants in the absolute control cultures was as described for the previous experiment.

5. Summary. The visual observations made of the development of the plants, can be summarized as follows: (1) The frit cultures produced normal, green plants over a range in pH from 4.0 to 7.0 of the nutrient solution. (2) The corresponding control cultures of these frits produced more or less chlorotic plants whose growth was inferior to that of the corresponding frit grown plants. The degree of chlorosis and the difference in growth between the control plants and the corresponding frit grown plants increased with increase in pH of the nutrient solution. (3) Frits of the series 6285 and 6287 produced at all pH levels conspicuously larger plants than the ones obtained in the absolute control cultures receiving complete nutrient solution. (4) The growth of the plants in the control cultures seemed to be related to the growth of the plants in the corresponding frit cultures in such a way that a good growth of the plants in the frit culture generally was associated with a good growth of the corresponding control plants.

The visible appearances of the frit grown plants clearly showed that the favorable effect of the frits, as compared to the corresponding control cultures, increased as the pH value of the nutrient solution increased.

B. Fresh weight of the plants

The fresh weights of the plants obtained in the individual cultures at the various levels of pH of the nutrient solution are listed in tables 3 and 4 (pH 4.0), tables 5 and 6 (pH 5.0), tables 7 and 8 (pH 6.0), and tables 9 and 10 (pH 7.0).

The data show that the fresh weights obtained in the individual frit cultures are, at all pH levels, significantly larger than the fresh weights obtained in the corresponding control cultures. Further, it will also be noticed that the fresh weight of the control plants is closely correlated with the fresh weight of the corresponding frit grown plants. Thus, a relatively large fresh weight of the plants grown in the frit was generally associated with a relatively large fresh weight of the corresponding control plants.

The frits of the 6285 and the 6286 series have invariably produced larger yields of fresh weight than have the frits of the 6286 and 6288 series, and, similarly, the fresh weights obtained in the control cultures corresponding to the 6285 and 6287 frit series are almost invariably larger than the fresh weights obtained in the control cultures corresponding to the 6286 and 6288 frit series.

The relative average fresh weight obtained in the individual cultures, calculated in percent of the average fresh weight obtained in the absolute control culture receiving complete nutrient solution, is plotted against frit composition in figures 2, 3, 4, and 5. These figures show that at all pH levels, the fresh weights obtained on the

6285 and 6287 frit cultures were significantly larger than the average fresh weight of the absolute control cultures receiving a complete nutrient solution. The same is true for the fresh weight obtained in the 6286 and 6288 frit cultures except when the nutrient solution was maintained at a pH of 5.0, in which case the plants grown in these frits obtained about the same fresh weight as the absolute control plants receiving complete nutrient solution.

The figures also demonstrate that within each individual frit series there was a change in fresh weight from one frit culture to another reflected in a parallel change in the fresh weight obtained in the corresponding control cultures. The figures do, however, not indicate that the fresh weights obtained have any correlation with the amount of iron or manganese present in the frit. At pH 5.0 and 6.0 of the nutrient solution (figures 3 and 4) frit No. 6287-B (2.0 percent MnO_2) gave rise to an exceptionally large fresh weight, which would indicate that this frit represents the most favorable composition with regard to iron and manganese.

The average fresh weight obtained in the control cultures within each individual frit series was calculated in percent of the average fresh weights obtained in the corresponding frit cultures, and the values obtained are plotted against pH of the nutrient solution in figure 6. The effect of raising the pH of the nutrient solution from 4.0 to 7.0 has been to increase the difference in fresh weight between the frit grown plants and the corresponding control plants. The

exceptionally low percentage value found at pH 5.0 of the nutrient solution, especially in the case of the 6288 frit series, can be explained as being due to a relatively large difference in the physiological age between the frit and the control plants in this particular experiment. At the time of harvest the frit plants had in most cases begun to joint, while the control plants had not reached the jointing stage. In the other experiments the plants were harvested at a somewhat earlier stage in their development.

C. Dry weight of plants

The dry weight of the plants obtained in the individual cultures at different levels of pH of the nutrient solution is listed in tables 11 and 12 (pH 4.0), 13 and 14 (pH 5.0), 15 and 16 (pH 6.0) and 17 and 18 (pH 7.0).

The data show that at all pH levels the dry weights obtained in the frit cultures were significantly larger than the dry weights obtained in the corresponding control cultures, and that the dry weight of the control plants is closely correlated with the dry weight of the plants grown in the corresponding frit cultures.

It is further noticed, from figures 7, 8, 9, and 10, that the frit series 6285 and 6287, at all pH levels, have produced significantly higher yields of dry plant material than did the absolute control culture receiving complete nutrient solution. The same result is obtained with respect to the frits of the 6286 and 6288 series except at pH 5.0 of the nutrient solution. At this pH the dry weight

of the plants grown in the 6286 and 6288 frits is not significantly different from the fresh weight obtained in the absolute control cultures receiving complete nutrient solution.

The figures do not indicate any correlation between the amount of iron or manganese present in the frit and the dry weight of the plants produced. It is, however, noticed that frit No. 6287-B (2.0 percent MnO_2) has increased the dry weight of the plants about 100 percent as compared to the dry weight obtained in the absolute control cultures receiving complete nutrient solution, and that frit No. 6285-C (7.5 percent Fe_2O_3) on the same basis has increased the dry weight about 80 percent.

The effect of pH of the nutrient solution on the relative difference in dry weight between the plants grown in frit and the ones grown in the corresponding control cultures is demonstrated in figure 11. It will be seen that the same relative differences were obtained for dry weight as were obtained with respect to fresh weight of the plants.

D. Absorption of iron by the plants

Surface contamination of dust may be a major source of error in iron determinations of plant material. Unfortunately, this error was not fully recognized in the present study until the plant material obtained from the two first experiments (pH 6.0 and 7.0) had been analyzed. The inconsistencies of the analytical data pointed towards serious contaminations of the material. In an attempt to eliminate this

error, the plants in the third experiment (pH 4.0) were washed by repeated dippings in distilled water shortly after they had been harvested. Somewhat more consistent results were thus obtained. A still higher degree of consistency was obtained, however, in the last experiment (pH 5.0) in which the plants were dipped several times in a dilute hydrochloric acid solution and rinsed in distilled water before they were placed in the drying oven.

1. Iron content as parts per million of dry tissue

a. At pH 4.0 of the nutrient solution. The iron content expressed as parts per million of oven dry material, is listed in tables 19 and 20. The differences in iron content between the plants grown in frit and the ones grown in the corresponding control cultures are, in most instances, smaller than the differences in iron content between plants grown in duplicate cultures. There is thus no basis to conclude that the plants grown in frit contain more iron per unit dry weight than the plants grown in the corresponding control cultures. Further, the data do not indicate that the amount of iron present in the frit has had any influence upon the concentration of iron in the dry material of the plants, nor is there any indication that the manganese content of the frit has had such an influence.

As shown in table 20, the addition of iron to the nutrient solution has had but little influence upon the concentration of iron in the dry matter of the plants grown in the absolute control cultures. In the case where manganese but no iron has been added to the solution a

slight depression of the iron concentration of the dry matter of the plants is observed.

b. At pH 5.0 of the nutrient solution. The iron content expressed as parts per million of the oven dry material is listed in tables 21 and 22. It will be seen from these tables, that even though there existed large differences in the data obtained from duplicate cultures, a consistently higher average value for iron content was obtained for the plants grown in frit than for those grown in the corresponding control cultures. Figure 12 demonstrates that the frit series 6285 has produced plants with a higher concentration of iron in the dry matter than has the frit series 6286, and, similarly, that the frit series 6287 has produced plants with a higher concentration of iron in the dry matter than the frit series 6288. A close parallelism between the frit and the corresponding control cultures with respect to iron concentration in the dry matter of the plants is characteristic for both iron-frit series.

From figure 12 it is also seen that the addition of manganese to the frits has increased the concentration of iron in the dry matter of the plants. This finding is not in accordance with the general belief that manganese has a depressing effect on the absorption of iron by plants. Such a depressing effect of manganese is, however, demonstrated by the data presented in table 22. It will be seen that when both iron and manganese are added to the nutrient solution of the absolute control cultures, the concentration of iron in the dry matter of the plants is less than when only iron is added.

Similarly, when only manganese is added, the concentration of iron in the dry matter is less than when none of the two elements is added.

c. At pH 6.0 and 7.0 of the nutrient solution. As already mentioned, no measures were taken in order to eliminate iron contamination of the material obtained in these experiments. It will be seen from tables 23, 24, 25, and 26 that the data obtained for iron content in the dry matter are of a higher order of magnitude than the corresponding data obtained in the previous experiments, and that the differences between the duplicate cultures are generally very large. No conclusion, therefore, can be drawn as to the relative concentration of iron in the plant material.

2. Total absorption of iron by the plants

a. At pH 4.0 of the nutrient solution. The concentration of iron in the dry matter of the plants grown in frit and the plants grown in the corresponding control cultures did, as already pointed out, not show any significant differences. The total amount of iron absorbed is, however, larger in the frit cultures than in the corresponding control cultures as shown in table 27. The plants grown in the frits of the 6285 and 6287 series have absorbed more iron than the plants grown in the frits of the 6286 and 6288 series. Further, the control plants corresponding to the 6285 and 6287 frit series have absorbed more iron than the control plants corresponding to the 6286 and 6288 frit series. The average amount of iron absorbed by the plants grown

in the absolute control cultures receiving complete nutrient solution is in most instances lower than the amount of iron absorbed by the frit grown plants.

b. At pH 5.0 of the nutrient solution. At this pH of the nutrient solution it was found to be a higher concentration of iron in the dry matter of the plants grown in frit than in the dry matter of the plants grown in the corresponding control cultures. The total amounts of iron absorbed in the various cultures are listed in table 28, and the average values are plotted against frit composition in figure 12. It will be noticed that the plants in the frit cultures have absorbed about twice as much iron as the plants in the corresponding control cultures. This is true for all four frit series. It will also be noticed (table 28) that the plants grown in the frits of the 6285 and 6287 series generally have absorbed more iron than the plants grown in the absolute control cultures receiving a complete nutrient solution.

c. At pH 6.0 and 7.0 of the nutrient solution. Tables 29 and 30 show that, in spite of the inconsistencies of the analytical results, there is indication of a definitely larger absorption of iron by the plants grown in frit than by the plants grown in the corresponding control cultures. This difference is especially noticeable when the frit series 6285 and 6287 are considered.

3. Summary of iron absorption

The data obtained for iron absorption by the plants at a pH of 5.0 of the nutrient solution are the most reliable ones, since special

precautions were taken in this experiment to eliminate iron contaminations of the plant material. The data from this experiment show:

(1) The plants grown in the frit cultures have accumulated more iron in the tissue than the plants grown in the corresponding control cultures. This result indicates that the frit grown plants have had a better access to available iron than the control plants. (2) The plants grown in the frits of the 6285 and 6287 frit series have absorbed more iron than the plants grown in the 6286 and 6288 frit series, which indicates that the iron present in the former frits is more available than the iron present in the latter. (3) The control plants corresponding to the 6285 and 6287 frit series have generally absorbed more iron than the control plants corresponding to the 6286 and 6288 frit series, which would indicate that the iron in the former frits is slightly more soluble than the iron in the latter frits. (4) There is no indication of a correlation between the amount of iron in the frit and the amount absorbed by the plants.

E. Absorption of manganese by the plants

1. Manganese content as parts per million of the oven dry tissue

a. At pH 4.0 of the nutrient solution. Manganese content of the dry plant material is listed in tables 31 and 32. It is readily seen that the presence of manganese in the frit has had a considerable influence upon the concentration of manganese in the dry plant tissue.

An increase in the manganese content of the frit from 1.0 to 4.0 per cent MnO_2 has greatly increased the concentration of manganese in the plants.

It will also be noticed that the concentration of manganese in the dry matter of the control plants is of the same order of magnitude as the concentration of manganese in the corresponding frit grown plants. This is an indication of a relatively large solubility of the frit manganese.

The plants grown in the 6287 frit series contain all higher amounts of manganese per unit dry weight than the plants grown in the 6288 frit series. The solubility of the manganese in the 6287 frits, therefore, is larger apparently than that of the manganese in the 6288 frits.

The absolute control plants which were supplied with a nutrient solution from which manganese was excluded did not contain any detectable amounts of manganese in the dry tissue.

b. At pH 5.0 of the nutrient solution. Manganese content in the oven dry tissue is listed in tables 33 and 34. The data show the same tendency towards an increase in manganese concentration of the dry tissue following an increase of the manganese concentration of the frit. In contrast to what was found in the previous experiment, a large difference is observed between frit and corresponding control cultures with respect to manganese concentration in the dry tissue. In both iron frit series (6285 and 6286) the control plants have a higher concentration of manganese than the corresponding frit grown plants. The same large difference in the concentration of manganese in the dry

plant material is observed between frit and the corresponding control cultures of the manganese frit series 6287. No such difference is observed with respect to the frit series 6288. This finding, together with the relatively low manganese concentration of the plants grown in this frit, again indicates that the manganese in the 6288 frit is less available to the plants than the manganese in the 6287 frit. The data also indicate that the manganese in the 6288 frit is less soluble than the manganese in the 6287 frit since the control plants associated with the latter frit contain relatively large amounts of manganese.

c. At pH 6.0 and 7.0 of the nutrient solution. Manganese concentration in the dry plant material is listed in tables 35, 36, 37, and 38. The data from the two experiments point out the same general relationships as mentioned for the previous experiment. The observations already made regarding the relative availability of manganese in the two frit series 6287 and 6288 are confirmed in these two experiments.

2. Total absorption of manganese by the plants

Total absorption of manganese by the plants, expressed as milligrams per ten plants, is listed in table 39 (pH 4.0), table 40 (pH 5.0), table 41 (pH 6.0) and table 42 (pH 7.0). The average values are plotted against frit composition in figure 13 (pH 4.0), figure 14 (pH 5.0), figure 15 (pH 6.0) and figure 16 (pH 7.0).

The total amounts of manganese absorbed by the plants grown in the frit cultures of the iron series (6285 and 6286) is in most cases of the same order of magnitude as the amount absorbed by the corresponding

frit grown plants. The higher concentration of manganese observed in the control plants is thus largely compensated for by a smaller total weight of dry matter. There are no indications in the data presented that the amount of iron present in the frit has had any influence upon the total absorption of manganese by the plants.

The total amounts of manganese absorbed by the plants grown in the manganese containing frits are, in most cases, increased as the manganese concentration of the frit is increased. The same relationship holds true for the corresponding control plants.

The most manganese has been absorbed by the plants grown in the 6287 frit series. The control plants corresponding to this frit series have in most cases absorbed more manganese than the plants grown in the 6288 frit series.

3. Summary of manganese absorption

A review of the data pertaining to manganese in the plants points out the following: (1) The concentration of manganese in the dry matter of the control plants is of the same order of magnitude as the concentration of manganese in the dry matter of the corresponding frit grown plants when the data from the experiment at pH 4.0 of the nutrient solution are considered. In the rest of the experiments, the control plants corresponding to the frit series 6285, 6286 and 6287 contain significantly more manganese in the dry matter than the corresponding frit grown plants. The control plants corresponding to the

frit series 6288 contain also in these experiments about the same amount of manganese in the dry matter as the corresponding frit grown plants. These findings seem to indicate that the control plants of the manganese frit series have had access to appreciable amounts of manganese, and that the manganese in the frits has been relatively soluble.

(2) There is a strong correlation between the total amount of manganese absorbed by the plants and the amount of manganese present in the frit. This holds true both for the frit grown plants and the control plants, indicating that the amounts of manganese released from the frit by the nutrient solution has increased with increase in the amount of manganese present in the frit.

(3) The large amounts of manganese absorbed by the plants grown in the 6287 frit series as compared to the amounts absorbed by the plants in the 6288 series indicate that the manganese in the 6287 frits has been more easily available than the manganese in the 6288 frits. The large amounts of manganese absorbed by the control plants corresponding to the frit series 6287 as compared to the amounts absorbed by the control plants corresponding to the 6288 series, likewise indicate a larger solubility of the manganese in the 6287 than in the 6288 frits.

IV. DISCUSSION

The most striking result of the experiments is the difference in growth between the plants in the individual control cultures and the plants in the corresponding control cultures, the frit grown plants generally being larger and having a greener and healthier appearance than the corresponding control plants.

Since both the frit and the control culture received identical amounts of nutrients in the culture solution, the better growth of the plants in the frit culture must be attributed to a component of the frit only available to the plant roots upon contact with the frit.

When iron containing frit was used in connection with a nutrient solution devoid in iron, the better growth of the plants grown in contact with the frit as compared to that of the plants grown in the control culture must be due to a direct absorption of iron from the frit.

The objection may be put forth that the iron in the frit may be soluble, but does not reach the plant roots in the control culture due to precipitation in the carboy containing the nutrient solution. In order to test this possibility, determinations were made of the amounts of iron present in the nutrient solutions at the end of the experimental periods. The results obtained in connection with the experiments carried out at pH 4.0 and pH 5.0 of the nutrient solution are listed in tables 43 and 44. It will be seen that iron was present in the nutrient solutions in negligible amounts, and that the amounts are of

the same order of magnitude as the amounts found in the absolute control solutions receiving no iron. The data obtained in connection with the other experiments were of the same low order of magnitude.

The data for iron in the nutrient solutions do not indicate any accumulation of iron with increase in the iron content of the frits. Apparently no iron was released from the frits in amounts sufficient to support plant growth.

The fact remains, however, that the control plants corresponding to the 6285 frit series made a better growth and absorbed slightly more iron than did the control plants corresponding to the 6286 frit series (see figure 12). The only explanation for this difference seems to be that the control plants corresponding to the 6285 frit series have had a slightly better access to iron than have the control plants corresponding to the 6286 frit series. In spite of the negligible amounts of iron found in the nutrient solutions, it is not possible to rule out completely that a slight amount of iron may have been released by the nutrient solution flooding the 6285 frits. The amounts released has, however, not been sufficient to prevent chlorosis and stunted growth of the control plants.

Another fact pointing towards a slight solubility of the frit iron is the close parallelism observed between iron absorption of the frit grown plants and the control plants. This parallelism is clearly demonstrated by the curves for p.p.m. of iron in the dry matter of the plants grown in the 6285 frit series and corresponding control cultures

and the p.p.m. of iron in the dry matter of the plants grown in the 6286 frit series and corresponding control cultures.

In contrast to what is found for the iron present in the frit, the manganese in the frit exhibits a considerable solubility, as indicated by the amounts of manganese absorbed by the control plants grown in connection with the manganese containing frits. The indication of a relatively large solubility of the manganese is substantiated by chemical analysis of the nutrient solutions flooding the manganese frits. Figure 17 demonstrates the amounts of manganese released by the various nutrient solutions. It is seen that the largest amounts of manganese are released from the 6287 frits and that the pH of the nutrient solution has had a strong influence upon the amounts released. At pH 4.0 of the nutrient solution there has been released about twice as much manganese as at pH 7.0.

Owing to the large solubility of the manganese in the frits there is no basis to conclude to what extent the plant roots have been able to absorb manganese from the frit by contact with the frit particles. The better growth of the plants grown in the manganese frits as compared to that of the plants grown in the corresponding control cultures, must be ascribed to an effect of the iron in the frit.

It is evident from various reports in the literature that the elements iron and manganese are functionally interrelated in their physiological effect on plants. Tottingham and Buck (1916) studied this interrelationship in nutrient cultures of wheat. Their data seem

to indicate that the best growth of the plants was obtained when the ratio of iron to manganese in the nutrient solution was 1:1.

More recently Somers and Shive (1942) have reported that the best growth of soybeans in nutrient solution culture was obtained when the ratio of iron to manganese in the nutrient solution was within a narrow limit of 2.5, the absolute concentration of the elements being of a lesser importance than the ratio between their concentrations. The ratio of iron to manganese in the nutrient solution flooding the manganese frits in the present experiments was apparently extremely low, especially in the case of the 6287 frit series. It will be seen from figure 17 that at pH 4.0 of the nutrient solution, the frit 6287-D (4.0 percent MnO_2) released manganese to the solution in amounts corresponding to 10 p.p.m. of Mn at the end of the experimental period. Table 43 shows that the iron concentration of the solution was about 5 milligrams per carboy or 0.3 p.p.m. of Fe. This will give a ratio of iron to manganese of about 0.03 which is far below the optimum ratios reported in the literature. The possibility exists, therefore, that the chlorotic condition and stunted growth observed in the control cultures in certain cases may be due to manganese toxicity. If this is true, it is of interest to notice that the plants grown in the corresponding frit cultures did not show any toxicity symptoms, although they were supplied with the same high manganese solution as the control plants. The effect of the frit must, therefore, have been to eliminate

the unfavorable iron-manganese ratio due to the presence of the iron in the frit.

Assuming that the concentrations of iron and manganese in the plant tissue will be determined largely by their concentrations in the substrate, the ratio of iron to manganese in the dry matter of the plants should give an indication of the relative availability of the elements to the plant roots. This ratio is calculated for the plant material obtained in the experiment carried out at a pH of 5.0 of the nutrient solution. The data are presented in table 45. It will be noticed that the ratio of iron to manganese in the control plants is smaller than the ratio of iron to manganese in the corresponding frit grown plants. This would indicate that the frit grown plants have had a better access to iron than the corresponding control plants. It is further noticed that the difference in the iron-manganese ratio between the control plants and the corresponding frit grown plants is larger in the case of the 6285 and 6287 frit series than in the case of the 6286 and 6288 frit series. This is another indication to the effect that the plants grown in the frits of the 6285 and 6287 series have absorbed relatively more iron than the plants grown in the 6286 and 6288 frit series.

