

The need for a thorough understanding of fertilizer-soil-plant interactions is especially important for phosphatic materials. The need takes on even greater significance in the light of today's trend toward granular materials

W. L. HILL, Agricultural Research Service, USDA, Beltsville, Md.

IN THE COMMERCIALIZATION of a new product, the heat of the quest for technically suitable manufacturing processes often creates a blind spot that temporarily blots out critical factors in the product's end use. In the current strong trend toward the granular form for fertilizers, just such a blind spot appears to have developed in the area of phosphate utilization. That granulation is a new and immature art is witnessed by the lively interest in processes for accomplishing it. But the agronomic performance of the end product should not be lost to view.

In the production of granulated fertilizers, the part played by phosphorus differs only in relatively minor respects from its role in producing powdered goods. In either case, successful production pivots on the technology of phosphate solubilization and desolubilization. The growing emphasis on granulation points up anew the need for a thorough grasp of the important general aspects of phosphate technology.

Technology and Agricultural Use of Fertilizer

Agricultural scientists find numerous subjects for profitable experimental study in the manifold of interacting factors that govern the feeding processes of the growing plant as those processes are conditioned by soil influence, by the fertilizer-soil reaction pattern, and by plant needs. Curiously enough, fertilizer-soil relationships have never received a fair share of the investigative effort. Nevertheless, the behavior of the fertilizer in soil environments is the principal aspect of fertilizer use over which the fertilizer technologist can exercise some control. The crop responds to the assemblage of fertilizer and soil, the character of which changes with time and crop stress. The fertilizer

technologist has at his disposal means for adjusting the reaction pattern of the fertilizer in the soil and is thus responsible for the behavior of his product in the fertilizer-soil reaction.

He must at the same time provide the nutrient elements required by the cultural practices in the market area. Fertilizer people are prone to forget the relative importance of the elements necessary to plant growth (Table I). Ranked by amount in the whole plant, calcium and sulfur are above phosphorus, and are indeed major nutrients. Their removal from fertilizer in the zealous drive toward high-analysis with respect to N, P₂O₅, and K₂O makes the products unsuited for use on some economic soils without application of proper amendments, and thus specializes their effective use.

The technologist who wishes to develop a fertilizer that meets the demands of a crop, which is to say, a fertilizer that possesses marked agronomic worth, ought to have an understanding of fertilizer-soil reactions and some appreciation of crop demands for nutrients. Since the development engineer can hardly be expected to be an expert in soil science and agronomy, competent counsel in such matters should be provided before the development work starts. A prevailing practice among fertilizer manufacturers is the attachment of agronomists and soil scientists to the sales department. Cast in this role, these people cannot be expected to supply adequate counsel to the development group. The reason is a simple one. They do not speak the engineer's language, nor he their own. The two groups need to live together, share in projects, and learn from one another by exchanging information through steady contact, until the engineer becomes a fair soils man and the agronomist a fair engineer. Then company funds need not be unwisely spent on the development

of fertilizers that do not fit into the farm use pattern.

Reactivity of Fertilizer Compounds

A clump of fertilizer lying in a moist soil reacts with and pays out its nutrient substance to the environment according to physico-chemical laws. In the presence of adequate moisture for crop development, some fertilizers react more rapidly than others; thus, fertilizer materials can be classified on the basis of reactivity or tendency to pay out nutrients to the environment. Thermodynamic solubility is a convenient measure of the reactivity of powdered materials, since in the case of most fertilizer compounds rate of dissolution is proportional to solubility. Familiar fertilizer compounds and materials are plotted on a solubility scale in Figure 1. As an aid in orientation, the solubilities of table salt and of two slightly-soluble compounds used in gravimetric chemical analysis are shown on the right-hand margin of the chart.

The great range in solubility marked by the phosphorus carriers is especially noteworthy. It covers more than eight orders of magnitude. The solubility of diammonium phosphate, for example, is more than 10 million times that of hydroxylapatite and 10,000 times that of dicalcium phosphate, the most soluble of the slightly-soluble phosphorus carriers. The common nitrogen and potassium carriers lie at the top of the scale.