The difference in effect observed between the frits of the 6285 and 6287 series and the frits of the 6286 and 6288 series with respect to growth and chemical composition of the plants has been very pronounced, and much more so than the effect of changes in iron and manganese concentration of the frits. The main difference between the two basic

formulas represented by these frits is that the formula underlying the 6286 and 6288 frits contains about 40 percent more silica than that underlying the 6285 and 6287 frits. This difference in the basic formula has been shown to affect markedly the solubility of the frits as indicated by the data for manganese release presented in figure 17. Figures 18 and 19 demonstrate the amounts of sodium released from the frits by the nutrient solution maintained at a pH of 4.0. Again are larger amounts of the element released from the 6285 and 6287 frits than from the 6286 and 6288 frits. A correlation between the amount of sodium present in the frit and the amount released by the nutrient solution is apparent. Similar tests were made for accumulation of potassium and phosphorus in the nutrient solutions, but since these elements were added to the nutrient solution in comparatively large amounts, it was difficult to detect the small amounts which might have been derived from the frits.

The conclusion which can be drawn from the experiments is that glassy frits might be developed in which plant nutrients are held with forces strong enough to prevent their dissolution in water but which are not strong enough to prevent them from being released by the action of acid solutions or by the action of absorbing root surfaces. Since the relative difference in growth between the plants grown in frit and the plants grown in corresponding control cultures was larger at pH 7.0 than at pH 4.0 of the nutrient solution (see figures 6 and 11), one might assume that a contact absorption was more prominent at the

high than at the low pH of the solutions.

The value of using frit as a source of minor elements in large scale hydroponic gravel culture is apparent. One of the main difficulties met with in this form for crop production is the maintenance of a sufficient supply of iron to the plants. Frequent applications of iron to the nutrient solution together with continuous adjustments of the pH is necessary in order to maintain a proper iron level in the solution flooding the plant roots. The results of the present experiments have indicated that wheat plants can grow well, without developing chlorosis, at a pH value of 7.0 of the nutrient solution when the plant roots are in contact with iron-containing frit.

In an experiment where the growth of soybean plants grown on frit was compared to that of soybean plants grown on some other materials suggested in the literature as media for gravel culture, the frit was found superior as a source of iron. The experimental procedure was identical with the one described for the present wheat experiments, the pH value of the iron-free nutrient solution being maintained at 7.0. The materials which were compared were: (1) Frit No. 9140-1 (5.0 percent Fe_2O_3 and 69.0 percent SiO_2), (2) Finely ground magnetite as suggested by Eaton (1936), (3) Pumice gravel as suggested by Matlin (1942), and (4) Glass wool as suggested by Ellis and Swaney (1938). No quantitative measurements of the growth of the plants were made. Plate X demonstrates, however, the green and healthy appearance of the terminal leaves of the plants grown in frit as compared to the chlorotic condition of the terminal leaves of the plants grown in the

other media.

While the development of frits with the property of releasing iron and manganese to plant roots so far has been based mainly upon greenhouse studies, a few experiments in which the frit has been applied to soil under field conditions have been carried out. Wynd and Stromme (1951b) applied finely ground iron and manganese containing frit to a calcareous soil, and found an increase in the yield and the manganese content of seeds and stems of bean plants, while the iron content of the same fractions was appreciably decreased. This result suggested that the ratios of iron to manganese in the frit must be carefully adjusted in order to avoid unfavorable ratios of available iron to manganese in the soil. Wynd and Bowden (1951c) applied a finely ground iron containing frit to a fertile greenhouse soil and found increased growth of snapdragons, which seems to indicate that iron may be a limiting factor in plant growth even though no deficiency symptoms are visible.

Due to the complexity of the factors responsible for minor element deficiencies in plants, the ultimate goal of developing frits with the property of eliminating specific deficiencies when applied to the soil can only be obtained through further extensive and systematic studies.

V. SUMMARY

1. The occurrence of iron and manganese deficiencies in plants are primarily due to adverse soil conditions which render the elements unavailable to the plants. The use of sprays or injections of salts of these elements in order to avoid the disturbing soil factors are not always applicable and do not always give satisfactory results.

2. The possibility of supplying the elements by adding slowly available compounds or artificially prepared physical complexes to the soil has been suggested and the ideal properties of such a material have been defined. It has been pointed out that the absorption of the elements will have to take place through contact between the material and the plant roots. Cases in which such contact absorption is assumed to take place have been cited.

3. The use of especially compounded glassy frits as a source of mineral elements for plants has been suggested, and successful preliminary experiments carried out in order to explore the value of frits as a source of iron to plants have been discussed.

4. Two frit formulas, one with 40 percent of SiO_2 and 21 percent of P_2O_5 and one with 59 percent of SiO_2 and 15 percent of P_2O_5 , both giving good results in the preliminary experiments, formed the basis for the present study. On basis of each of the formulas, two series of frits were made up, one containing 2.5, 5.0, 7.5, and 10.0 percent of Fe_2O_3 and no manganese, and one containing 1.0, 2.0, 3.0, and 4.0 percent of MnO_2 and a constant amount of 5.0 percent of Fe_2O_3 . The

complete chemical compositions of all 16 frits are given.

5. The nutritional experiments were carried out by using the frit as a medium in hydroponic gravel culture. The growth and chemical composition of wheat seedlings grown in a pot containing the frit was compared with the growth and chemical composition of wheat seedlings grown in a pot containing quartz gravel equal in particle size to that of the frit. Both pots were flooded at four hour intervals with identical nutrient solution supplied from the same carboy. The nutrient solution was complete except that iron was omitted when iron was the variable factor in the frit, and both iron and manganese were omitted when manganese was the variable factor in the frit. A constant and uniform pH was maintained in the nutrient solutions, and individual experiments were carried out at pH 4.0, 5.0, 6.0, and 7.0 of the nutrient solution.

6. Description of the visual appearance of the plants together with data and graphs demonstrating fresh weight, dry weight, absorption of iron and manganese are presented.

7. The frit cultures produced normal, green plants over the entire range of pH of the nutrient solution. The quartz cultures produced more or less chlorotic plants, and the growth, as judged by fresh and dry weight data, was inferior to that of the corresponding frit grown plants. The frit series with the lowest silica content produced at all pH levels significantly larger plants than was obtained in absolute control cultures where plants grown in quartz were supplied

with a complete nutrient solution containing 4.0 p.p.m. of iron and 0.5 p.p.m. of manganese.

8. The data for fresh and dry weight, the data for iron absorption, together with data showing that no accumulation of iron took place in the nutrient solution, have all indicated that the plants have been able to obtain iron from the frit by contact absorption. Data for manganese absorption and manganese accumulation in the nutrient solution have indicated a relatively large release of manganese by the nutrient solution, especially at low pH values. No conclusion can thus be drawn as to what extent contact absorption has played a role in the absorption of manganese from the frit.

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VII. APPENDIXES. ANALYTICAL PROCEDURES

1. Determination of iron

REAGENTS**Acetic acid. 2 N**

Dilute 114 milliliters of glacial acetic acid (Sp. Gr. 1.04)
to one liter with distilled water.

Hydrochloric acid. 1:1**Ammonium citrate. $(\text{NH}_4)_2\text{HC}_6\text{H}_5\text{O}_7$ 1 percent**

Dissolve 1 gram of ammonium citrate in distilled water and
dilute to 100 milliliters.

Bromophenol blue indicator solution. 0.4 percent

Grind 1 gram of solid bromophenol blue in a mortar with 3
milliliters of 0.05 N NaOH. Transfer to a volumetric
flask and dilute to 250 milliliters with distilled water.

Buffer solutions.

1. Solution of pH 3.5. Mix 6.4 milliliters of 2 N sodium acetate solution with 93.6 milliliters of 2 N acetic acid solution and dilute to one liter with distilled water.
2. Solution of pH 4.5. Mix 43 milliliters of 2 N sodium acetate solution with 57 milliliters of 2 N acetic acid solution and dilute to one liter with distilled water.

Hydroquinone solution.

Dissolve 1 gram of hydroquinone in 100 milliliters of a

buffer solution of pH 4.5. Store in a refrigerator.

Discard as soon as color develops.

O-phenanthroline solution.

Dissolve 1 gram of o-phenanthroline monohydrate in distilled water. Warm if necessary to effect solution, and dilute to 200 milliliters.

Sodium acetate. 2 M.

Dissolve 272 grams of sodium acetate trihydrate in distilled water and dilute to one liter.

Iron. Standard solution.

Dissolve 1.000 gram of electrolytic iron in 50 milliliters of a ten percent sulfuric acid solution. Warm if necessary to hasten reaction. Cool, and dilute to one liter with distilled water. One milliliter contains one milligram of iron.

PROCEDURE

Pipet an aliquot of 10 milliliters into both a 25 milliliters volumetric flask and a 30 milliliters beaker. To the solution in the beaker add 5 drops of bromophenol blue indicator. Titrate this section with 2 M sodium acetate until the color matches that of an equal volume of a buffer solution of pH 3.5 containing the same quantity of indicator. Add 1 milliliter of the hydroquinone solution and 2 milliliters of the o-phenanthroline solution to the section in the volumetric flask and adjust the pH of the contents to 3.5 by adding the

same volume of sodium acetate. If a turbidity develops upon adjustment of the pH of the aliquot in the beaker, add one milliliter of ammonium citrate solution to the volumetric flask before adding the sodium acetate solution. Make to volume with distilled water, mix, and let stand for one hour to assure complete color development.

Measure optical density in the Coleman spectrophotometer using a PC-4 filter, a wave length of $510\text{ m}\mu$, and a water blank. Prepare a series of standard solutions containing 0.01 to 0.10 milligrams of iron per 25 milliliter volumetric flask. Develop color as above. Plot optical density against concentration of iron.

2. Determination of manganese

REAGENTS

Sodium metaperiodate. Fine powder.

Phosphoric acid. 85 percent

Sulfuric acid. Concentrated

Sodium sulfite. Fine powder

Potassium permanganate. Standard solution containing 0.0250 milligrams of manganese per milliliter.

Prepare a 0.10 N standard potassium permanganate solution.

Add 22.8 milliliters of the standard solution to a 250 milliliters Erlenmeyer flask. Add about 50 milliliters of distilled water and 1 milliliter of concentrated sulfuric acid. Heat to boiling and reduce the permanganate by adding sodium sulfite powder. Avoid a large excess of the sulfite. Boil off the excess sulfur dioxide and dilute to one liter. Each milliliter of this solution contains 0.0250 milligram of manganese.

PROCEDURE

Pipet an aliquot of 20 milliliters into a 25 milliliter volumetric flask. Add 1 milliliter of 85 percent phosphoric acid and about 50 milligrams of the sodium periodate. Mix well, and place in water bath at 95° C. Let stand for two hours.

Cool, make to volume with distilled water, mix, and measure optical density in the Coleman spectrophotometer using a PC-4 filter,

a wave length of 530 $m\mu$ and a water blank. Prepare a series of standard solutions containing 0.0125 to 0.250 milligram of manganese per 25 milliliter volumetric flask. Develop color as above. Plot optical density against concentration of manganese.

3. Determination of Potassium and sodium in nutrient solutions by means of flame-photometer

POTASSIUM

Potassium nitrate. Standard solution containing 1000 parts per million of potassium.

Dissolve 2.5859 grams of KNO_3 in 1000 milliliters of distilled water.

Background solution. Dissolve 0.75 gram of $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ and 0.25 grams of $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ in 1000 milliliters of distilled water. This solution contains magnesium and calcium in approximately the same concentration as the sample of the nutrient solution prepared for flame photometric analysis.

Procedure

By proper dilutions of the standard potassium nitrate solution with the background solution prepare a series of solutions containing 0 to 150 parts per million of potassium. Calibrate the instrument to read 100 for the 150 parts per million solution and 0 for the 0 parts per million solution. Prepare a standard curve by plotting the intensity reading of each solution in the series against concentration. Read the concentration of the unknown from the curve.

SODIUM

Sodium chloride. Standard solution containing 1000 parts per million of sodium.

Dissolve 2.5416 grams of NaCl in 1000 milliliters of distilled water.

Background solution. Dissolve 0.75 gram of $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, 0.25 gram of $\text{Ca}(\text{NO}_3)_2$, and 0.55 gram of KH_2PO_4 in 1000 milliliters of distilled water. This solution contains magnesium, calcium, and potassium in approximately the same concentration as the sample of the nutrient solution prepared for flame photometric analysis.

Procedure

By proper dilutions of the standard sodium chloride solution with the background solution, prepare a series of solutions containing 0 to 100 parts per million of sodium. Calibrate the instrument to read 100 for the 100 parts per million solution and 0 for the 0 parts per million solution. Prepare a standard curve by plotting the intensity reading of each solution in the series against concentration. Read the concentration of the unknown from the curve.

4. Determination of the solubility of frits

The frit was finely ground in a mortar and then screened to obtain a sample of material passing a 200 mesh screen. The screened sample was dried at 110° C. for thirty minutes. A 2 gram sample was transferred to a 100 milliliter volumetric flask, and water was added to give 100 milliliters. The flask was held at 70° C. for 90 hours in a water bath, and the suspension was filtered through No. 42 Whatman filter paper. The filtrate was brought to 100 milliliters and the dissolved material determined by evaporating a suitable aliquot in a platinum dish. The residue was heated to a dull red color before cooling and weighing. Solubility was calculated in percent.

As basis for the evaluation of the solubilities found for the frits, determinations were made of the solubility of the glass used for an ordinary Coca Cola bottle and that used for a commercial plate glass. The solubility was in both cases found to be 1.5 percent.

Table 1. Chemical composition of frits used in preliminary studies on the availability of iron in frit to wheat plants.

Group	Frit No.	Percentage of							Sum percent	Solubility percent
		Fe ₂ O ₃	SiO ₂	P ₂ O ₅	CaO	MgO	K ₂ O	Na ₂ O		
1	6224-A	5.0	66.0	5.0	5.6	3.6	7.4	7.4	100.0	0.8
	6224-B	5.0	62.4	10.0	5.3	3.5	6.9	6.9	100.0	0.6
	6224-C	5.0	58.6	15.0	5.0	3.3	6.6	6.6	100.1	0.3
2	6238-A	5.0	46.0	8.4	9.4	6.1	12.5	12.5	99.9	20.0
	6238-B	5.0	43.7	15.8	8.4	5.5	10.9	10.9	100.2	8.0
	6238-C	5.0	40.4	21.8	8.6	4.8	9.6	9.6	99.8	2.0
3	6241-A	5.0	36.4	10.1	11.3	7.2	15.0	15.0	100.0	36.0
	6241-B	5.0	34.3	18.6	9.9	6.5	12.9	12.9	100.1	31.0
	6241-C	5.0	31.7	25.3	10.0	5.6	11.2	11.2	100.0	11.0

Table 2. Chemical composition of frits used in the present study on the availability of iron and manganese in frit to wheat plants.

Frit No.	Percentage of							Sum percentage	
	Fe ₂ O ₃	MnO ₂	CaO	MgO	K ₂ O	Na ₂ O	P ₂ O ₅		SiO ₂
6285-A	2.5	0	8.9	5.0	9.85	9.85	22.2	41.6	99.9
6285-B	5.0	0	8.6	4.8	9.6	9.6	21.8	40.4	99.8
6285-C	7.5	0	8.4	4.7	9.34	9.34	21.2	39.4	99.9
6285-D	10.0	0	8.2	4.6	9.1	9.1	20.5	38.3	99.8
6287-A	5.0	1.0	8.5	4.7	9.5	9.5	21.6	40.0	99.8
6287-B	5.0	2.0	8.5	4.7	9.4	9.4	21.4	39.6	100.0
6287-C	5.0	3.0	8.3	4.6	9.3	9.3	21.2	39.2	99.9
6287-D	5.0	4.0	8.2	4.6	9.2	9.2	20.9	38.8	99.9
6286-E	2.5	0	6.0	3.4	6.9	6.9	15.4	59.3	100.4
6286-F	5.0	0	5.9	3.3	6.7	6.7	15.0	57.7	100.3
6286-G	7.5	0	5.7	3.2	6.6	6.6	14.6	56.2	100.4
6286-H	10.0	0	5.6	3.1	6.4	6.4	14.2	54.7	100.4
6288-E	5.0	1.0	5.8	3.2	6.6	6.6	14.8	57.3	100.3
6288-F	5.0	2.0	5.8	3.2	6.6	6.6	14.7	56.8	100.7
6288-G	5.0	3.0	5.7	3.2	6.5	6.5	14.5	56.0	100.4
6288-H	5.0	4.0	5.6	3.2	6.4	6.4	14.4	55.6	100.6

Table 3. Fresh weight, in grams per ten plants, obtained in frit and quartz control cultures supplied with nutrient solution of pH 4.0.

Frit No.	Percent		Culture 1		Culture 2		Average		Relative average absolute control (†Fe+Mn) = 100	
	Fe ₂ O ₃	MnO ₂	Quartz	Frit	Quartz	Frit	Quartz	Frit	Quartz	Frit
6285-A	2.5	0	10.5	13.9	10.4	14.3	10.5	14.1	115	155
6285-B	5.0	0	9.9	10.7	11.2	13.6	10.6	12.2	116	134
6285-C	7.5	0	11.5	15.0	9.4	12.3	10.5	13.7	115	151
6285-D	10.0	0	8.9	14.6	9.5	13.1	9.2	13.9	101	153
6287-A	5.0	1.0	12.6	13.2	11.8	12.9	12.2	13.1	134	144
6287-B	5.0	2.0	10.5	13.9	10.4	13.6	10.5	13.7	115	151
6287-C	5.0	3.0	10.4	14.6	9.7	12.7	10.1	13.7	111	151
6287-D	5.0	4.0	10.8	13.3	10.4	12.1	10.6	12.7	116	140
6286-E	2.5	0	8.5	11.4	8.2	12.1	8.4	11.8	92	130
6286-F	5.0	0	8.5	10.5	7.6	13.4	8.1	12.0	89	132
6286-G	7.5	0	8.6	10.4	9.4	10.6	9.0	10.5	99	115
6286-H	10.0	0	7.4	9.9	11.9	12.3	9.7	11.1	107	122
6288-E	5.0	1.0	9.2	9.9	10.4	11.7	9.8	10.8	108	119
6288-F	5.0	2.0	9.3	11.4	6.1	9.8	7.7	10.6	85	116
6288-G	5.0	3.0	8.8	9.3	8.4	11.3	8.6	10.3	95	113
6288-H	5.0	4.0	9.1	11.1	8.9	10.9	9.0	11.0	99	121

Table 4. Fresh weight, in grams per ten plants, obtained in absolute control cultures supplied with nutrient solution of pH 4.0.

Treatment		Culture 1		Culture 2		Culture 3		Average Relative of all average pots	
Fe p.p.m.	Mn p.p.m.	pot 1	pot 2	pot 1	pot 2	pot 1	pot 2		
4.0	0.5	6.6	6.7	10.3	13.3	8.4	9.2	9.1	100
0	0.5	7.1	7.6	10.5	10.5	11.3	11.3	9.7	107
4.0	0	8.6	8.0	9.1	8.2	8.3	8.3	8.4	92
0	0	3.1	3.3	9.4	9.1	9.4	9.9	7.3	80

Table 5. Fresh weight, in grams per ten plants, obtained in frit and quartz control cultures supplied with nutrient solution of pH 5.0.

Frit No.	Percent		Culture 1		Culture 2		Average		Relative average absolute control (Fe Mn) = 100	
	Fe ₂ O ₃	MnO ₂	Quartz	Frit	Quartz	Frit	Quartz	Frit	Quartz	Frit
6285-A	2.5	0	11.3	26.8	19.1	26.4	15.2	26.6	70	123
6285-B	5.0	0	17.0	22.1	22.1	27.5	19.6	24.8	90	114
6285-C	7.5	0	18.5	22.8	17.5	26.3	18.0	24.6	83	113
6285-D	10.0	0	23.2	27.0	21.2	26.7	22.2	26.9	102	124
6287-A	5.0	1.0	23.7	21.0	12.5	26.4	18.1	23.7	83	109
6287-B	5.0	2.0	23.5	31.0	27.8	30.9	25.7	31.0	118	143
6287-C	5.0	3.0	21.2	32.2	20.9	25.8	21.1	29.0	97	134
6287-D	5.0	4.0	19.3	27.5	17.7	28.5	18.5	28.0	85	129
6286-E	2.5	0	20.3	20.9	13.6	20.9	17.0	20.9	78	96
6286-F	5.0	0	17.6	20.6	15.4	23.4	16.5	22.0	76	101
6286-G	7.5	0	13.2	19.4	16.8	21.5	15.0	20.5	69	94
6286-H	10.0	0	16.7	21.3	17.5	24.7	17.1	23.0	79	106
6288-E	5.0	1.0	14.2	19.3	7.2	22.4	10.7	20.9	49	96
6288-F	5.0	2.0	12.9	20.8	4.2	17.6	8.6	19.4	40	89
6288-G	5.0	3.0	12.1	14.1	8.8	21.6	10.5	17.9	48	82
6288-H	5.0	4.0	13.1	18.5	4.6	23.0	8.9	20.8	41	96

Table 6. Fresh weight, in grams per ten plants, obtained in absolute control cultures supplied with nutrient solution of pH 5.0.

Treatment		Culture 1		Culture 2		Culture 3		Average of all pots	Relative average
Fe p.p.m.	Mn p.p.m.	pot 1	pot 2	pot 1	pot 2	pot 1	pot 2		
4.0	0.5	23.2	18.2	23.6	25.1	20.3	19.6	21.7	100
0	0.5	12.6	13.5	12.0	14.4	13.8	15.2	13.6	63
4.0	0	17.0	16.4	16.6	14.7	21.9	22.0	18.1	83
0	0	12.0	12.2	10.5	9.0	16.8	16.3	12.8	59

Table 7. Fresh weight, in grams per ten plants, obtained in frit and quartz control cultures supplied with nutrient solution of pH 6.0.