Nature of Monocalcium Phosphate

Superphosphate carries phosphorus mainly in the form of monocalcium phosphate, a very reactive compound. Monoammonium phosphate is also very reactive. Both compounds are classed as water-soluble phosphates, which, indeed, they are under the conditions obtaining in the conven-

vs. Performance

tional test for available phosphorus. Nevertheless, complete water solubility of monocalcium phosphate in the soil environment is most unlikely. It is well established that this salt in contact with water decomposes with moderate speed at ordinary temperatures to yield dicalcium phosphate and a solution of phosphoric acid. Although this decomposition does not proceed very far in the usual laboratory test for available phosphorus, it goes to substantial completion in many soil environments, with the result that only a part of the phosphorus moves promptly away from the fertilizer grain or granule. The rest remains behind as a relatively unreactive compound deposited in the skeleton of the granule or in its vicinage. Thus, it appears that perhaps about half of the phosphorus in monocalcium phosphate is held at the placement site by virtue of hydrolytic decomposition of the salt, whereas the other half, like monoammonium phosphate, is free to move away immediately under the normal restraints of the soil environment.

Measured Quality of Fertilizer

The potential value of a material used to supplement the nutrient supply in soil is determined by its nutrient content. That the effectiveness of some nutrient-bearing substances can be improved by treating them to alter their chemical properties was recognized long ago, whereupon the fertilizer industry came into existence. The chemical work performed on the nutrient compounds during processing gives rise to new products of greater reactivity. Since the nutrient in the "pepped-up" materials is more readily utilized by growing crops, such preparations command a premium price. Because of the enhanced market value of the processed materials some standard of reactivity is necessary for quality control in trade. A standard is

especially important for phosphates. Solubility has become the recognized criterion, and with great care laboratory procedures have been devised for measuring it. Accordingly, that part of the total phosphorus content that passes the test is called the available phosphorus content, which is the basis of value for processed phosphorus-bearing materials. Quite naturally, the procedure is often applied to non-processed materials, such as phosphate rock, and the results thus obtained are regarded as a measure of available nutrient content.

The restricted significance of the laboratory test for available nutrient is too frequently overlooked. The oversight is attributable in part to the use of another kind of "availability" in agronomic circles—an unfortunate circumstance. The laboratory test is concerned with the reactivity of the nutrient, whereas the agronomic test is concerned with the alibility of it. The laboratory test merely sets a minimum level of reactivity for phosphates that are classed as available phosphates. Above this floor is a wide range of phosphorus reactivity that includes both water-soluble and water-insoluble materials (Fig. 1). In-grade variability of phosphorus reactivity (water-solubility) of an $N-P_2O_5-K_2O$ mixture is illustrated by the data in the last column of Table II.

Failure to recognize the limited purpose of the laboratory test for available nutrient leads to abstract application of the results with almost no regard, beyond obstacles in processing and distribution, for the chemical and physical nature of the nutrient carriers that make the fertilizer what it is. Thus, undue emphasis falls on grade and manufacturing process, and too little attention is given to chemical transformations during the course of mixing nutrient-carrying substances; because of these transformations, the resident compounds in the finished

W. L. HILL is principal chemist with the Fertilizer and Agricultural Lime Section, Soil and Water Conservation Research Branch of the Agricultural Research Service. He has held various positions with USDA since 1928. Before that, he taught chemistry at a high school and college in Tennessee. His B.S. is from Milligan College and M.S. from the University of Virginia. Among his interests are: phosphate technology, phosphate utilization by plants, and process development.



fertilizer differ markedly from the input compounds. A noteworthy transformation occurs in unneutralized mixtures of superphosphate and ammonium sulfate (Table II). (The inversion of a mixture of monocalcium phosphate and ammonium sulfate was called ammoniation prior to the advent of neutralization with ammonia.) Although both superphosphate alone and superphosphate in mixture with ammonium sulfate present a large proportion of phosphorus in water-soluble form, their phosphorus reactivities differ as a consequence of the unlike reaction patterns of the two compounds.