Frit No.	Percent		Culture 1		Culture 2		Average		Relative average absolute control (Fe Mn) = 100	
	Fe ₂ O ₃	MnO ₂	Quartz	Frit	Quartz	Frit	Quartz	Frit	Quartz	Frit
6285-A	2.5	0	29.4	33.8	24.1	35.6	26.8	34.7	113	146
6285-B	5.0	0	29.1	39.5	24.7	33.9	26.9	36.7	114	155
6285-C	7.5	0	28.2	43.3	24.6	37.1	26.4	40.2	111	170
6285-D	10.0	0	23.8	33.8	25.9	36.0	24.9	34.9	105	147
6287-A	5.0	1.0	20.9	28.5	24.5	41.8	22.7	35.2	96	149
6287-B	5.0	2.0	22.2	39.3	27.6	46.7	24.9	43.0	105	181
6287-C	5.0	3.0	23.3	33.8	22.6	33.2	23.0	33.5	97	141
6287-D	5.0	4.0	21.1	32.3	19.5	27.7	20.3	30.0	86	127
6286-E	2.5	0	19.9	27.0	26.8	32.5	23.4	29.8	99	126
6286-F	5.0	0	14.7	26.2	24.9	28.9	19.8	27.6	84	116
6286-G	7.5	0	15.0	27.3	22.3	29.9	18.7	28.6	79	121
6286-H	10.0	0	11.5	19.6	22.6	26.9	17.1	23.3	72	98
6288-E	5.0	1.0	23.0	31.7	28.1	35.9	25.6	33.8	108	143
6288-F	5.0	2.0	20.4	25.1	—	—	20.4	25.1	86	106
6288-G	5.0	3.0	21.6	27.5	20.6	28.8	21.1	28.2	89	119
6288-H	5.0	4.0	19.5	22.4	20.0	32.3	19.8	27.4	84	116

Table 8. Fresh weight, in grams per ten plants, obtained in absolute control cultures supplied with nutrient solution of pH 6.0.

Treatment		Culture 1		Culture 2		Culture 3		Average of all pots	Relative average
Fe p.p.m.	Mn p.p.m.	pot 1	pot 2	pot 1	pot 2	pot 1	pot 2		
4.0	0.5	21.9	22.0	22.6	24.9	24.5	26.3	23.7	100
0	0.5	23.5	22.1	16.0	17.9	25.5	26.8	22.0	93
4.0	0	21.6	22.1	22.2	22.4	—	—	22.1	93
0	0	16.4	19.5	22.9	21.5	14.1	16.3	18.5	78

Table 9. Fresh weight, in grams per ten plants, obtained in frit and quartz control cultures supplied with nutrient solution of pH 7.0.

Frit No.	Percent		Culture 1		Culture 2		Average		Relative average absolute control (Fe Mn) = 100	
	Fe ₂ O ₃	MnO ₂	Quartz	Frit	Quartz	Frit	Quartz	Frit	Quartz	Frit
6285-A	2.5	0	5.3	10.9	5.8	11.4	5.6	11.2	72	144
6285-B	5.0	0	6.8	11.1	5.0	10.6	5.9	10.9	76	140
6285-C	7.5	0	6.3	10.4	4.7	9.4	5.5	9.9	71	127
6285-D	10.0	0	5.4	10.0	6.2	10.6	5.8	10.3	74	132
6287-A	5.0	1.0	7.2	11.5	6.0	13.3	6.6	12.4	85	159
6287-B	5.0	2.0	6.5	10.9	6.5	11.3	6.5	11.1	83	142
6287-C	5.0	3.0	6.6	10.4	6.4	11.2	6.5	10.8	83	138
6287-D	5.0	4.0	5.8	10.1	7.4	10.4	6.6	10.3	85	132
6286-E	2.5	0	5.6	8.1	5.7	9.0	5.7	8.6	73	110
6286-F	5.0	0	5.1	7.0	5.9	8.3	5.5	7.7	71	99
6286-G	7.5	0	5.5	8.5	5.0	8.4	5.3	8.5	68	109
6286-H	10.0	0	5.1	8.4	5.7	9.4	5.4	8.9	69	114
6288-E	5.0	1.0	5.1	7.9	6.5	9.5	5.8	8.7	74	112
6288-F	5.0	2.0	6.4	7.5	5.8	9.7	6.1	8.6	78	110
6288-G	5.0	3.0	5.8	8.1	6.8	10.6	6.3	9.4	81	121
6288-H	5.0	4.0	5.0	9.0	5.9	10.7	5.5	9.9	71	127

Table 10. Fresh weight, in grams per ten plants, obtained in absolute control cultures supplied with nutrient solution of pH 7.0.

Treatment		Culture 1		Culture 2		Culture 3		Average of all pots	Relative average
Fe p.p.m.	Mn p.p.m.	pot 1	pot 2	pot 1	pot 2	pot 1	pot 2		
4.0	0.5	6.5	6.6	8.5	7.9	8.1	9.4	7.8	100
0	0.5	7.0	6.7	5.1	4.5	7.5	7.3	6.4	82
4.0	0	9.3	9.1	7.6	6.8	10.4	11.0	9.0	115
0	0	5.8	6.0	5.5	5.6	7.9	8.3	6.5	83

Table 11. Dry weight, in grams per ten plants, obtained in frit and quartz control cultures supplied with nutrient solution of pH 4.0.

Frit No.	Percent		Culture 1		Culture 2		Average		Relative average absolute control (Fe Mn) = 100	
	Fe ₂ O ₃	MnO ₂	Quartz	Frit	Quartz	Frit	Quartz	Frit	Quartz	Frit
6285-A	2.5	0	1.33	1.73	1.35	1.74	1.34	1.74	108	140
6285-B	5.0	0	1.30	1.38	1.44	1.64	1.37	1.51	110	122
6285-C	7.5	0	1.59	2.00	1.15	1.54	1.37	1.77	110	143
6285-D	10.00	0	1.19	1.76	1.23	1.60	1.21	1.68	98	135
6287-A	5.0	1.0	1.63	1.67	1.53	1.61	1.58	1.64	127	132
6287-B	5.0	2.0	1.38	1.79	1.37	1.46	1.38	1.63	111	131
6287-C	5.0	3.0	1.41	1.82	1.30	1.66	1.36	1.74	110	140
6287-D	5.0	4.0	1.44	1.66	1.36	1.55	1.40	1.61	113	130
6286-E	2.5	0	1.13	1.39	1.18	1.58	1.16	1.49	94	120
6286-F	5.0	0	1.06	1.20	1.11	1.81	1.09	1.51	88	122
6286-G	7.5	0	1.11	1.19	1.30	1.40	1.21	1.30	98	105
6286-H	10.0	0	1.02	1.24	1.58	1.62	1.30	1.43	105	115
6288-E	5.0	1.0	1.24	1.29	1.40	1.53	1.32	1.41	106	114
6288-F	5.0	2.0	1.16	1.45	0.83	1.25	1.00	1.35	81	109
6288-G	5.0	3.0	1.11	1.18	1.16	1.53	1.14	1.36	92	110
6288-H	5.0	4.0	1.20	1.40	1.18	1.40	1.19	1.40	96	113

Table 12. Dry weights, in grams per ten plants, obtained in absolute control cultures supplied with nutrient solution of pH 4.0.

Treatment		Culture 1		Culture 2		Culture 3		Average of all pots	Relative average
Fe p.p.m.	Mn p.p.m.	pot 1	pot 2	pot 1	pot 2	pot 1	pot 2		
4.0	0.5	0.93	0.93	1.38	1.82	1.14	1.26	1.24	100
0	0.5	0.97	1.02	1.43	1.43	1.54	1.45	1.31	105
4.0	0	1.09	0.91	1.16	1.13	1.09	1.13	1.09	88
0	0	0.55	0.55	1.24	1.20	1.36	1.35	1.04	84

Table 13. Dry weights, in grams per ten plants, obtained in frit and quartz control culture supplied with nutrient solution of pH 5.0.

Frit No.	Percent		Culture 1		Culture 2		Average		Relative average absolute control (Fe Mn) = 100	
	Fe ₂ O ₃	MnO ₂	Quartz	Frit	Quartz	Frit	Quartz	Frit	Quartz	Frit
6285-A	2.5	0	1.38	3.94	2.26	3.62	1.82	3.78	62	129
6285-B	5.0	0	2.14	3.21	2.70	3.97	2.42	3.59	82	122
6285-C	7.5	0	2.43	3.31	2.08	3.75	2.26	3.53	77	120
6285-D	10.0	0	3.19	3.97	2.68	3.71	2.94	3.84	100	131
6287-A	5.0	1.0	2.81	3.47	1.47	3.94	2.14	3.71	73	126
6287-B	5.0	2.0	3.17	4.07	3.96	5.03	3.56	4.70	121	160
6287-C	5.0	3.0	2.74	4.60	2.90	3.87	2.82	4.24	96	144
6287-D	5.0	4.0	2.40	4.05	2.33	4.28	2.37	4.17	81	142
6286-E	2.5	0	2.39	2.68	1.69	2.79	2.04	2.74	69	93
6286-F	5.0	0	2.00	2.65	2.00	3.11	2.00	2.88	68	98
6286-G	7.5	0	1.43	2.56	1.89	3.15	1.66	2.86	56	97
6286-H	10.0	0	1.91	2.74	2.15	3.25	2.03	3.00	69	102
6288-B	5.0	1.0	1.67	2.59	1.80	3.15	1.74	2.87	59	98
6288-F	5.0	2.0	1.46	2.71	1.50	2.53	1.48	2.62	50	89
6288-G	5.0	3.0	1.39	2.07	2.20	3.41	1.80	2.74	61	93
6288-H	5.0	4.0	1.49	2.63	1.59	3.17	1.54	2.90	52	99

Table 14. Dry weights, in grams per ten plants, obtained in absolute control cultures supplied with nutrient solution of pH 5.0.

Treatment		Culture 1		Culture 2		Culture 3		Average of all pots	Relative average
Fe p.p.m.	Mn p.p.m.	pot 1	pot 2	pot 1	pot 2	pot 1	pot 2		
4.0	0.5	2.96	2.50	3.17	3.32	2.94	2.77	2.94	100
0	0.5	1.29	1.37	1.26	1.59	1.40	1.58	1.42	48
4.0	0	2.12	1.97	2.05	1.87	2.67	2.62	2.22	76
0	0	1.30	1.32	1.20	0.97	1.86	1.79	1.41	48

Table 15. Dry weights, in grams per ten plants, obtained in frit and quartz control cultures supplied with nutrient solution of pH 6.0.

Frit No.	Percent		Culture 1		Culture 2		Average		Relative average absolute control (Fe Mn) = 100	
	Fe ₂ O ₃	MnO ₂	Quartz	Frit	Quartz	Frit	Quartz	Frit	Quartz	Frit
6285-A	2.5	0	4.15	4.95	3.51	5.68	3.83	5.32	110	153
6285-B	5.0	0	4.23	5.97	3.30	5.02	3.77	5.50	108	158
6285-C	7.5	0	3.95	6.93	2.75	5.52	3.35	6.23	96	179
6285-D	10.0	0	3.25	4.95	4.03	5.68	3.64	5.32	105	153
6287-A	5.0	1.0	2.92	4.36	3.18	5.55	3.05	4.96	88	143
6287-B	5.0	2.0	3.19	6.28	4.76	8.47	3.98	7.38	114	212
6287-C	5.0	3.0	3.64	5.76	3.15	5.08	3.40	5.42	98	156
6287-D	5.0	4.0	3.27	4.03	3.05	4.17	3.16	4.10	91	118
6286-E	2.5	0	2.77	3.83	4.05	4.95	3.41	4.39	98	126
6286-F	5.0	0	2.00	3.81	3.68	4.34	2.84	4.08	82	117
6286-G	7.5	0	1.95	3.90	3.14	4.49	2.55	4.20	73	121
6286-H	10.0	0	1.51	2.88	3.38	4.24	2.45	3.56	70	102
6288-E	5.0	1.0	3.49	4.70	4.23	5.28	3.86	4.99	111	143
6288-F	5.0	2.0	2.77	3.52	---	---	2.77	3.52	80	101
6288-G	5.0	3.0	3.17	3.55	2.90	4.54	3.04	4.05	87	116
6288-H	5.0	4.0	2.93	3.41	2.84	4.83	2.89	4.14	83	119

Table 16. Dry weights, in grams per ten plants, obtained in absolute control cultures supplied with nutrient solution of pH 6.0.

Treatment		Culture 1		Culture 2		Culture 3		Average of all pots	Relative average
Fe p.p.m.	Mn p.p.m.	pot 1	pot 2	pot 1	pot 2	pot 1	pot 2		
4.0	0.5	3.14	3.32	3.46	3.92	3.49	3.54	3.48	100
0	0.5	3.43	3.02	2.15	2.44	3.78	3.89	3.12	90
4.0	0	3.38	3.26	3.44	3.20	—	—	3.32	95
0	0	2.24	2.73	3.23	3.00	2.20	2.58	2.66	76

Table 17. Dry weights, in grams per ten plants, obtained in frit and quartz control cultures supplied with nutrient solution of pH 7.0.

Frit No.	Percent		Culture 1		Culture 2		Average		Relative average absolute control (Fe Mn) = 100	
	Fe ₂ O ₃	MnO ₂	Quartz	Frit	Quartz	Frit	Quartz	Frit	Quartz	Frit
6285-A	2.5	0	0.78	1.83	0.89	1.79	0.84	1.81	72	155
6285-B	5.0	0	1.03	1.81	0.73	1.77	0.83	1.79	71	153
6285-C	7.5	0	0.95	1.69	0.79	1.17	0.87	1.43	74	122
6285-D	10.0	0	0.80	1.56	0.97	1.66	0.89	1.61	76	138
6287-A	5.0	1.0	1.18	1.95	0.86	2.16	1.02	2.06	87	176
6287-B	5.0	2.0	1.10	1.88	1.00	1.86	1.05	1.87	90	160
6287-C	5.0	3.0	1.05	1.49	0.95	1.84	1.00	1.67	85	143
6287-D	5.0	4.0	0.98	1.73	1.14	1.74	1.06	1.74	91	149
6286-E	2.5	0	0.83	1.16	0.83	1.42	0.83	1.29	71	110
6286-F	5.0	0	0.74	1.05	0.92	1.34	0.83	1.20	71	102
6286-G	7.5	0	0.73	1.22	0.77	1.36	0.75	1.29	64	110
6286-H	10.0	0	0.76	1.26	0.86	1.44	0.81	1.35	69	115
6288-E	5.0	1.0	0.73	1.25	0.84	1.44	0.79	1.35	68	115
6288-F	5.0	2.0	0.97	1.18	0.78	1.59	0.88	1.39	75	118
6288-G	5.0	3.0	0.86	1.23	0.89	1.61	0.88	1.42	75	121
6288-H	5.0	4.0	0.74	1.37	0.84	1.58	0.79	1.48	68	126

Table 18. Dry weights, in grams per ten plants, obtained in absolute control cultures supplied with nutrient solution of pH 7.0.

Treatment		Culture 1		Culture 2		Culture 3		Average of all pots	Relative average
Fe p.p.m.	Mn p.p.m.	Pot 1	pot 2	pot 1	pot 2	pot 1	pot 2		
4.0	0.5	1.03	1.03	1.36	1.28	1.17	1.17	1.17	100
0	0.5	0.93	0.89	0.73	0.63	1.09	1.00	0.88	75
4.0	0	1.38	1.26	1.05	0.98	1.58	1.64	1.31	112
0	0	0.82	0.83	0.73	0.71	1.26	1.32	0.95	81

Table 19. Iron content, expressed as parts per million of oven dry tissue, of plants grown in frit and quartz control cultures supplied with nutrient solution of pH 4.0.

Frit No.	Percent		Culture 1			Culture 2			Average of both cultures
	Fe ₂ O ₃	MnO ₂	Det. 1	Det. 2	Ave.	Det. 1	Det. 2	Ave.	
6285-A	2.5	0	151	151	151	79	80	75	113
control			47	56	52	93	83	88	70
6285-B	5.0	0	119	107	113	79	83	81	97
control			111	105	108	76	83	80	94
6285-C	7.5	0	91	107	99	79	87	83	91
control			110	119	115	78	63	71	93
6285-D	10.0	0	87	83	85	67	71	69	77
control			85	87	86	71	66	69	78
6287-A	5.0	1.0	78	75	77	75	—	75	76
control			83	83	83	95	92	94	89
6287-B	5.0	2.0	109	102	106	79	78	79	93
control			103	103	103	83	99	91	97
6287-C	5.0	3.0	91	89	90	73	69	71	81
control			107	105	106	79	78	79	93
6287-D	5.0	4.0	79	85	82	95	80	88	85
control			88	88	88	87	88	88	88
6286-E	2.5	0	91	86	89	96	95	96	93
control			14	14	14	83	87	85	85
6286-F	5.0	0	83	79	81	75	75	75	78
control			112	99	106	87	88	88	97
6286-G	7.5	0	93	87	90	51	40	46	68
control			95	90	93	76	79	78	86
6286-H	10.0	0	94	96	95	79	84	82	86
control			95	94	95	81	87	84	90
6288-E	5.0	1.0	107	—	107	88	88	88	98
control			110	112	111	83	87	85	98
6288-F	5.0	2.0	90	—	90	95	92	94	92
control			75	68	72	116	—	116	94
6288-G	5.0	3.0	43	32	38	76	—	76	57
control			89	95	92	62	—	62	77
6288-H	5.0	4.0	97	95	96	79	81	80	88
control			103	103	103	62	—	62	83

Table 20. Iron content, expressed as parts per million of oven dry tissue, of plants grown in absolute control cultures supplied with nutrient solution of pH 4.0.

Treatment		Culture 1						Culture 2						Culture 3						Average
Fe p.p.m.	Mn p.p.m.	pot 1			pot 2			pot 1			pot 2			pot 1			pot 2			
		Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	
		1	2		1	2		1	2		1	2		1	2		1	2		
4.0	0.5	95	94	95	87	87	87	95	103	99	87	89	88	83	99	91	97	97	97	93
0	0.5	75	75	75	73	70	72	—	—	—	—	75	75	80	81	81	73	71	72	75
4.0	0	101	95	98	95	87	91	85	80	83	—	—	—	114	—	114	97	—	97	97
0	0	110	—	110	79	—	79	75	74	75	87	79	83	105	—	105	95	99	97	92

Table 21. Iron content, expressed as parts per million of oven dry tissue, of plants grown in frit and quartz control cultures supplied with nutrient solution of pH 5.0.

Frit No.	Percent		Culture 1			Culture 2			Average of both cultures
	Fe ₂ O ₃	MnO ₂	Det. 1	Det. 2	Ave.	Det. 1	Det. 2	Ave.	
6285-A	2.5	0	91	76	84	80	81	81	83
control			58	56	57	91	96	94	76
6285-B	5.0	0	72	74	73	76	75	76	75
control			53	52	53	73	77	75	64
6285-C	7.5	0	70	71	71	119	111	115	93
control			79	83	81	64	66	65	73
6285-D	10.0	0	79	78	79	79	74	77	78
control			64	60	62	56	56	56	59
6287-A	5.0	1.0	108	108	108	89	94	92	100
control			60	64	62	105	85	95	79
6287-B	5.0	2.0	89	95	82	110	111	111	97
control			83	79	81	91	83	87	84
6287-C	5.0	3.0	95	95	95	111	112	112	104
control			67	70	69	95	97	96	83
6287-D	5.0	4.0	90	83	87	117	117	117	102
control			75	67	71	135	121	128	100
6286-E	2.5	0	47	46	47	87	81	84	66
control			46	34	39	75	75	75	57
6286-F	5.0	0	65	72	69	56	67	62	66
control			57	55	56	55	56	56	56
6286-G	7.5	0	56	63	60	77	73	75	68
control			51	50	51	83	64	74	63
6286-H	10.0	0	79	78	79	66	67	67	73
control			70	72	76	57	57	57	67
6288-E	5.0	1.0	75	79	77	80	93	87	82
control			65	65	65	62	62	62	64
6288-F	5.0	2.0	70	71	71	83	87	85	78
control			60	65	63	79	79	79	71
6288-G	5.0	3.0	81	102	92	87	93	90	91
control			75	75	75	98	89	94	85
6288-H	5.0	4.0	86	100	93	102	98	100	97
control			78	71	75	84	76	80	78

Table 22. Iron content, expressed as parts per million of oven dry tissue, of plants grown in absolute control cultures supplied with nutrient solution of pH 5.0.

Treatment		Culture 1						Culture 2						Culture 3						Average
Fe	Mn	pot 1			pot 2			pot 1			pot 2			pot 1			pot 2			
		Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	
		1	2		1	2		1	2		1	2		1	2		1	2		
4.0	0.5	67	70	69	75	75	75	86	96	91	75	75	75	71	78	75	71	71	71	76
0	0.5	75	79	77	60	56	58	56	56	56	53	51	52	71	75	73	60	61	61	63
4.0	0	85	85	85	75	75	75	120	110	115	115	103	109	—	71	71	74	73	74	88
0	0	47	44	46	44	40	42	101	—	101	—	91	91	74	87	81	74	87	81	74

Table 23. Iron content, expressed as parts per million of oven dry tissue, of plants grown in frit and quartz control cultures supplied with nutrient solution of pH 6.0.

Frit No.	Percent		Culture 1			Culture 2			Average of both cultures
	Fe ₂ O ₃	MnO ₂	Det. 1	Det. 2	Ave.	Det. 1	Det. 2	Ave.	
6285-A	2.5	0	170	167	168	142	127	145	157
control			132	127	130	147	145	146	138
6285-B	5.0	0	147	140	144	180	180	180	162
control			122	122	122	155	155	155	136
6285-C	7.5	0	127	130	129	162	162	162	146
control			107	105	106	167	167	167	137
6285-D	10.0	0	140	140	140	167	157	162	151
control			132	135	134	152	152	152	143
6287-A	5.0	1.0	165	165	165	147	147	147	156
control			165	162	164	162	162	162	164
6287-B	5.0	2.0	135	135	135	120	122	121	128
control			167	162	165	140	135	137	152
6287-C	5.0	3.0	167	167	167	140	136	137	153
control			162	162	162	127	132	130	147
6287-D	5.0	4.0	312	312	312	147	152	150	150
control			140	140	140	152	147	150	145
6286-E	2.5	0	110	92	96	207	197	202	150
control			125	125	125	175	175	175	150
6286-F	5.0	0	145	145	145	162	157	160	153
control			137	135	136	152	152	152	145
6286-G	7.5	0	160	155	157	222	220	221	158
control			147	147	147	142	140	141	144
6286-H	10.0	0	160	160	160	140	141	141	150
control			155	155	155	157	157	157	156
6288-I	5.0	1.0	147	155	151	157	—	157	155
control			127	127	127	180	187	184	156
6288-F	5.0	2.0	175	175	175	—	—	—	175
control			179	180	179	—	—	—	180
6288-G	5.0	3.0	187	187	187	155	152	154	171
control			122	120	121	152	155	154	138
6288-H	5.0	4.0	132	132	132	147	147	147	140
control			110	112	111	155	155	155	133

Table 24. Iron content, expressed as parts per million of oven dry tissue, of plants grown in absolute control cultures supplied with nutrient solution of pH 6.0.

Treatment		Culture 1						Culture 2						Culture 3						Average
Fe p.p.m.	Mn p.p.m.	Pot 1			pot 2			pot 1			pot 2			pot 1			pot 2			
		Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	
		1	2		1	2		1	2		1	2		1	2		1	2		
4.0	0.5	145	142	143	155	147	148	165	162	163	140	132	136	122	127	125	125	125	125	140
0	0.5	155	155	155	157	157	157	182	180	181	162	162	162	167	167	167	140	140	140	160
4.0	0	163	167	165	123	123	123	95	95	95	177	177	177	---	---	---	---	---	---	140
0	0	147	170	158	132	132	132	132	132	132	115	115	115	152	150	151	282	282	282	162

Table 25. Iron content, expressed as parts per million of oven dry tissue, of plants grown in frit and quartz control cultures supplied with nutrient solution of pH 7.0.

Frit No.	Percent		Culture 1			Culture 2			Average of both cultures
	Fe ₂ O ₃	MnO ₂	Det. 1	Det. 2	Ave.	Det. 1	Det. 2	Ave.	
6285-A	2.5	0	155	160	158	155	155	155	156
control			200	200	200	115	115	115	158
6285-B	5.0	0	235	235	235	123	123	122	179
control			228	223	225	115	118	116	171
6285-C	7.5	0	218	218	218	130	128	129	173
control			250	255	253	130	133	131	192
6285-D	10.0	0	265	—	265	133	131	131	198
control			163	158	160	105	103	104	132
6287-A	5.0	1.0	163	168	165	113	110	111.5	138
control			128	128	128	123	123	122.5	125
6287-B	5.0	2.0	123	123	123	88	90	89	106
control			123	125	124	113	113	112.5	118
6287-C	5.0	3.0	113	113	113	110	110	110	111
control			130	130	130	105	105	105	118
6287-D	5.0	4.0	133	133	133	130	130	130	131
control			133	130	132	133	133	132.5	132
6286-E	2.5	0	128	132	130	105	105	105	118
control			153	147	150	272	272	272	211
6286-F	5.0	0	145	145	145	247	235	241	193
control			145	145	145	242	247	245	185
6286-G	7.5	0	130	132	131	250	250	250	191
control			168	167	167	230	250	240	204
6286-H	10.0	0	140	135	137	225	225	225	181
control			135	135	135	132	132	132	134
6288-I	5.0	1.0	133	132	132	115	110	112	123
control			128	127	127	120	120	120	124
6288-J	5.0	2.0	155	155	155	105	102	104	130
control			200	197	199	147	145	146	173
6288-G	5.0	3.0	153	147	150	157	162	160	155
control			163	162	162	125	127	126	145
6288-H	5.0	4.0	250	250	250	132	130	131	191
control			133	122	127	215	200	207	168

Table 26. Iron content, expressed as parts per million of oven dry tissue, of plants grown in absolute control cultures supplied with nutrient solution of pH 7.0.

Treatment		Culture 1						Culture 2						Culture 3						Average
Fe p.p.m.	Mn p.p.m.	pot 1			pot 2			pot 1			pot 2			pot 1			pot 2			
		Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	
		1	2		1	2		1	2		1	2		1	2		1	2		
4.0	0.5	187	187	187	162	155	159	122	122	122	130	132	131	122	120	121	120	120	120	140
0	0.5	152	152	152	157	157	157	127	130	128	132	132	132	135	140	137	145	145	145	142
4.0	0	122	122	122	140	147	144	122	122	122	125	127	126	125	127	126	127	127	127	128
0	0	140	140	140	120	120	120	155	147	149	140	140	140	155	157	156	157	157	157	144

Table 27. Total iron absorbed, in milligrams per ten plants, by plants grown in frit, quartz control, and absolute control cultures supplied with a nutrient solution of pH 4.0.

Frit No.	Percent		Culture 1		Culture 2		Average	
	Fe ₂ O ₃	MnO ₂	Quartz	Frit	Quartz	Frit	Quartz	Frit
6285-A	2.5	0	0.07	0.26	0.12	0.13	0.10	0.20
6285-B	5.0	0	0.14	0.16	0.12	0.13	0.13	0.15
6285-C	7.5	0	0.18	0.20	0.08	0.13	0.13	0.17
6285-D	10.0	0	0.10	0.15	0.08	0.11	0.09	0.13
6287-A	5.0	1.0	0.14	0.13	0.14	0.12	0.14	0.13
6287-B	5.0	2.0	0.14	0.19	0.12	0.12	0.13	0.16
6287-C	5.0	3.0	0.15	0.16	0.10	0.12	0.13	0.14
6287-D	5.0	4.0	0.13	0.14	0.12	0.14	0.13	0.14
6286-B	2.5	0	----	0.12	0.10	0.15	0.10	0.14
6286-F	5.0	0	0.11	0.10	0.10	0.14	0.11	0.13
6286-G	7.5	0	0.10	0.11	0.10	0.06	0.10	0.09
6286-H	10.0	0	0.10	0.12	0.13	0.13	0.12	0.13
6288-E	5.0	1.0	0.14	0.14	0.12	0.13	0.13	0.14
6288-F	5.0	2.0	0.08	0.13	0.09	0.12	0.09	0.13
6288-G	5.0	3.0	0.10	0.04	0.07	0.12	0.09	0.08
6288-H	5.0	4.0	0.12	0.13	0.07	0.11	0.10	0.12

Absolute control culture

Fe P.P.M.	Mn P.P.M.	Culture 1		Culture 2		Culture 3		Average
		pot 1	pot 2	pot 1	pot 2	pot 1	pot 2	
4.0	0.5	0.09	0.08	0.14	0.16	0.10	0.12	0.12
0	0.5	0.07	0.07	----	0.11	0.12	0.10	0.09
4.0	0	0.11	0.08	0.09	----	0.12	0.11	0.10
0	0	0.06	0.04	0.09	0.11	0.14	0.13	0.10

Table 28. Total iron absorbed, in milligrams per ten plants, by plants grown in frit, quartz control, and absolute control cultures supplied with a nutrient solution of pH 5.0.

Frit No.	Percent		Culture 1		Culture 2		Average	
	Fe ₂ O ₃	MnO ₂	Quartz	Frit	Quartz	Frit	Quartz	Frit
285-A	2.5	0	0.08	0.33	0.21	0.29	0.16	0.31
285-B	5.0	0	0.11	0.23	0.20	0.30	0.16	0.27
285-C	7.5	0	0.20	0.24	0.14	0.43	0.17	0.34
285-D	10.0	0	0.20	0.31	0.15	0.29	0.18	0.30
287-A	5.0	1.0	0.17	0.37	0.14	0.36	0.16	0.37
287-B	5.0	2.0	0.26	0.36	0.34	0.56	0.30	0.46
287-C	5.0	3.0	0.19	0.44	0.28	0.43	0.24	0.44
287-D	5.0	4.0	0.17	0.35	0.28	0.50	0.23	0.43
286-E	2.5	0	0.09	0.13	0.13	0.23	0.11	0.18
286-F	5.0	0	0.11	0.18	0.11	0.19	0.11	0.19
286-G	7.5	0	0.07	0.15	0.14	0.24	0.11	0.20
286-H	10.0	0	0.15	0.22	0.12	0.22	0.14	0.22
288-E	5.0	1.0	0.11	0.20	0.11	0.27	0.11	0.24
288-F	5.0	2.0	0.09	0.19	0.12	0.22	0.11	0.21
288-G	5.0	3.0	0.10	0.19	0.21	0.31	0.16	0.25
288-H	5.0	4.0	0.11	0.24	0.13	0.32	0.12	0.28

Absolute control culture

Fe p.p.m.	Mn p.p.m.	Culture 1		Culture 2		Culture 3		Average
		pot 1	pot 2	pot 1	pot 2	pot 1	pot 2	
1.0	0.5	0.20	0.19	0.29	0.25	0.22	0.20	0.23
1.0	0.5	0.10	0.08	0.07	0.08	0.10	0.10	0.09
1.0	0	0.18	0.15	0.24	0.20	0.19	0.19	0.19
1.0	0	0.06	0.06	0.12	0.09	0.15	0.14	0.10

Table 29. Total iron absorbed, in milligrams per ten plants, by plants grown in frit, quartz control, and absolute control cultures supplied with a nutrient solution of pH 6.0.

Frit No.	Percent		Culture 1		Culture 2		Average	
	Fe ₂ O ₃	MnO ₂	Quartz	Frit	Quartz	Frit	Quartz	Frit
285-A	2.5	0	0.54	0.84	0.52	0.82	0.53	0.83
285-B	5.0	0	0.52	0.86	0.51	0.90	0.52	0.88
285-C	7.5	0	0.42	0.89	0.46	0.90	0.44	0.90
285-D	10.0	0	0.44	0.69	0.62	0.93	0.53	0.81
287-A	5.0	1.0	0.48	0.72	0.52	0.82	0.50	0.77
287-B	5.0	2.0	0.53	0.85	0.66	1.03	0.60	0.94
287-C	5.0	3.0	0.59	0.97	0.41	0.70	0.50	0.84
287-D	5.0	4.0	0.46	1.26	0.46	0.63	0.46	0.95
286-E	2.5	0	0.35	0.37	0.71	1.00	0.53	0.69
286-F	5.0	0	0.27	0.55	0.56	0.69	0.42	0.62
286-G	7.5	0	0.29	0.62	0.44	—	0.37	0.62
286-H	10.0	0	0.23	0.46	0.53	0.60	0.38	0.53
288-E	5.0	1.0	0.45	0.71	0.78	0.83	0.62	0.77
288-F	5.0	2.0	0.50	0.62	—	—	0.50	0.62
288-G	5.0	3.0	0.39	0.67	0.45	0.70	0.42	0.69
288-H	5.0	4.0	0.33	0.46	0.44	0.71	0.39	0.59

Absolute control culture

Fe p.p.m.	Mn p.p.m.	Culture 1		Culture 2		Culture 3		Average
		pot 1	pot 2	pot 1	pot 2	pot 1	pot 2	
4.0	0.5	0.45	0.49	0.57	0.53	0.44	0.44	0.49
0	0.5	0.53	0.48	0.39	0.40	0.64	0.54	0.50
4.0	0	0.56	0.40	0.33	0.57	—	—	0.47
0	0	0.36	0.36	0.43	0.35	0.33	0.73	0.43

Table 30. Total iron absorbed, in milligrams per ten plants, by plants grown in frit, quartz control, and absolute control cultures supplied with a nutrient solution of pH 7.0.

Frit No.	Percent		Culture 1		Culture 2		Average	
	Fe ₂ O ₃	MnO ₂	Quartz	Frit	Quartz	Frit	Quartz	Frit
6285-A	2.5	0	0.16	0.29	0.10	0.28	0.13	0.29
6285-B	5.0	0	0.23	0.43	0.09	0.22	0.16	0.33
6285-C	7.5	0	0.24	0.37	0.10	0.15	0.17	0.26
6285-D	10.0	0	0.13	0.41	0.10	0.22	0.12	0.32
6287-A	5.0	1.0	0.15	0.32	0.11	0.24	0.13	0.28
6287-B	5.0	2.0	0.14	0.23	0.11	0.17	0.12	0.20
6287-C	5.0	3.0	0.14	0.17	0.10	0.20	0.12	0.19
6287-D	5.0	4.0	0.13	0.23	0.15	0.23	0.14	0.23
6286-E	2.5	0	0.12	0.15	0.23	0.15	0.18	0.15
6286-F	5.0	0	0.11	0.15	0.23	0.32	0.17	0.24
6286-G	7.5	0	0.12	0.16	0.18	0.34	0.15	0.25
6286-H	10.0	0	0.10	0.17	0.11	0.32	0.11	0.25
6288-E	5.0	1.0	0.09	0.17	0.10	0.19	0.10	0.18
6288-F	5.0	2.0	0.19	0.18	0.11	0.17	0.15	0.18
6288-G	5.0	3.0	0.14	0.18	0.11	0.26	0.13	0.22
6288-H	5.0	4.0	0.09	0.34	0.17	0.21	0.13	0.28

Absolute control culture

Fe p.p.m.	Mn p.p.m.	Culture 1		Culture 2		Culture 3		Average
		pot 1	pot 2	pot 1	pot 2	pot 1	pot 2	
4.0	0.5	0.19	0.16	0.17	0.17	0.14	0.14	0.16
0	0.5	0.14	0.15	0.09	0.09	0.15	0.15	0.13
4.0	0	0.17	0.18	0.13	0.12	0.20	0.21	0.17
0	0	0.11	0.10	0.11	0.10	0.20	0.21	0.14

Table 31. Manganese content, expressed as parts per million of oven dry tissue, of plants grown in frit and quartz control cultures supplied with a nutrient solution of pH 4.0.

Frit No.	Percent		Culture 1			Culture 2			Average of both cultures
	Fe ₂ O ₃	MnO ₂	Det. 1	Det. 2	Ave.	Det. 1	Det. 2	Ave.	
5285-A	2.5	0	183	188	186	162	162	162	174
control			171	174	173	154	154	154	164
5285-B	5.0	0	154	154	154	159	162	160	157
control			140	137	139	128	138	133	136
5285-C	7.5	0	154	137	146	159	159	159	153
control			132	128	130	176	171	174	152
5285-D	10.0	0	128	128	128	132	138	135	132
control			130	130	130	128	128	128	129
5287-A	5.0	1.0	256	266	261	270	270	270	266
control			307	299	303	324	316	320	312
5287-B	5.0	2.0	350	343	347	302	302	302	325
control			299	295	297	315	308	312	305
5287-C	5.0	3.0	317	304	311	375	359	367	339
control			283	292	288	418	415	417	353
5287-D	5.0	4.0	333	350	342	370	362	366	354
control			418	418	418	398	410	404	411
5286-E	2.5	0	120	120	120	121	126	124	122
control			133	136	135	119	116	118	127
5286-F	5.0	0	120	111	116	121	120	121	119
control			135	137	136	121	123	121	129
5286-G	7.5	0	116	126	121	145	138	142	132
control			126	136	131	160	157	159	145
5286-H	10.0	0	111	124	118	121	120	121	120
control			124	111	118	153	143	148	133
6288-I	5.0	1.0	154	158	156	191	196	194	175
control			113	111	112	147	170	159	136
6288-F	5.0	2.0	227	227	227	213	—	213	220
control			213	210	212	196	188	192	202
6288-G	5.0	3.0	243	244	244	251	248	250	247
control			278	268	273	227	224	226	250
6288-H	5.0	4.0	196	196	196	256	273	265	231
control			216	213	215	273	282	278	247

Table 32. Manganese content, expressed as parts per million of oven dry tissue, of plants grown in absolute control cultures supplied with nutrient solution of pH 4.0.

Treatment		Culture 1						Culture 2						Culture 3						Average
Fe	Mn	pot 1			pot 2			pot 1			pot 2			pot 1			pot 2			
p.p.m.	p.p.m.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	
		1	2		1	2		1	2		1	2		1	2		1	2		
4.0	0.5	128	136	132	130	125	128	125	126	126	138	137	138	---	---	---	---	---	---	131
0	0.5	132	143	138	142	145	144	202	188	195	212	213	213	205	212	209	190	200	195	182
4.0	0	traces*			traces			traces			traces			traces			traces			
0	0	traces			traces			traces			traces			traces			traces			

traces* less than 10 p.p.m.

Table 33. Manganese content, expressed as parts per million of oven dry tissue, of plants grown in frit and quartz control cultures supplied with a nutrient solution of pH 5.0.

Frit No.	Percent		Culture 1			Culture 2			Average of both cultures
	Fe_2O_3	MnO_2	Det. 1	Det. 2	Ave.	Det. 1	Det. 2	Ave.	
85-A	2.5	0	145	145	145	137	137	137	141
control			244	251	248	222	210	216	232
85-B	5.0	0	157	150	154	128	125	127	141
control			211	208	210	202	205	204	207
85-C	7.5	0	128	130	130	142	140	141	136
control			210	217	214	213	222	218	216
85-D	10.0	0	128	128	128	120	134	127	128
control			210	200	205	213	—	213	209
87-A	5.0	1.0	142	142	142	235	234	235	189
control			401	384	393	392	384	388	390
87-B	5.0	2.0	213	213	213	205	205	205	209
control			282	278	280	297	289	293	287
87-C	5.0	3.0	222	225	224	227	217	222	223
control			415	418	417	384	380	382	400
87-D	5.0	4.0	304	290	297	239	246	243	270
control			478	483	481	418	420	419	450
86-E	2.5	0	200	171	186	219	217	218	202
control			254	256	255	273	270	272	264
86-F	5.0	0	191	191	191	213	213	213	202
control			280	282	281	268	273	271	276
86-G	7.5	0	198	188	193	205	196	201	297
control			297	300	299	290	290	290	295
86-H	10.0	0	179	186	183	196	193	195	189
control			260	248	254	290	295	293	273
88-E	5.0	1.0	116	116	116	85	85	85	101
control			94	91	93	68	68	68	81
88-F	5.0	2.0	145	147	146	111	111	111	128
control			120	120	120	85	91	88	104
88-G	5.0	3.0	113	120	117	171	183	177	147
control			196	196	196	154	155	155	176
88-H	5.0	4.0	237	241	239	207	202	205	222
control			176	193	185	217	213	215	200

Table 34. Manganese content, expressed as parts per million of oven dry tissue, of plants grown in absolute control cultures supplied with nutrient solution of pH 5.0.

Treatment		Culture 1						Culture 2						Culture 3						Average
Fe	Mn	pot 1			pot 2			pot 1			pot 2			pot 1			pot 2			
p.p.m.	p.p.m.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	
		1	2		1	2		1	2		1	2		1	2		1	2		
4.0	0.5	210	213	212	210	213	212	188	193	191	196	196	196	213	213	213	196	205	201	204
0	0.5	333	299	316	324	319	322	362	354	358	347	340	344	340	342	341	333	350	342	337
4.0	0	traces*			traces			traces			traces			traces			traces			
0	0	traces			traces			traces			traces			traces			traces			

traces* less than 10 p.p.m.

Table 35. Manganese content, expressed as parts per million of oven dry tissue, of plants grown in frit and quartz control cultures supplied with a nutrient solution of pH 6.0.

Frit No.	Percent		Culture 1			Culture 2			Average of both cultures
	Fe ₂ O ₃	MnO ₂	Det. 1	Det. 2	Ave.	Det. 1	Det. 2	Ave.	
5285-A	2.5	0	75	79	78	75	75	75	77
control			109	109	109	123	120	123	116
5285-B	5.0	0	58	59	59	81	81	81	70
control			103	103	104	126	126	126	115
5285-C	7.5	0	66	68	68	78	81	80	74
control			137	136	137	156	156	156	147
5285-D	10.0	0	76	79	78	95	92	94	86
control			137	137	138	134	137	136	137
5287-A	5.0	1.0	146	146	146	180	180	180	163
control			245	245	245	350	344	348	297
5287-B	5.0	2.0	194	194	194	163	163	163	179
control			354	354	355	340	354	348	352
5287-C	5.0	3.0	208	208	209	194	194	194	202
control			290	293	292	418	421	420	356
5287-D	5.0	4.0	222	222	223	217	217	217	220
control			305	290	298	404	418	411	355
5286-E	2.5	0	151	149	150	113	109	112	131
control			203	193	198	134	134	135	167
5286-F	5.0	0	178	177	178	117	120	120	148
control			217	217	217	151	151	152	185
5286-G	7.5	0	156	149	153	99	99	99	126
control			234	242	239	177	183	180	210
5286-H	10.0	0	122	122	122	127	127	128	125
control			197	197	197	174	177	176	187
288-E	5.0	1.0	113	109	112	83	---	84	98
control			85	89	88	100	95	98	93
288-F	5.0	2.0	151	149	151	---	---	---	151
control			171	171	172	---	---	---	172
288-G	5.0	3.0	202	198	201	217	217	217	209
control			202	202	203	220	220	220	212
288-H	5.0	4.0	217	219	219	220	208	214	217
control			251	251	251	254	254	254	253

Table 36. Manganese content, expressed as parts per million of oven dry tissue, of plants grown in absolute control cultures supplied with nutrient solution of pH 6.0.

Treatment		Culture 1						Culture 2						Culture 3						Average
Fe p.p.m.	Mn p.p.m.	pot 1			pot 2			pot 1			pot 2			pot 1			pot 2			
		Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	
		1	2		1	2		1	2		1	2		1	2		1	2		
4.0	0.5	117	123	120	132	132	132	106	106	106	117	117	117	117	117	117	127	132	130	120
0	0.5	194	194	194	194	194	194	198	191	195	197	198	198	166	174	170	137	149	143	182
4.0	0	traces*			traces			traces			traces			traces			traces			
0	0	traces			traces			traces			traces			traces			14	14		

traces* less than 10 p.p.m.

Table 37. Manganese content, expressed as parts per million of oven dry tissue, of plants grown in frit and quartz control cultures supplied with a nutrient solution of pH 7.0.