Agronomic Merit of Phosphates

The establishment of criteria of quality both within and without the class of available phosphates is the principal task in the nutritive evaluation of fertilizers. Phosphate rock, nature's principal store of phosphorus for man's use, is less soluble than hydroxylapatite (Fig. 1). The phosphate fertilizer industry is concerned with the task of raising the reactivity of the phosphorus from that in the rock to some favorable value. The statutory definition of available phosphorus requires it to be soluble in neutral ammonium citrate in accordance with an established analytical procedure. Nevertheless, the open agronomic question has been, and still is: "How far up the solubility scale should the reactivity be?"

Background for an answer to this question appears in fairly clear outline, when the charted scale of solubilities (Fig. 1) is viewed broadly in the light of the results of agronomic experimentation. The preponderance of evidence indicates that under many conditions of use dicalcium phosphate would be more effective if it were a little more soluble, and that the water-soluble phosphates would give better results in many instances if they were

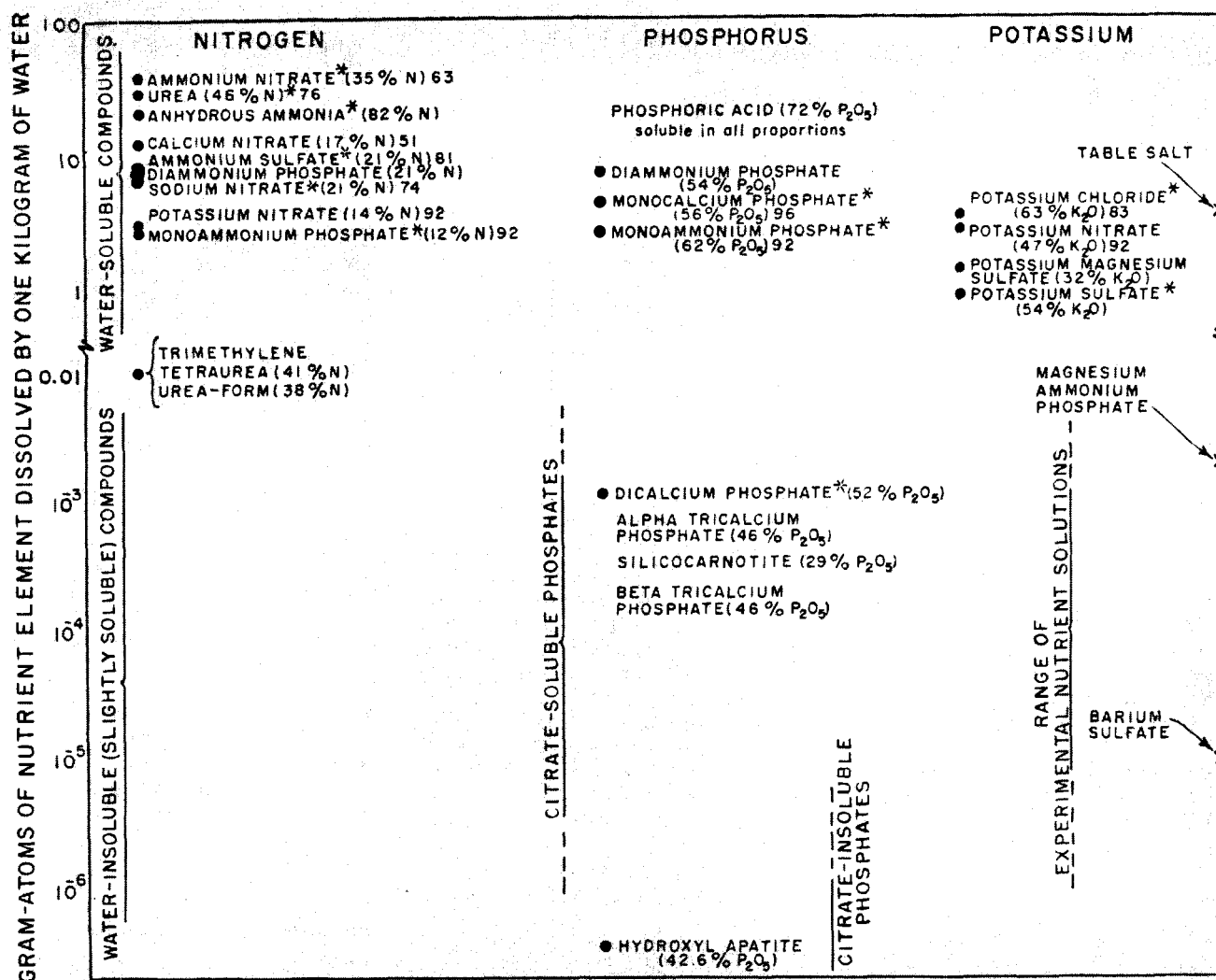


Figure 1. Solubility of nutrient-bearing substances

less soluble. Optimal reactivity would seem to be somewhere between that of dicalcium phosphate and that of monoammonium phosphate. The plausibility of this conclusion is strengthened by the circumstance that plant roots actually feed at very low nutrient concentrations (less than 10^{-3} moles of P per liter), and by the recent development of ureaform, a synthetic nitrogen carrier with a selected low reactivity that imparts to the product superior performance under certain practical conditions of use.

Reactivity Gap

The logical supposition that the optimal phosphorus reactivity lies between that of dicalcium phosphate and that of monoammonium phosphate is not at the present time susceptible of direct proof, because suitable test materials have not been developed. The intermediate range in solubilities (Fig. 1) is represented by a barren gap of more than three orders of magnitude. Even though several gener-

ations of fertilizer research have come and gone, this circumstance still stands as a challenge to development people. Unfortunately, very little direct effort has been turned toward phosphorus carriers with intermediate solubilities, whereas large outlays and much time have been devoted to materials that lie on or just above the statutory floor of available phosphates. People concerned with nitrogen have begun to extend the reactivity range downward; those concerned with potassium are working on the problem; those interested in phosphate fertilizer materials might look to materials with intermediate solubilities with profit.