Frit No.	Percent		Culture 1			Culture 2			Average of both cultures
	Fe ₂ O ₃	MnO ₂	Det. 1	Det. 2	Ave.	Det. 1	Det. 2	Ave.	
285-A	2.5	0	39	38	39	83	83	83	61
control			121	123	122	122	113	118	120
285-B	5.0	0	67	66	66	89	92	91	79
control			104	95	99	106	109	107	103
285-C	7.5	0	142	137	139	99	99	99	119
control			47	52	50	136	140	138	94
285-D	10.0	0	53	52	52	92	92	92	72
control			56	55	55	89	89	89	72
287-A	5.0	1.0	138	134	136	166	166	166	151
control			166	175	170	170	166	168	169
287-B	5.0	2.0	163	163	163	163	163	163	163
control			277	262	269	248	251	249	260
287-C	5.0	3.0	177	174	176	190	190	190	183
control			277	276	276	349	351	350	214
287-D	5.0	4.0	227	227	227	203	205	204	216
control			362	333	347	333	322	327	338
286-E	2.5	0	135	134	134	100	100	100	118
control			170	170	170	170	170	170	170
286-F	5.0	0	146	149	147	156	151	154	151
control			220	221	220	180	183	181	201
286-G	7.5	0	118	112	115	134	134	134	125
control			200	198	199	180	183	181	190
286-H	10.0	0	104	103	103	134	137	136	120
control			184	184	184	191	188	190	187
288-E	5.0	1.0	114	113	113	35	38	37	75
control			81	78	79	35	35	35	58
288-F	5.0	2.0	129	136	132	72	75	74	103
control			118	117	117	66	66	66	92
288-G	5.0	3.0	175	174	174	245	251	248	211
control			160	160	160	85	85	85	128
288-H	5.0	4.0	211	205	208	163	170	166	188
control			189	185	185	208	218	213	200

Table 38. Manganese content, expressed as parts per million of oven dry tissue, of plants grown in absolute control cultures supplied with nutrient solution of pH 7.0.

Treatment		Culture 1						Culture 2						Culture 3						Average
Fe	Mn	pot 1			pot 2			pot 1			pot 2			pot 1			pot 2			
p.p.m.	p.p.m.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	Det.	Det.	Ave.	
		1	2		1	2		1	2		1	2		1	2		1	2		
4.0	0.5	127	127	127	134	132	133	109	109	109	89	92	91	265	276	271	193	191	192	154
0	0.5	197	197	197	217	214	215	205	208	207	236	236	236	134	134	134	134	140	137	188
4.0	0	21	21		21	20		14	21		traces*			traces			traces			
0	0	traces			traces			21	21		17	11		traces			traces			

traces* less than 10 p.p.m.

Table 39. Total manganese absorbed, in milligrams per ten plants, by plants grown in frit, quartz control, and absolute control cultures supplied with a nutrient solution of pH 4.0.

Frit No.	Percent		Culture 1		Culture 2		Average	
	Fe ₂ O ₃	MnO ₂	Quartz	Frit	Quartz	Frit	Quartz	Frit
5285-A	2.5	0	0.23	0.32	0.21	0.28	0.22	0.30
5285-B	5.0	0	0.18	0.21	0.19	0.26	0.19	0.24
5285-C	7.5	0	0.21	0.29	0.20	0.24	0.21	0.27
5285-D	10.0	0	0.15	0.23	0.16	0.22	0.16	0.23
6287-A	5.0	1.0	0.49	0.44	0.49	0.43	0.49	0.44
6287-B	5.0	2.0	0.41	0.62	0.43	0.44	0.42	0.53
6287-C	5.0	3.0	0.41	0.57	0.54	0.61	0.48	0.59
6287-D	5.0	4.0	0.60	0.57	0.55	0.57	0.58	0.57
6286-E	2.5	0	0.13	0.17	0.14	0.31	0.14	0.24
6286-F	5.0	0	0.14	0.14	0.13	0.22	0.14	0.18
6286-G	7.5	0	0.15	0.14	0.21	0.20	0.18	0.17
6286-H	10.0	0	0.12	0.15	0.23	0.20	0.18	0.18
6288-E	5.0	1.0	0.14	0.20	0.22	0.30	0.18	0.25
6288-F	5.0	2.0	0.25	0.33	0.16	0.27	0.20	0.30
6288-G	5.0	3.0	0.30	0.29	0.26	0.38	0.28	0.34
6288-H	5.0	4.0	0.26	0.27	0.33	0.37	0.30	0.32

Absolute control culture

Fe p.p.m.	Mn p.p.m.	Culture 1		Culture 2		Culture 3		Average
		pot 1	pot 2	pot 1	pot 2	pot 1	pot 2	
4.0	0.5	0.12	0.12	0.17	0.25	—	—	0.17
0	0.5	0.13	0.15	0.28	0.30	0.32	0.28	0.28

Table 40. Total manganese absorbed, in milligrams per ten plants, by plants grown in frit, quartz control, and absolute control cultures supplied with a nutrient solution of pH 5.0.

Frit No.	Percent		Culture 1		Culture 2		Average	
	Fe ₂ O ₃	MnO ₂	Quartz	Frit	Quartz	Frit	Quartz	Frit
6285-A	2.5	0	0.34	0.57	0.49	0.50	0.42	0.54
6285-B	5.0	0	0.45	0.49	0.55	0.50	0.50	0.50
6285-C	7.5	0	0.52	0.43	0.45	0.53	0.49	0.48
6285-D	10.0	0	0.65	0.51	0.57	0.47	0.61	0.49
6287-A	5.0	1.0	1.10	0.49	0.57	0.93	0.84	0.71
6287-B	5.0	2.0	0.89	0.93	1.16	1.03	1.03	0.98
6287-C	5.0	3.0	1.14	1.03	1.11	0.86	1.12	0.95
6287-D	5.0	4.0	1.15	1.20	0.98	1.04	1.07	1.12
6286-E	2.5	0	0.61	0.50	0.46	0.61	0.54	0.56
6286-F	5.0	0	0.56	0.51	0.54	0.66	0.55	0.59
6286-G	7.5	0	0.43	0.49	0.55	0.63	0.49	0.57
6286-H	10.0	0	0.49	0.50	0.63	0.63	0.56	0.57
6288-E	5.0	1.0	0.15	0.30	0.12	0.27	0.14	0.29
6288-F	5.0	2.0	0.18	0.40	0.13	0.28	0.16	0.34
6288-G	5.0	3.0	0.27	0.24	0.34	0.60	0.31	0.42
6288-H	5.0	4.0	0.28	0.63	0.34	0.65	0.31	0.64

Absolute control culture

Fe p.p.m.	Mn p.p.m.	Culture 1		Culture 2		Culture 3		Average
		pot 1	pot 2	pot 1	pot 2	pot 1	pot 2	
4.0	0.5	0.63	0.53	0.61	0.65	0.63	0.56	0.60
0	0.5	0.41	0.44	0.45	0.55	0.48	0.54	0.48

Table 41. Total manganese absorbed, in milligrams per ten plants, by plants grown in frit, quartz control, and absolute control cultures supplied with a nutrient solution of pH 6.0.

Frit No.	Percent		Culture 1		Culture 2		Average	
	Fe ₂ O ₃	MnO ₂	Quartz	Frit	Quartz	Frit	Quartz	Frit
285-A	2.5	0	0.45	0.39	0.43	0.43	0.44	0.41
285-B	5.0	0	0.44	0.35	0.42	0.41	0.43	0.38
285-C	7.5	0	0.54	0.47	0.43	0.44	0.49	0.46
285-D	10.0	0	0.45	0.39	0.55	0.53	0.50	0.46
287-A	5.0	1.0	0.72	0.64	1.11	1.00	0.92	0.82
287-B	5.0	2.0	1.13	1.22	1.66	1.38	1.40	1.30
287-C	5.0	3.0	1.06	1.20	1.32	0.99	1.19	1.10
287-D	5.0	4.0	0.97	0.90	1.25	0.90	1.11	0.90
286-E	2.5	0	0.55	0.57	0.55	0.55	0.55	0.56
286-F	5.0	0	0.43	0.68	0.56	0.52	0.50	0.60
286-G	7.5	0	0.47	0.60	0.57	0.44	0.52	0.52
286-H	10.0	0	0.30	0.35	0.59	0.54	0.45	0.45
288-E	5.0	1.0	0.31	0.53	0.41	0.44	0.36	0.49
288-F	5.0	2.0	0.48	0.53	---	---	0.48	0.53
288-G	5.0	3.0	0.64	0.71	0.64	0.99	0.64	0.85
288-H	5.0	4.0	0.74	0.75	0.72	1.03	0.73	0.89

Absolute control cultures

Fe p.p.m.	Mn p.p.m.	Culture 1		Culture 2		Culture 3		Average
		pot 1	pot 2	pot 1	pot 2	pot 1	pot 2	
4.0	0.5	0.38	0.44	0.37	0.46	0.41	0.45	0.42
0	0.5	0.67	0.59	0.42	0.48	0.65	0.56	0.56

Table 42. Total manganese absorbed, in milligrams per ten plants, by plants grown in frit, quartz control, and absolute control cultures supplied with a nutrient solution of pH 7.0.

Frit No.	Percent		Culture 1		Culture 2		Average	
	Fe ₂ O ₃	MnO ₂	Quartz	Frit	Quartz	Frit	Quartz	Frit
6285-A	2.5	0	0.10	0.07	0.11	0.15	0.11	0.11
6285-B	5.0	0	0.10	0.12	0.08	0.16	0.09	0.14
6285-C	7.5	0	0.05	0.23	0.11	0.18	0.08	0.21
6285-D	10.0	0	0.04	0.08	0.09	0.15	0.07	0.12
6287-A	5.0	1.0	0.20	0.27	0.14	0.36	0.17	0.32
6287-B	5.0	2.0	0.30	0.31	0.16	0.30	0.23	0.31
6287-C	5.0	3.0	0.30	0.26	0.18	0.35	0.24	0.30
6287-D	5.0	4.0	0.34	0.39	0.23	0.36	0.29	0.38
6286-E	2.5	0	0.14	0.16	0.14	0.14	0.14	0.15
6286-F	5.0	0	0.16	0.15	0.17	0.21	0.17	0.18
6286-G	7.5	0	0.15	0.14	0.14	0.18	0.15	0.16
6286-H	10.0	0	0.14	0.13	0.16	0.20	0.15	0.17
6288-E	5.0	1.0	0.06	0.14	0.03	0.05	0.05	0.10
6288-F	5.0	2.0	0.11	0.16	0.05	0.12	0.08	0.14
6288-G	5.0	3.0	0.14	0.22	0.08	0.40	0.11	0.31
6288-H	5.0	4.0	0.14	0.29	0.18	0.26	0.16	0.28

Absolute control cultures

Fe p.p.m.	Mn p.p.m.	Culture 1		Culture 2		Culture 3		Average
		pot 1	pot 2	pot 1	pot 2	pot 1	pot 2	
4.0	0.5	0.13	0.14	0.15	0.12	0.32	0.23	0.18
0	0.5	0.18	0.19	0.15	0.15	0.15	0.14	0.16

Table 43. Milligrams of iron per carboy at the end of the experimental period at pH 4.0 of nutrient solution.

Frit No.	Carboy No.	
	1	2
6285-A	3.4	4.4
6285-B	5.7	4.2
6285-C	4.7	3.8
6285-D	5.6	3.1
6286-E	3.8	6.3
6286-F	5.7	7.8
6286-G	3.4	3.6
6286-H	8.4	3.6

Treatment	Absolute controls			
	Carboy No.			
	1	2	3	4
Fe added	25.0	18.8	36.0	20.2
Fe not added	4.2	3.3	4.2	2.7

Table 44. Milligrams of iron per carboy at the end of the experimental period at pH 7.0 of nutrient solution.

Frit No.	Carboy No.	
	1	2
6285-A	3.8	14.0
6285-B	7.0	11.5
6285-C	7.7	10.2
6285-D	7.7	10.2
6286-E	7.0	7.0
6286-F	8.3	6.4
6286-G	8.3	4.5
6286-H	8.9	2.6

Absolute controls

Treatment	Carboy No.		
	1	2	3
Fe added	56.3	--	--
Fe not added	7.7	7.6	5.1

Table 45. Fe/Mn ratio in dry matter of plants grown in frit and quartz control cultures supplied with nutrient solution of pH 5.0.

Frit No.	Percent		Culture 1		Culture 2		Average	
	Fe ₂ O ₃	MnO ₂	Quartz	Frit	Quartz	Frit	Quartz	Frit
6285-A	2.5	0	0.23	0.58	0.44	0.59	0.34	0.59
6285-B	5.0	0	0.25	0.47	0.37	0.60	0.31	0.54
6285-C	7.5	0	0.38	0.55	0.30	0.82	0.34	0.69
6285-D	10.0	0	0.30	0.62	0.26	0.61	0.28	0.62
6287-A	5.0	1.0	0.16	0.76	0.24	0.39	0.20	0.58
6287-B	5.0	2.0	0.30	0.38	0.30	0.54	0.30	0.46
6287-C	5.0	3.0	0.17	0.42	0.25	0.50	0.21	0.46
6287-D	5.0	4.0	0.15	0.29	0.31	0.48	0.23	0.39
6286-E	2.5	0	0.15	0.25	0.28	0.39	0.22	0.32
6286-F	5.0	0	0.20	0.36	0.21	0.29	0.21	0.33
6286-G	7.5	0	0.17	0.31	0.26	0.38	0.22	0.35
6286-H	10.0	0	0.30	0.43	0.19	0.34	0.25	0.39
6288-I	5.0	1.0	0.70	0.66	0.91	1.02	0.81	0.84
6288-J	5.0	2.0	0.53	0.49	0.90	0.77	0.72	0.63
6288-Q	5.0	3.0	0.38	0.79	0.61	0.61	0.50	0.70
6288-H	5.0	4.0	0.41	0.39	0.37	0.45	0.39	0.42

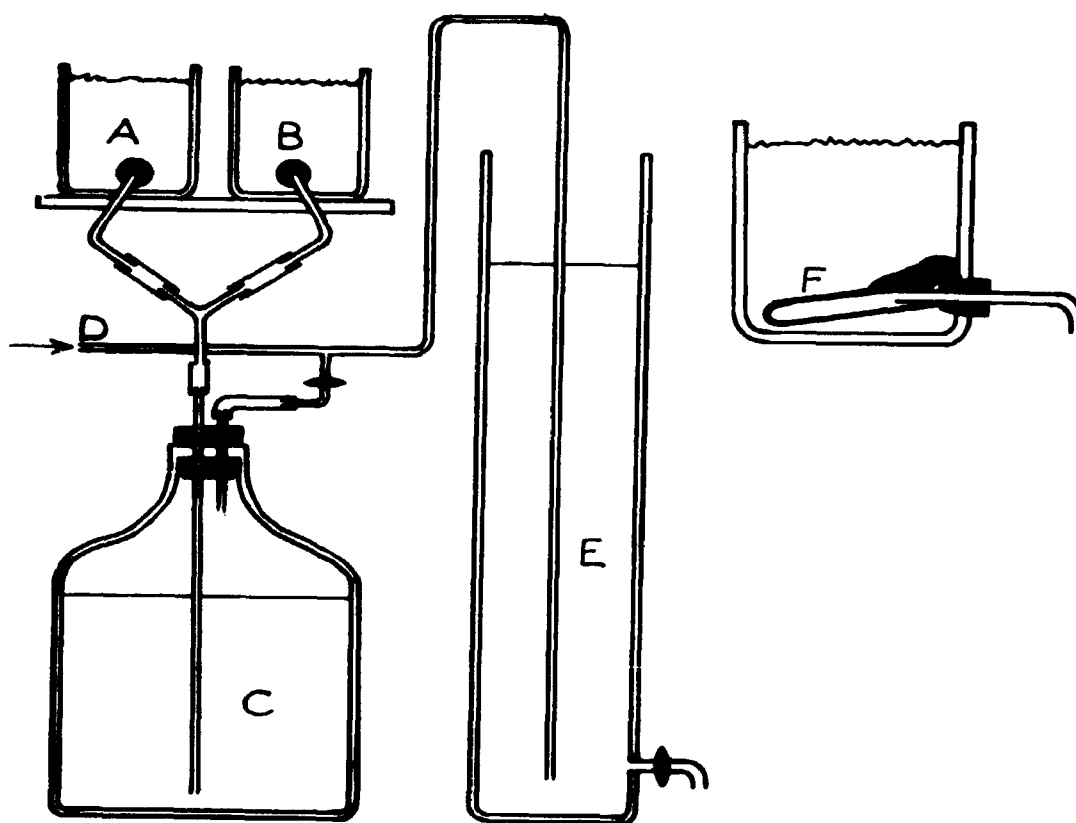


Figure 1. Mechanical arrangement of the cultures. (A) and (B) one-gallon glazed earthenware culture pots. (C) carboy containing 16 liters of nutrient solution. (D) Pipe leading compressed air to carboy. (E) Hydrostatic water column regulating the level of the nutrient solution in the culture pots. (F) Test tube and layer of glass wool covering end of glass tube leading the nutrient solution into the culture pot.

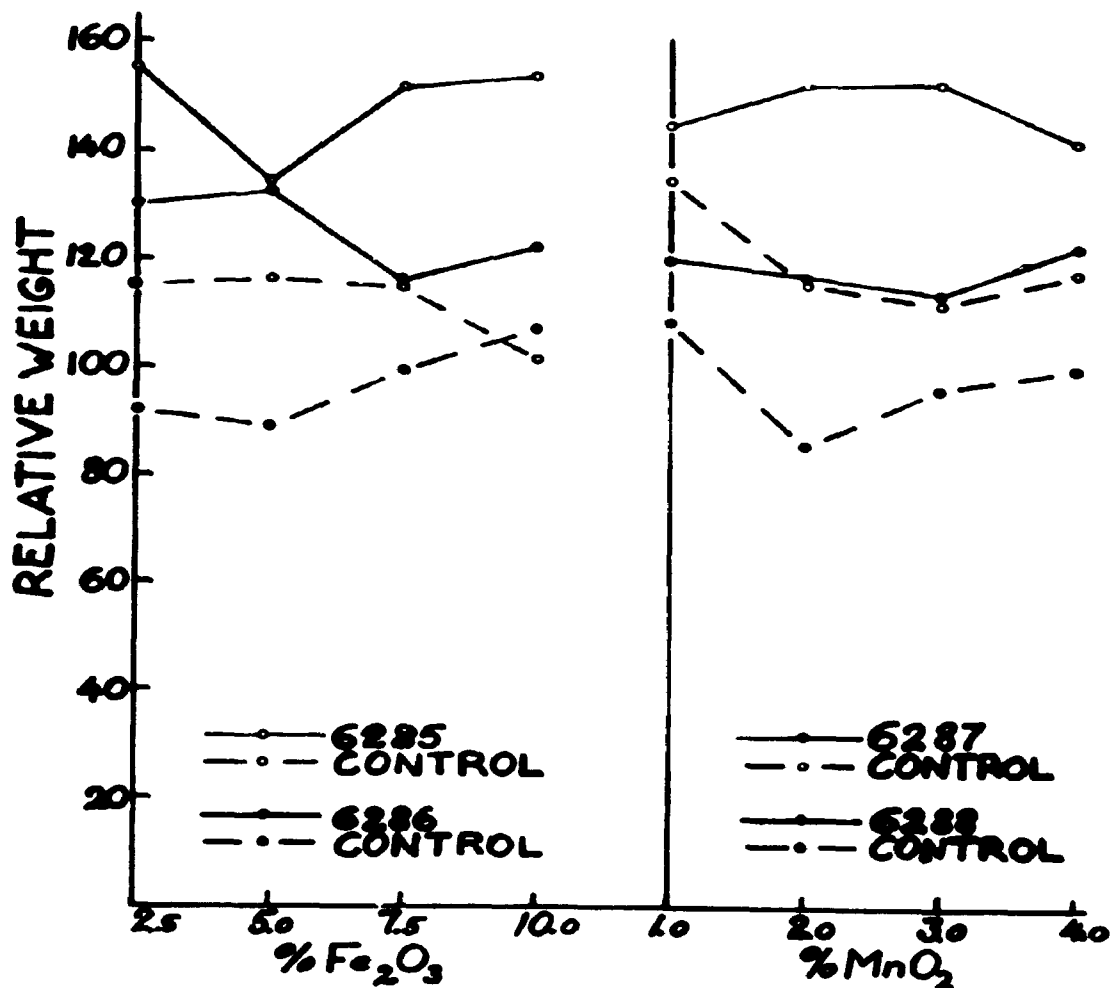


Figure 2. Average fresh weight of plants in frit and control cultures, calculated in percent of average fresh weight of plants in absolute control cultures receiving complete nutrient solution, plotted against frit composition. Nutrient solution of pH 4.0

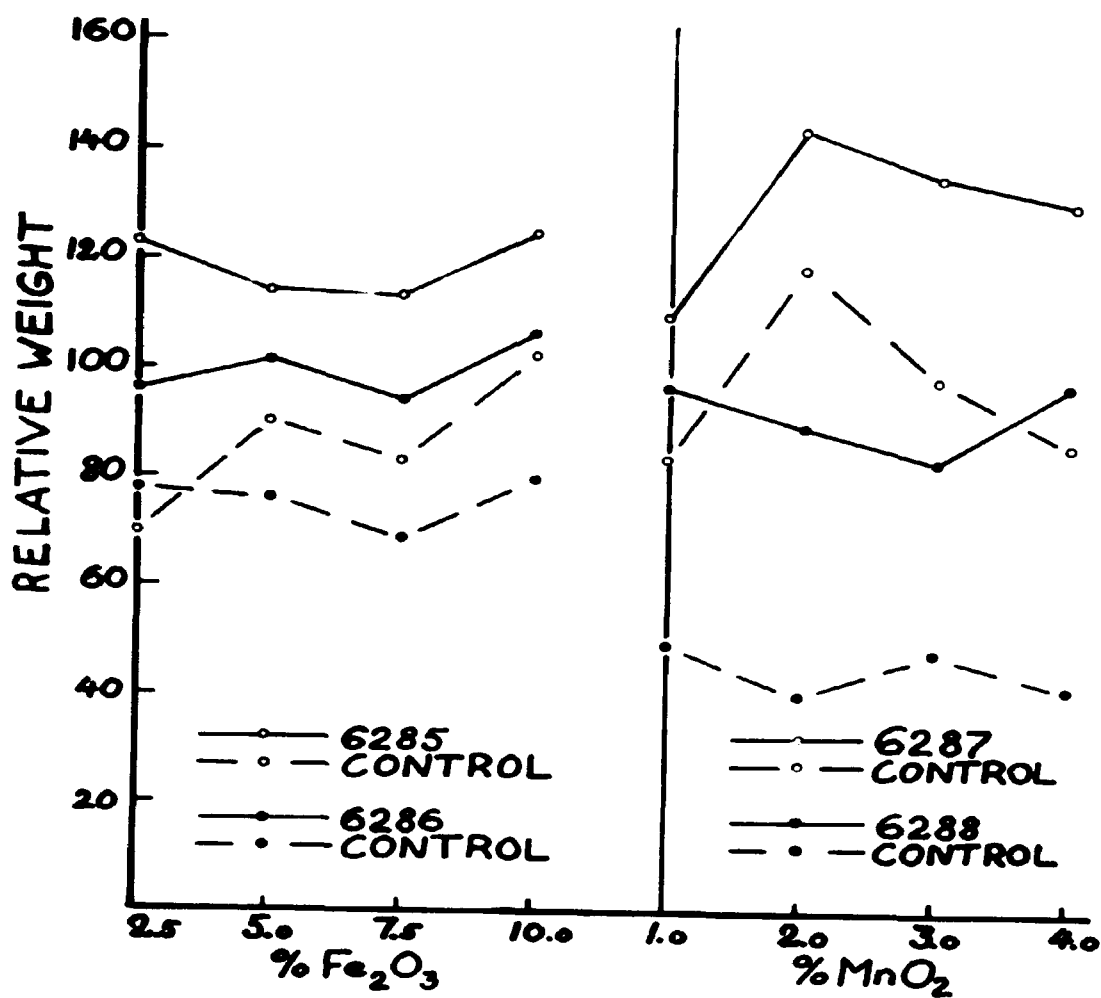


Figure 3. Average fresh weight of plants in frit and control cultures, calculated in percent of average fresh weight of plants in absolute control cultures receiving complete nutrient solution, plotted against frit composition. Nutrient solution of pH 5.0

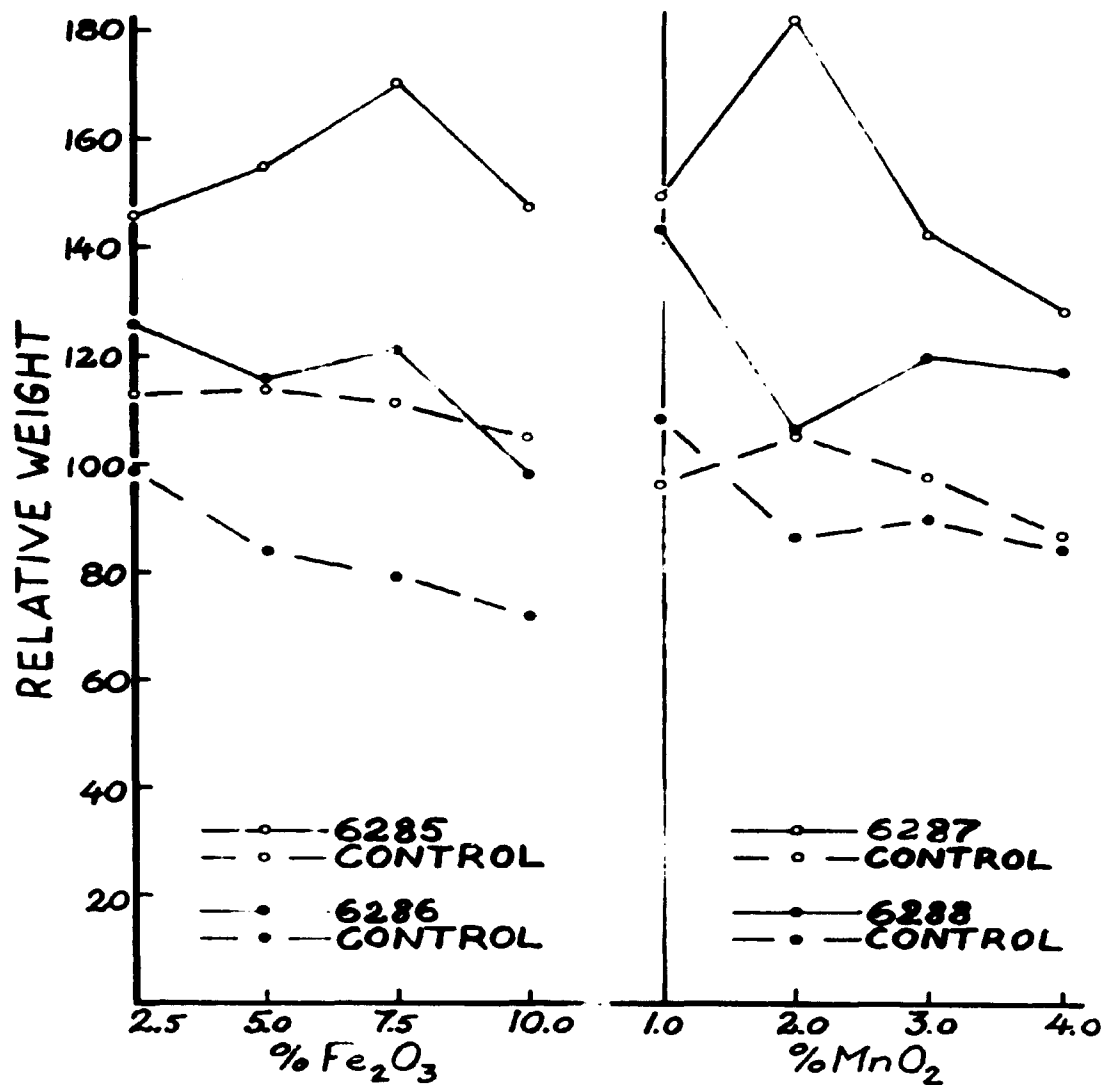


Figure 4. Average fresh weight of plants in frit and control cultures, calculated in percent of average fresh weight of plants in absolute control cultures receiving complete nutrient solution, plotted against frit composition. Nutrient solution of pH 6.0

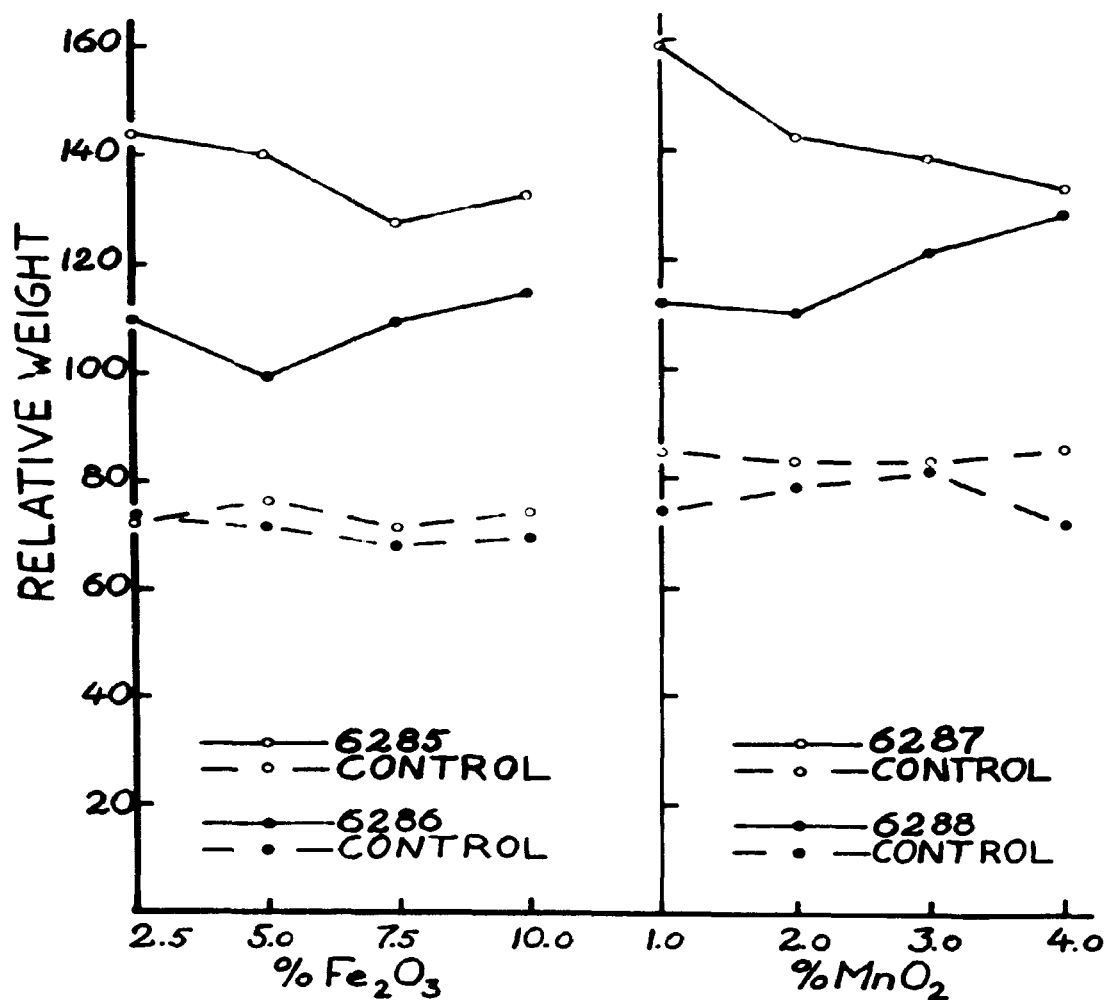


Figure 5. Average fresh weight of plants in frit and control cultures, calculated in percent of average fresh weight of plants in absolute control cultures receiving complete nutrient solution, plotted against frit composition. Nutrient solution of pH 7.0

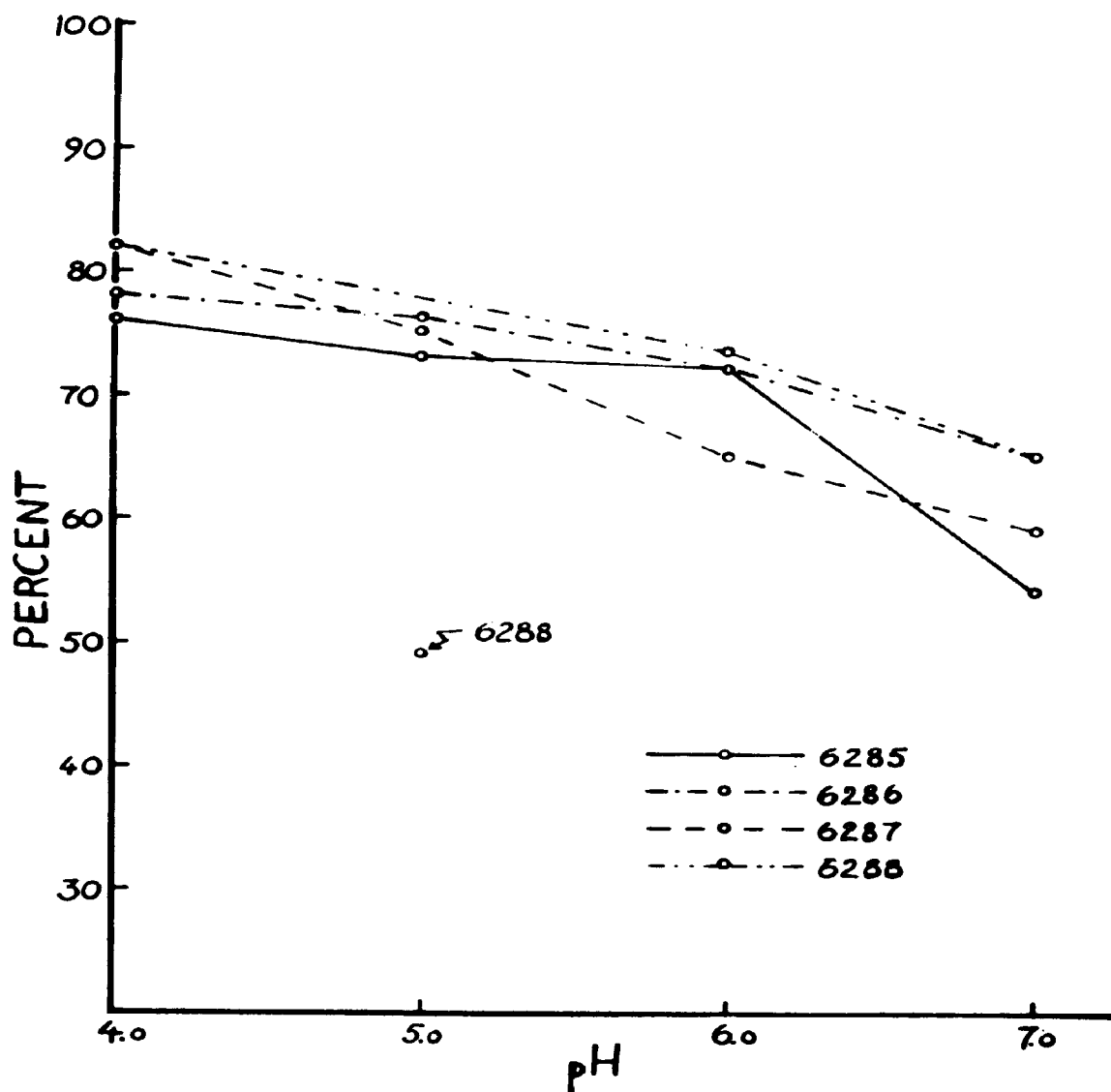


Figure 6. Average fresh weight of control plants, calculated in percent of average fresh weight of corresponding frit grown plants, plotted against pH of nutrient solution.

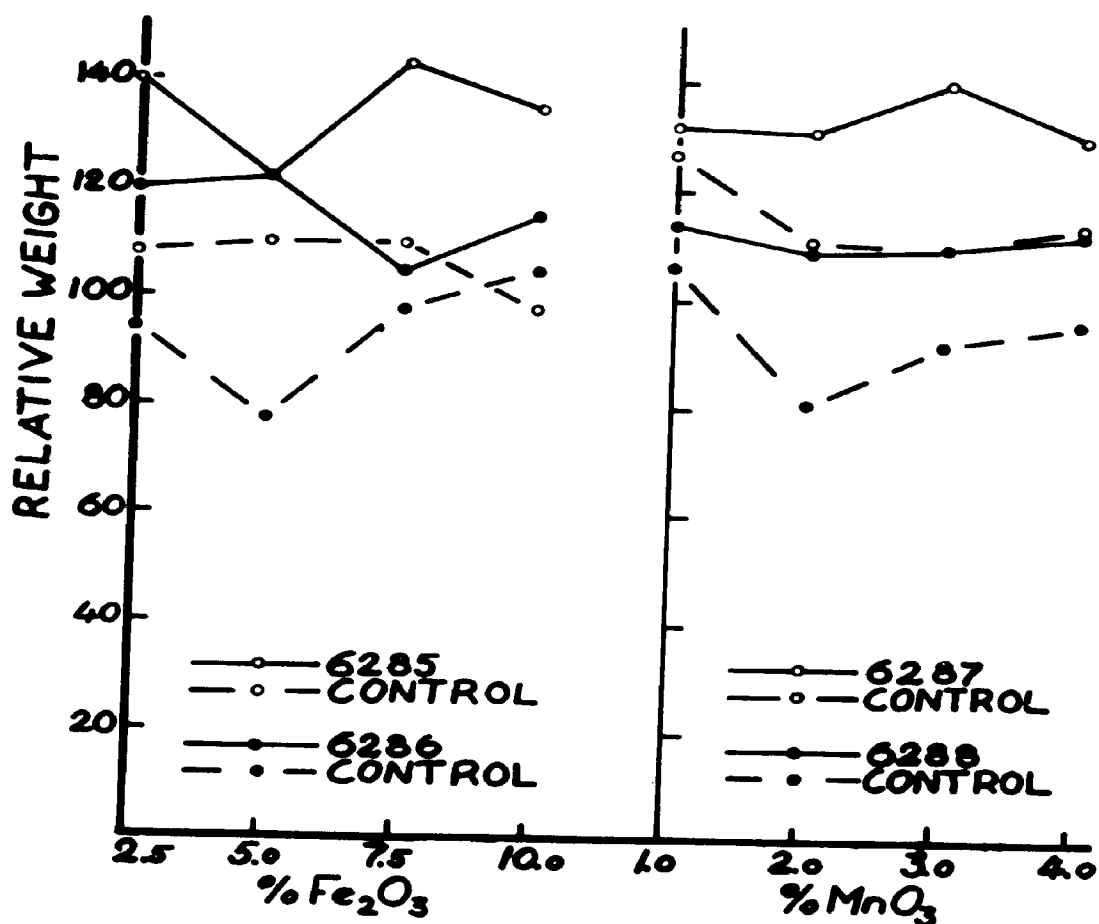


Figure 7. Average dry weight of plants in frit and control cultures, calculated in percent of average dry weight of plants in absolute control cultures receiving complete nutrient solution, plotted against frit composition. Nutrient solution of pH 4.0

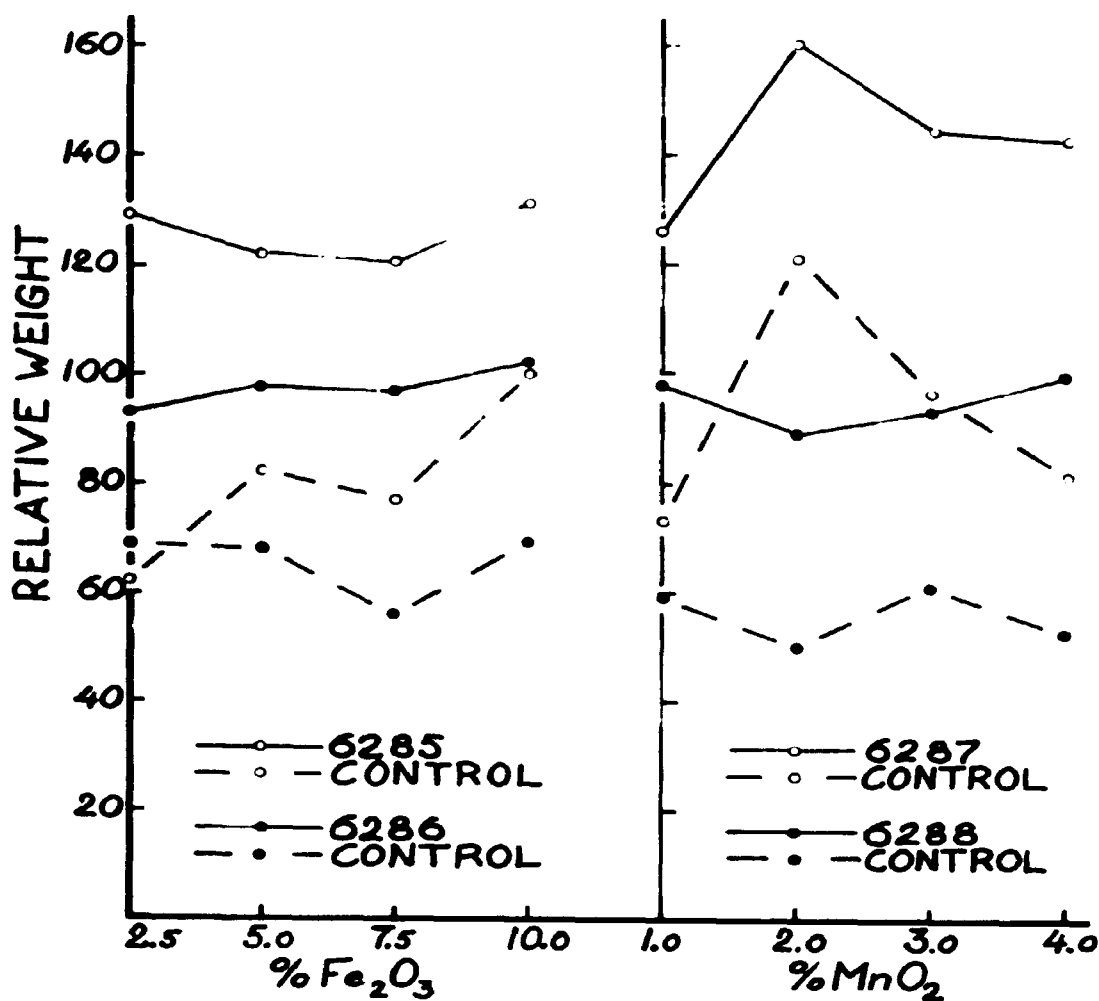


Figure 8. Average dry weight of plants in frit and control cultures, calculated in percent of average dry weight of plants in absolute control cultures receiving complete nutrient solution, plotted against frit composition. Nutrient solution of pH 5.0