Use Patterns of Phosphate Compounds

The bulk of the phosphorus consumed as fertilizer in this country arrives on the soil in five compounds, proportions of which in 1953 were: ammonium phosphates (mono- and dibasic), consumed directly and in mixed fertilizers, somewhat more than one-third; dicalcium phosphate,

consumed almost entirely in mixed fertilizers, about one-third; monocalcium phosphate, in superphosphate consumed in direct application, about one-fifth; and apatite, inclusive of phosphate rock for direct application and the citrate-insoluble phosphorus in marketed superphosphate and mixed fertilizers, about one-fifth. Thus, the phosphorus reactivity of present-day fertilizers is governed very largely by the behavior of these compounds as separate materials and in assemblages of compounds.

It is obvious from this use distribution among compounds that somewhat more than half of the phosphorus applied to the soil in 1953 was in water-soluble form—ammonium phosphates and monocalcium phosphate. Water-soluble phosphorus in marketed mixtures three years earlier was about 43% of the available phosphorus. Division of phosphorus consumption between mixed fertilizers and separate materials (exclusive of phosphate rock) is shown in Figure 2. The downward trend in direct use of mate-

rials for the country is paralleled by the trends in the eastern and central regions. Only in the far west has the use of separate materials kept a fairly even pace.

Special interest attaches to the share of water solubles in separate materials for the country as a whole. Thus, for the years shown in the figure, superphosphate (all grades), ammonium phosphates, and phosphoric acid accounted for 87, 82, 80, 83, and 82% of the phosphorus that arrived on the soil in separate materials. Viewed another way, less than one-fifth of the phosphorus in the separate materials was carried in products that belong to the water-insoluble class. Noting that separate materials account for only one-fifth of domestic consumption (Fig. 2), it is seen that water insolubles used directly on soil (exclusive of phosphate rock) account for less than 5% of the total available phosphorus consumption. This is the small corner of the domestic market in which the producer of a water-insoluble phosphate material must compete for continued existence.