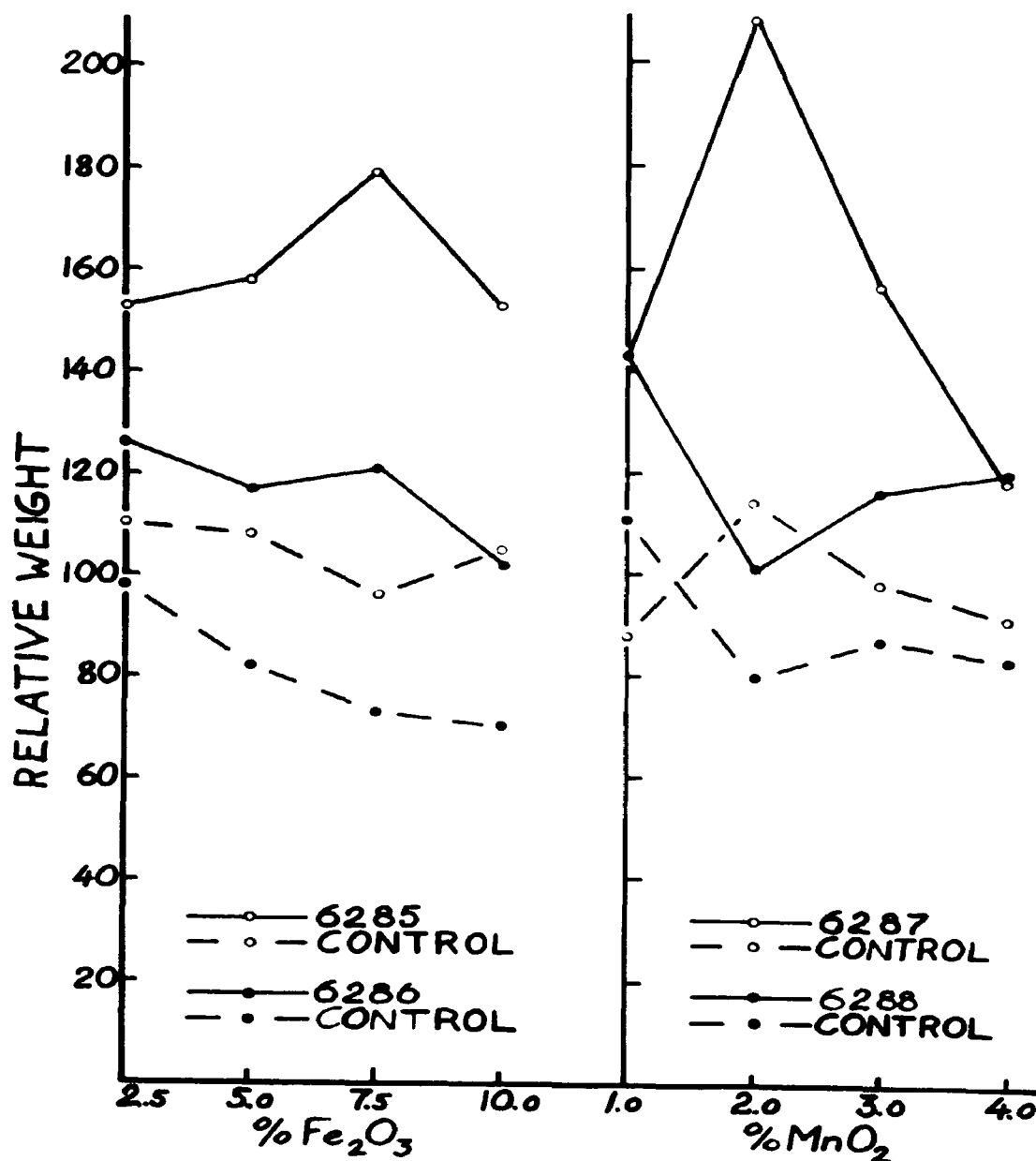


Figure 2. Average dry weight of plants in frit and control cultures, calculated in percent of average dry weight of plants in absolute control cultures receiving complete nutrient solution, plotted against frit composition. Nutrient solution of pH 6.0

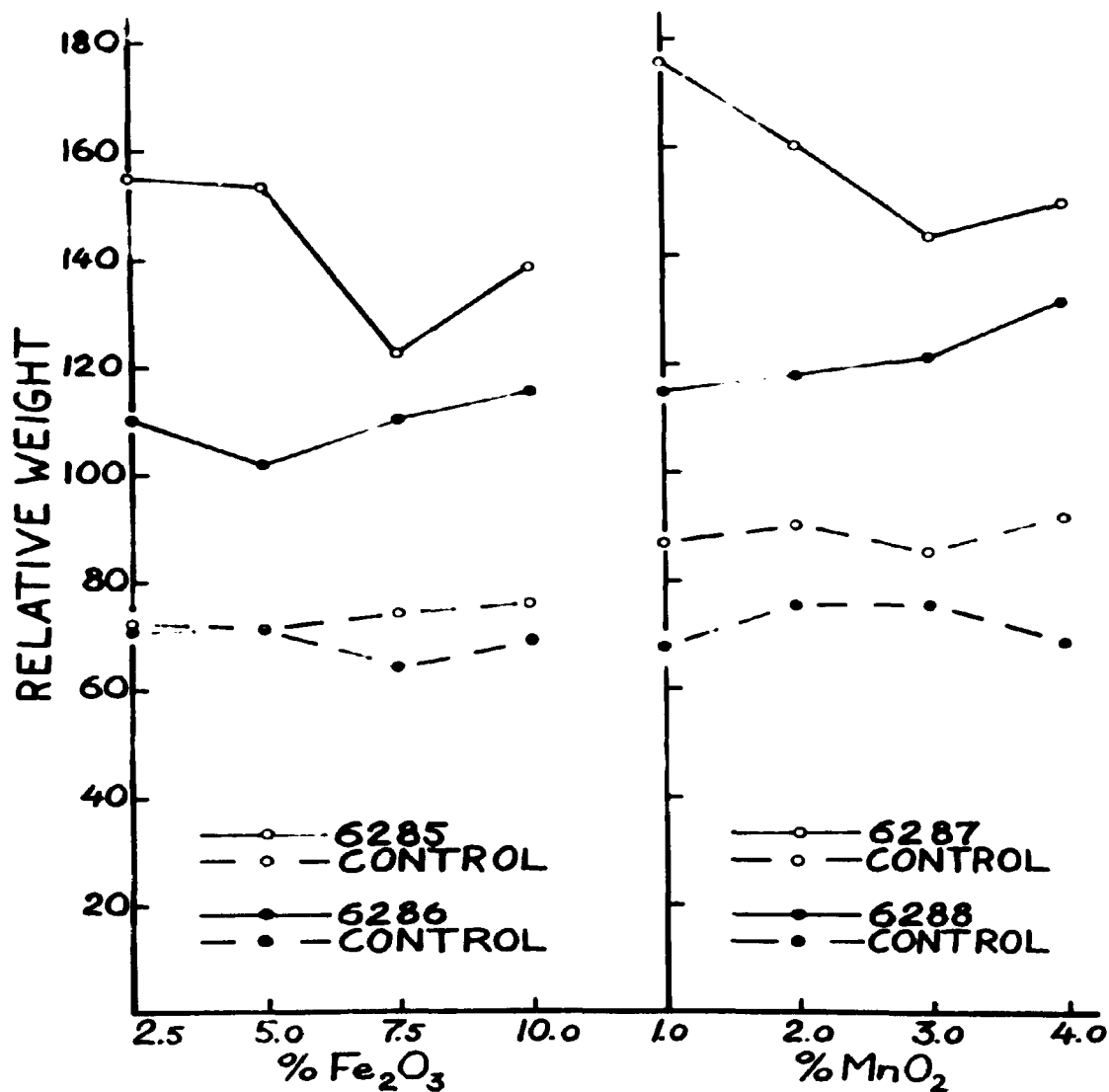


Figure 10. Average dry weight of plants in frit and control cultures, calculated in percent of average dry weight of plants in absolute control cultures receiving complete nutrient solution, plotted against frit composition. Nutrient solution of pH 7.0

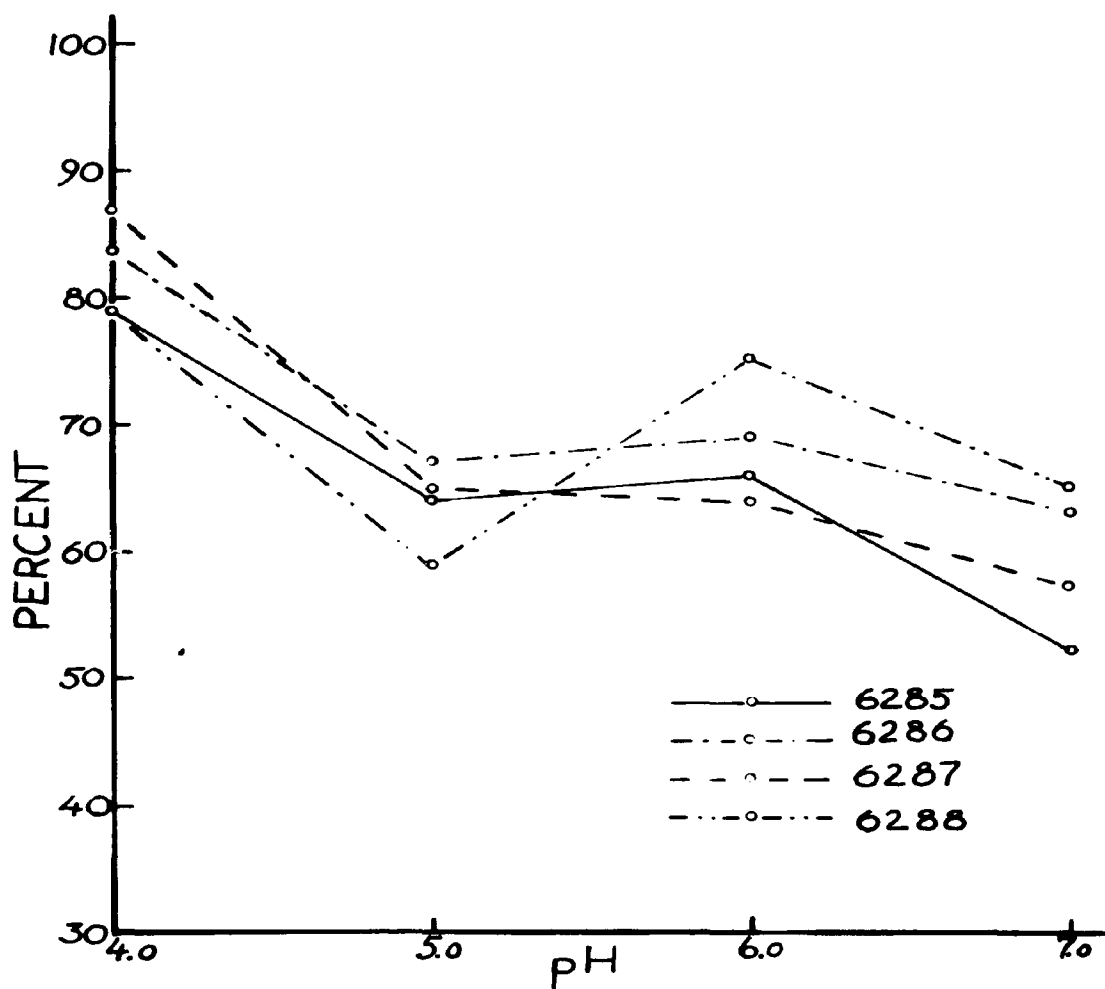


Figure 11. Average dry weight of control plants, calculated in percent of average dry weight of corresponding frit grown plants, plotted against pH of nutrient solution.

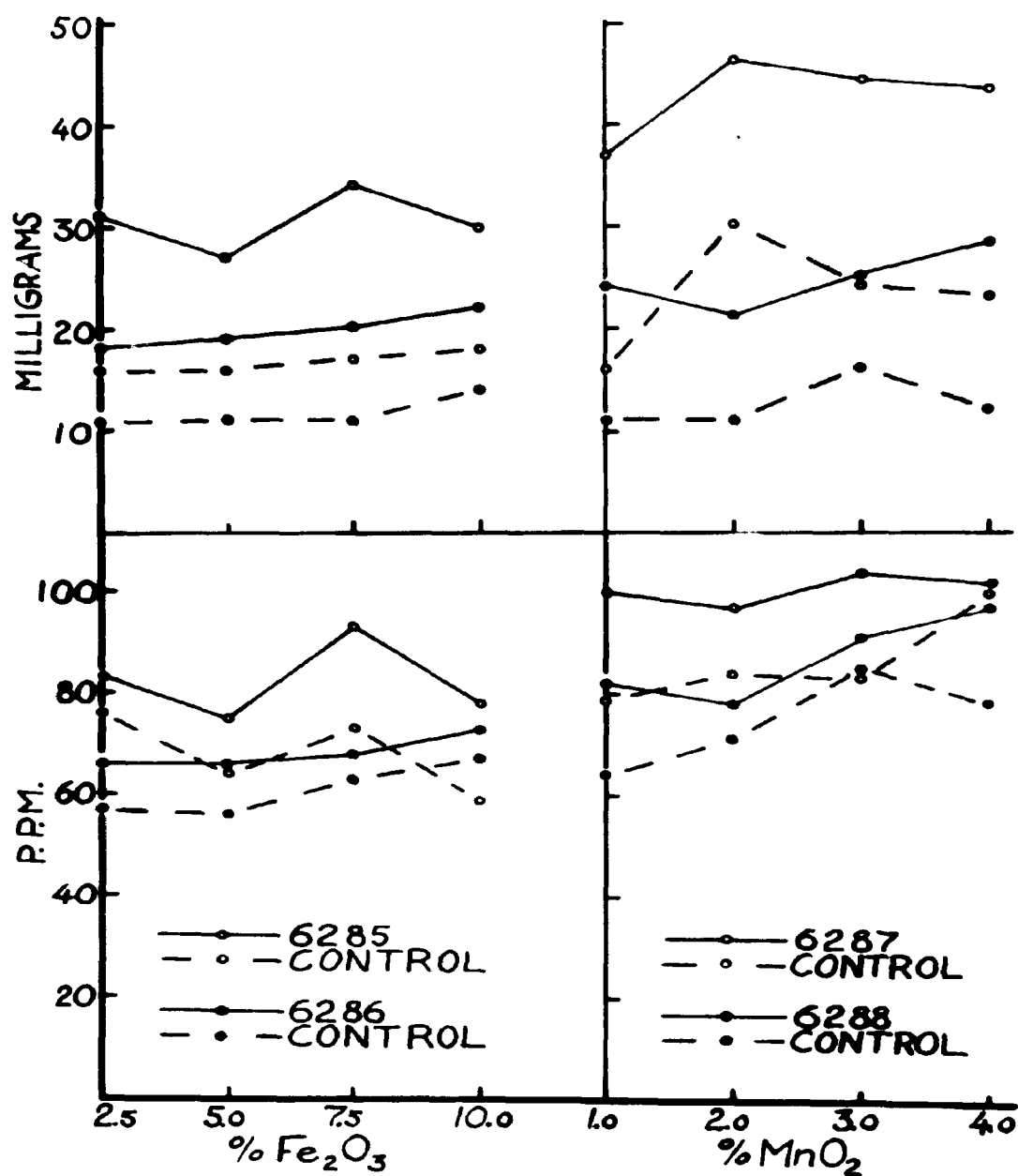


Figure 12. Parts per million of iron in the dry matter of the plants (lower curves) and total absorption of iron in milligrams per ten plants (upper curves) plotted against frit composition. Nutrient solution of pH 5.0

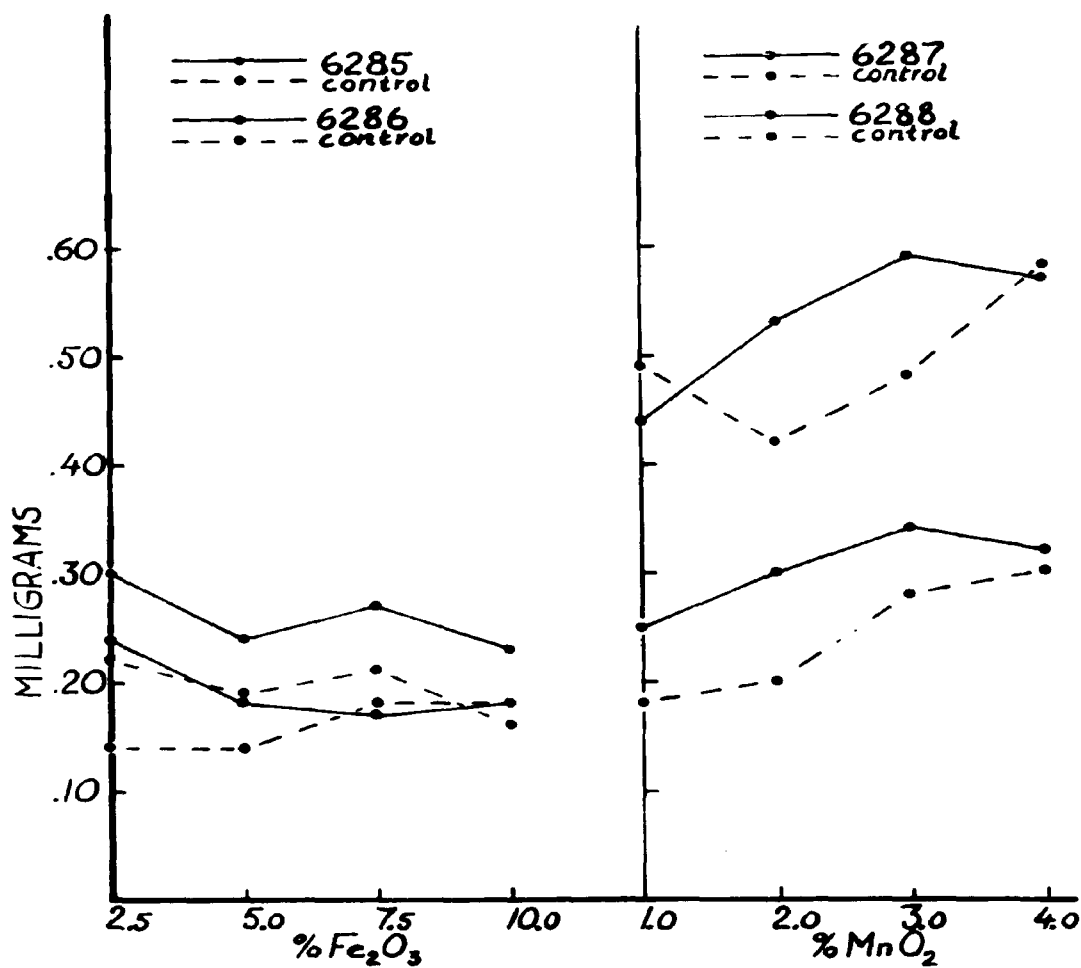


Figure 13. Total absorption of manganese in milligrams per ten plants plotted against frit composition. Nutrient solution of pH 4.0

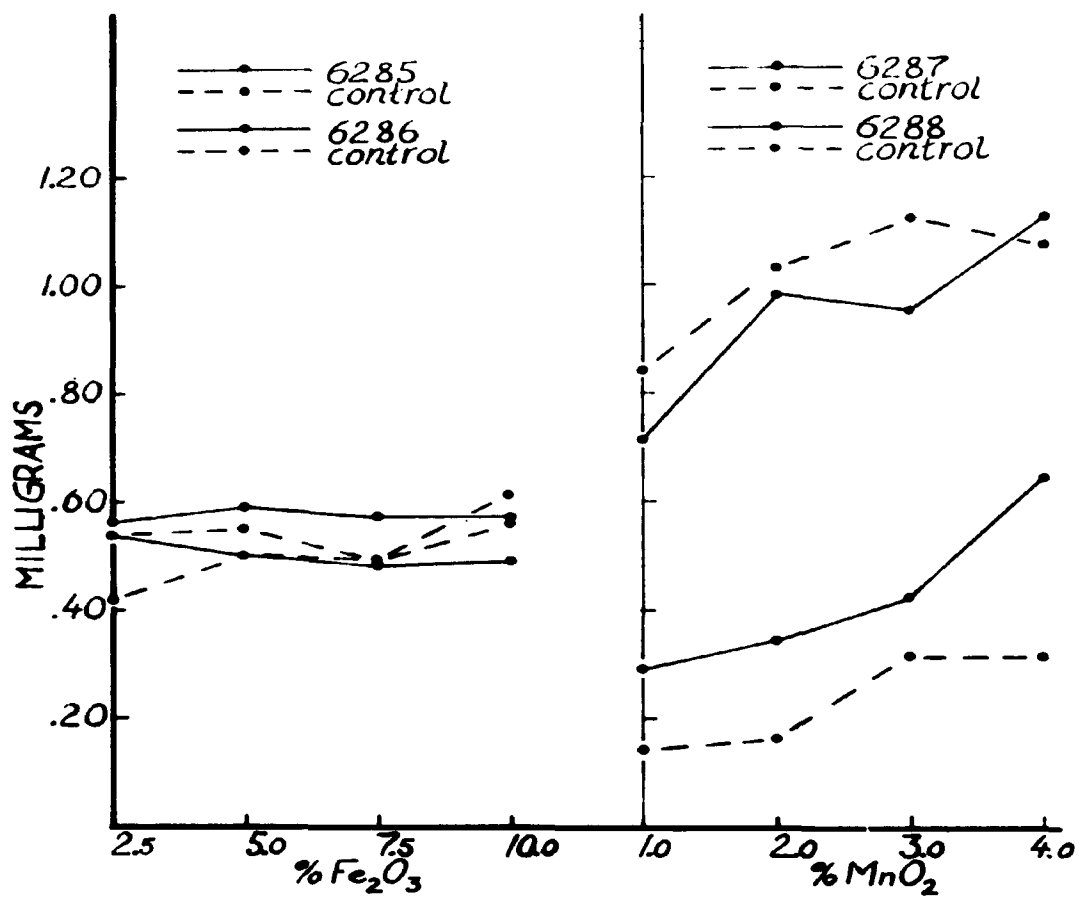


Figure 14. Total absorption of manganese in milligrams per ten plants plotted against frit composition. Nutrient solution of pH 5.0

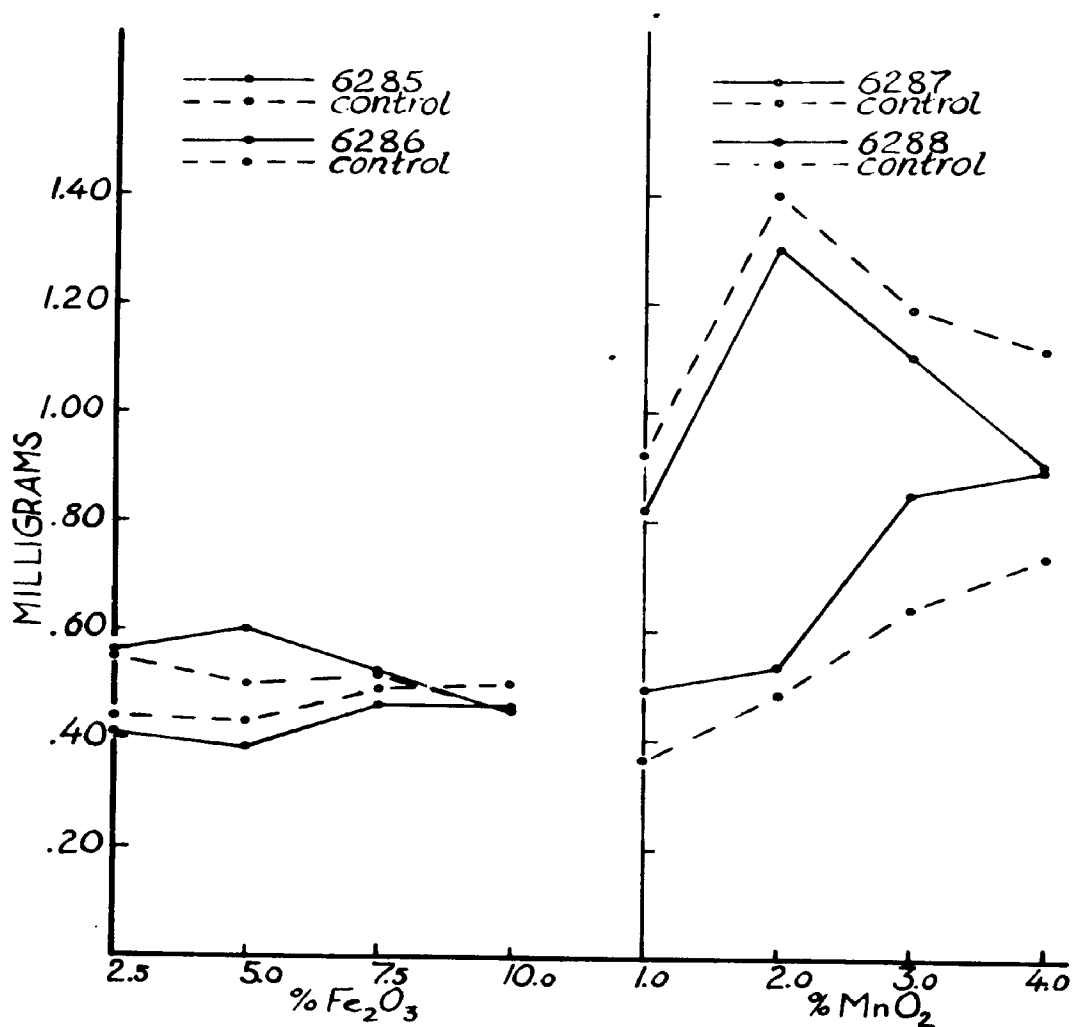


Figure 15. Total absorption of manganese in milligrams per ten plants plotted against frit composition. Nutrient solution of pH 6.0

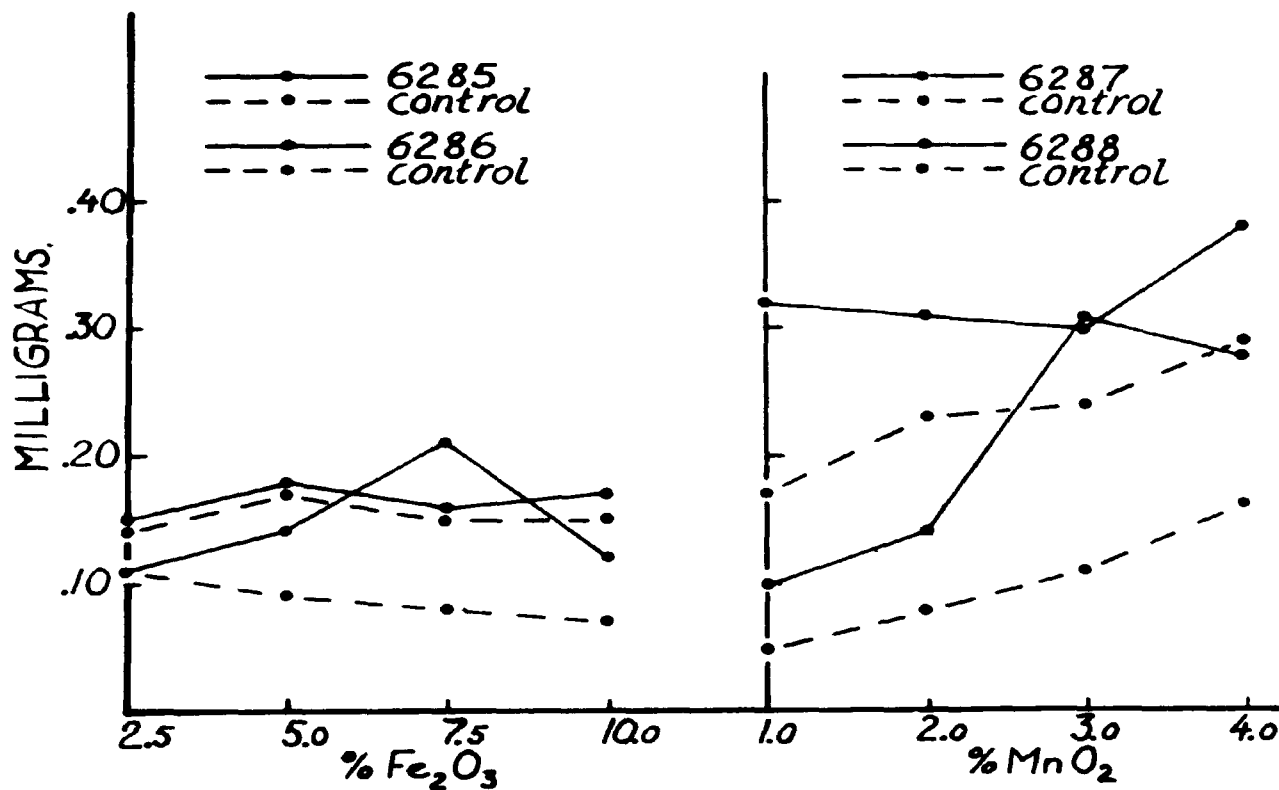


Figure 16. Total absorption of manganese in milligrams per ten plants plotted against frit composition. Nutrient solution of pH 7.0

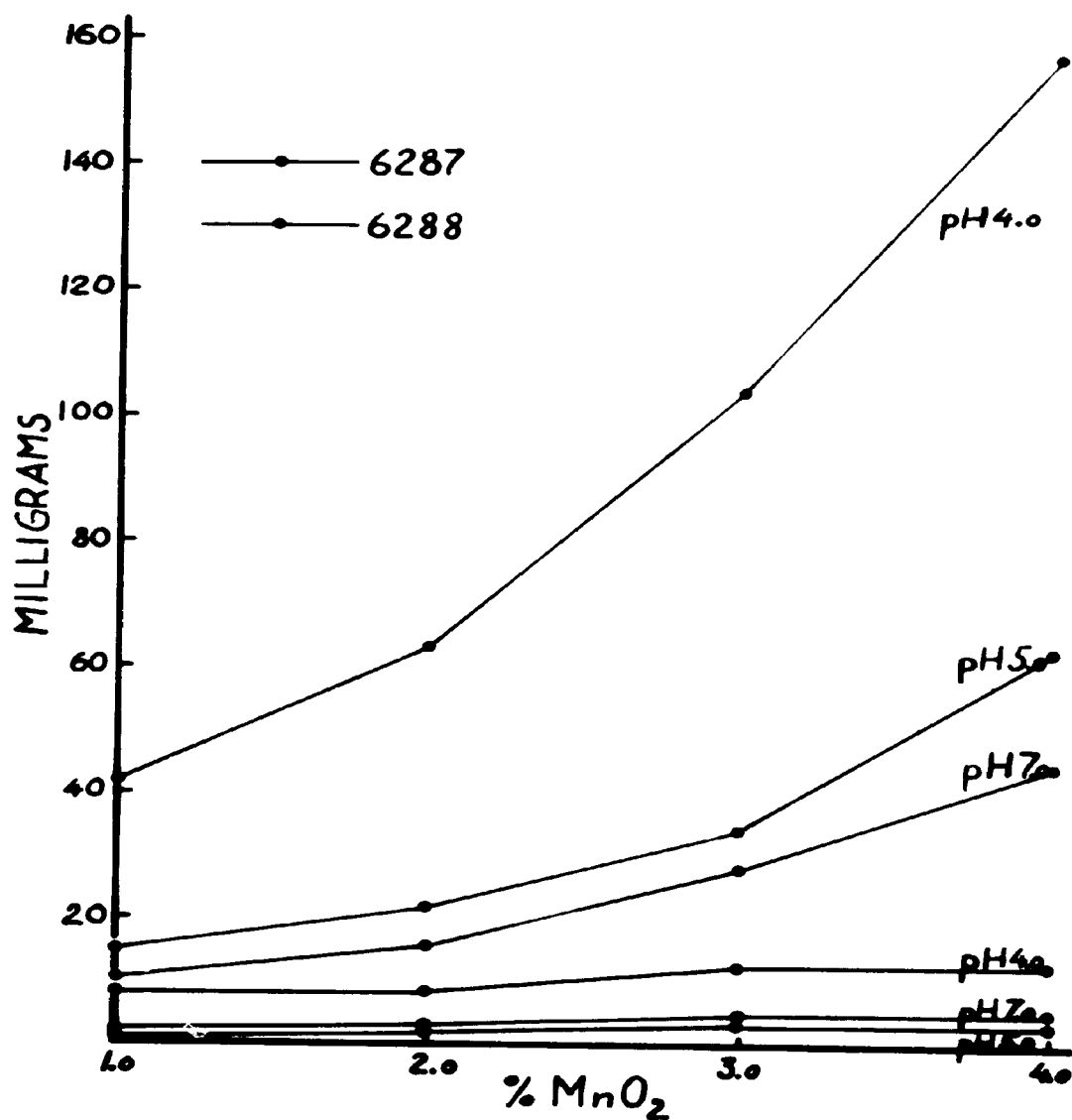


Figure 17. Milligrams of manganese accumulated in carboy at the end of the experimental period as affected by manganese content of the frit.

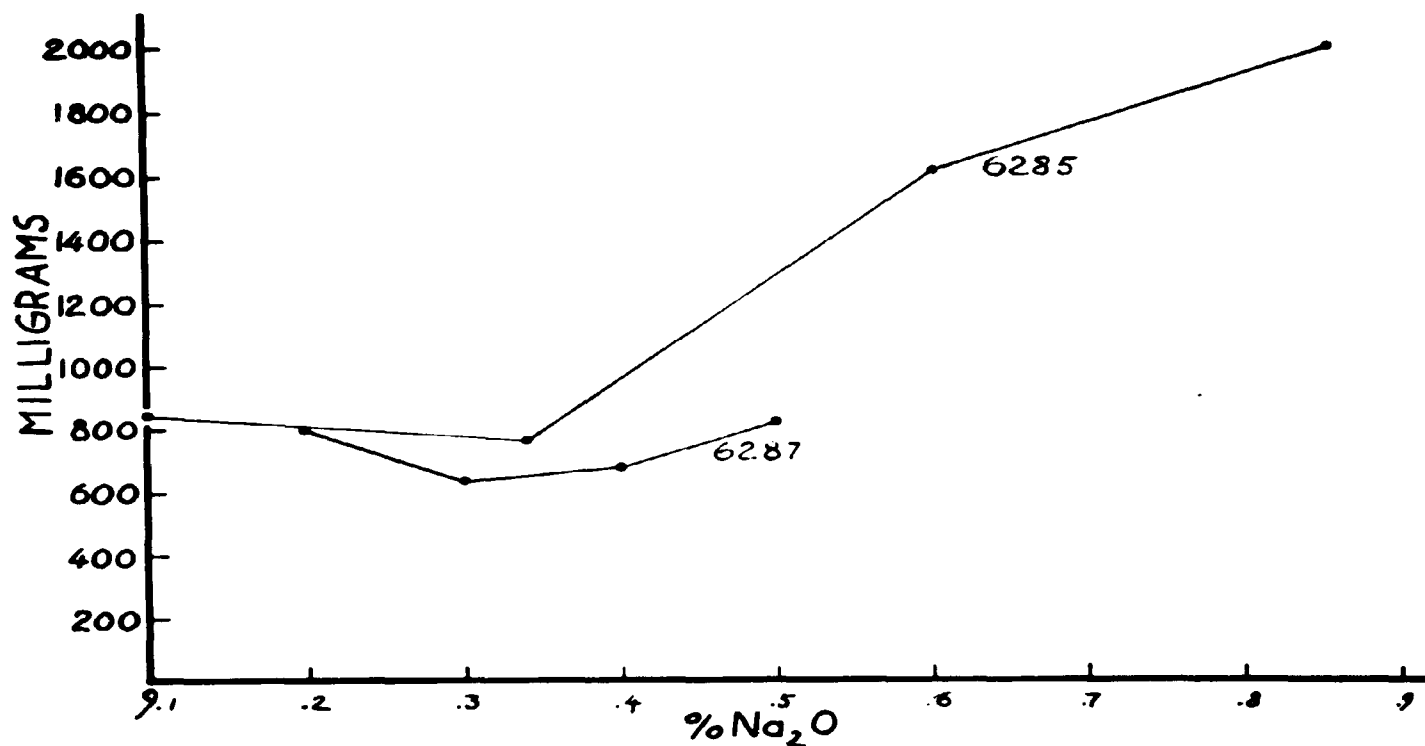


Figure 18. Milligrams of sodium accumulated in carboy at the end of the experimental period as affected by sodium content of the frit. Frit no. 6285 and 6287. Nutrient solution of pH 4.0

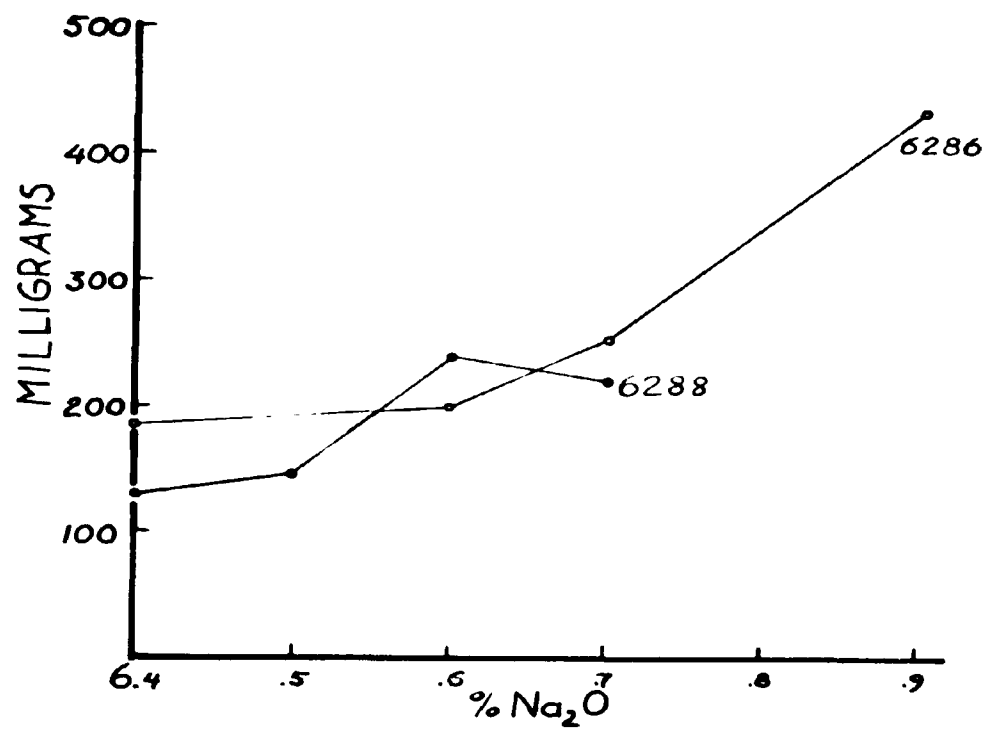


Figure 19. Milligrams of sodium accumulated in carboy at the end of the experimental period as affected by sodium content of the frit. Frit no. 6286 and 6288. Nutrient solution of pH 4.0

LEGEND TO PLATES

Plate I. Detail of mechanical arrangement of the cultures showing connection between main air line (underneath greenhouse table) and carboy, and connection between carboy and pair of culture pots. Pot to the left in each pair contains frit no. 6285-C and 6285-D respectively. Note the chlorotic condition of plants in the corresponding control pots. The plants were supplied with a nutrient solution of pH 6.0.

Plate II. Arrangement of pots on greenhouse table.

Plate III. General view of the arrangement of the experiments.

Plate IV. Four weeks old plants grown in frit no. 6285-A (to the left) and corresponding control culture at pH 6.0 of the nutrient solution.

Plate V. Four weeks old plants grown in frit no. 6285-D (to the left) and corresponding control culture at pH 6.0 of the nutrient solution.

Plate VI. Four weeks old plants grown in frit no. 6287-A (to the right) and corresponding control culture at pH 6.0 of the nutrient solution.

- Plate VII. Four weeks old plants grown in frit no. 6287-D (to the right) and corresponding control culture at pH 6.0 of the nutrient solution.
- Plate VIII. Four weeks old plants grown in absolute control cultures receiving complete nutrient solution of pH 6.0.
- Plate IX. Four weeks old plants grown in absolute control cultures receiving nutrient solution devoid in iron and manganese. The pH of the nutrient solution was 6.0.
- Plate X. Terminal leaf of soybean plants grown in media as indicated.

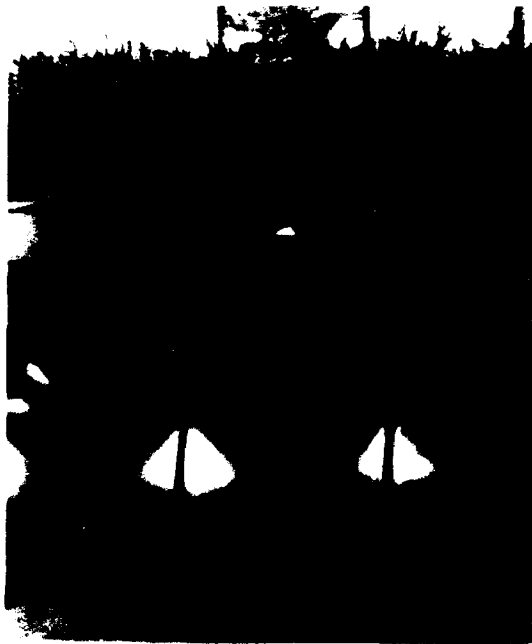


Plate I.



Plate II.



Plate III.

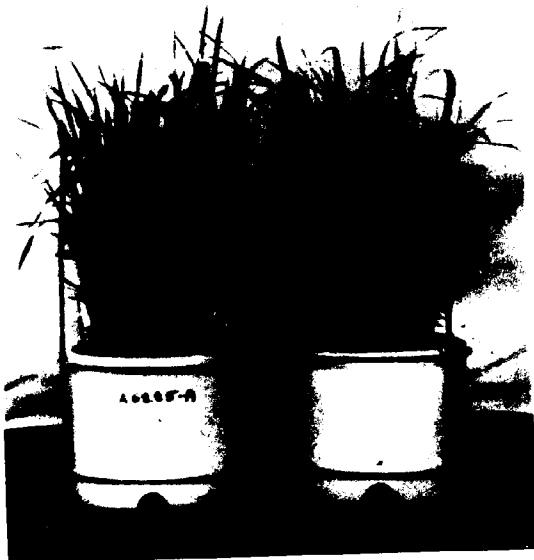


Plate IV.



Plate V.



Plate VI.



Plate VII.



Plate VIII.

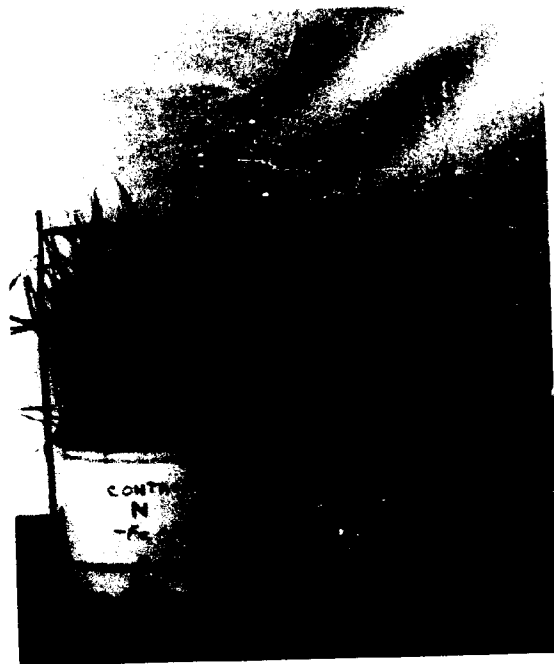


Plate IX.

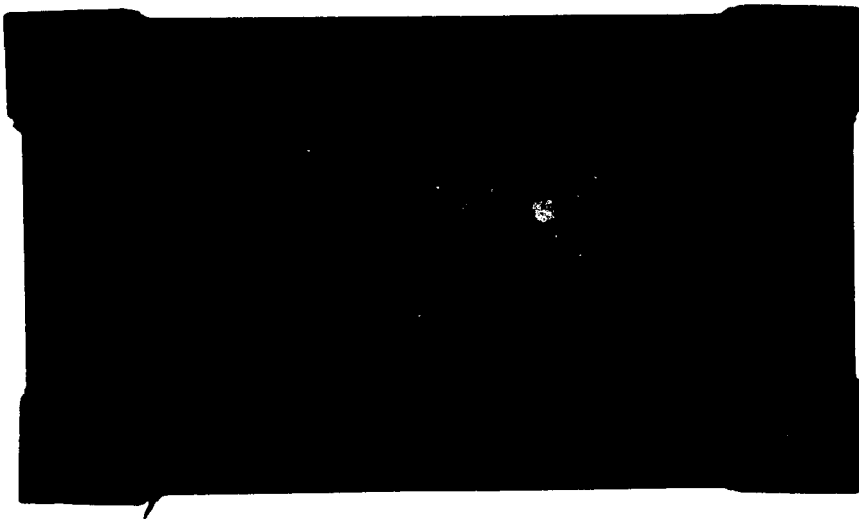


Plate X