Mixtures of Phosphate Compounds

Mixtures of water-soluble and water-insoluble phosphates provide the conventional means for bridging the solubility gap in commercial polynutrient fertilizers. Neutralization of mono-calcium phosphate or phosphoric acid with ammonia is the basis of currently-used processes for preparing these mixtures. As a consequence of the trend toward process integration, the neutralization step is more often than not blended with other operations. In all cases, however, the controlling motive is the production of water-insoluble phosphate *in mixtura* rather than *separato*. Thus, fertilizer-grade mono-ammonium phosphate prepared from wet-process phosphoric acid carries 10 to 20% of its phosphorus in a water-insoluble substance. When, as in the alkali phosphate industry and in certain processes for making diammonium phosphate, this insoluble material must be filtered out, the by-product thus obtained does not find a ready market in the fertilizer industry. It does not fit into manufacturing and use patterns that are based on water-soluble phosphates.

The same motive, extended, prevails in mixed-fertilizer preparation. Here, formation of both the water-insoluble and water-soluble components directly in the mixture is highly desirable. This method provides economic advantages and at the same time yields an intimate mixture of the sundry constituent compounds. The fertilizer industry encompasses factories that utilize a continuous sequence of integrated

steps from rock acidulation to the bagging of granulated $N-P_2O_5-K_2O$ fertilizer. Integration for *in mixtura* formation of phosphate compounds yields polynutrient fertilizers that are more homogeneous and less expensive to make than those prepared by mixing separate materials. Thus, ammonium phosphates produced *separato* are not used extensively in conventional mixed fertilizers. Instead, another class of polynutrient fertilizers is developing, which is derived with considerable loss in sulfuric acid economy (Table III) from phosphoric acid rather than from superphosphate. These fertilizers are characterized by a high water solubility, approaching 100%, and a low—if not zero—calcium content. They are likely to show poor performance on soil that does not provide an adequate calcium supply for the crop.

The reactivities of mixtures composed of water-soluble and water-insoluble phosphates can and do substitute for intermediate reactivities. However, the reaction pattern of the mixture differs markedly from that of a single carrier. A single compound with suitably low reactivity can provide a steady supplemental flow of phosphorus to the ambient nutrient supply in cropped soil, whereas the mixture at first presents a high reactivity, which a little later drops rather abruptly to the low reactivity

of the insoluble member. Thus, a practical gage of the over-all reactivity of the mixture is the size of the water-soluble fraction, and the question thereby raised is "How much water-soluble phosphorus is needed?"

The experimental answer to this question is at the moment somewhat confused by the circumstance that the reference standards widely used in the past have been about 50% water soluble—either superphosphate, which, though water-soluble by laboratory test, is probably only about half water-soluble in the soil, or lightly ammoniated superphosphate. It happens that farm-scale experience shows this level of solubility to be satisfactory for the fertilization of crops generally. This teaching stems from the nature of the fertilizers most widely consumed rather than from deliberate direct experimentation.

With the reference standard of reactivity thus established, a profitable inquiry is "What are the agronomic consequences of a marked change in phosphorus solubility from the 50% level?" The level in solid fertilizers can be raised to 100% or lowered to nearly zero by putting in or taking out ammonium phosphates in technically feasible ways. A preponderance of evidence points to the conclusion that alteration of the phosphorus solubility in either direction tends toward specialization in effective

Figure 2. Proportion of available phosphorus consumed in fertilizer materials applied directly on soil in different regions of the United States. Based on consumption reports by Scholl, et al. (East, states east of the Mississippi River except Ky., Tenn., Ala., and Miss.; Central, two tiers of states west of the Mississippi River and Ky., Tenn., Ala., and Miss.)

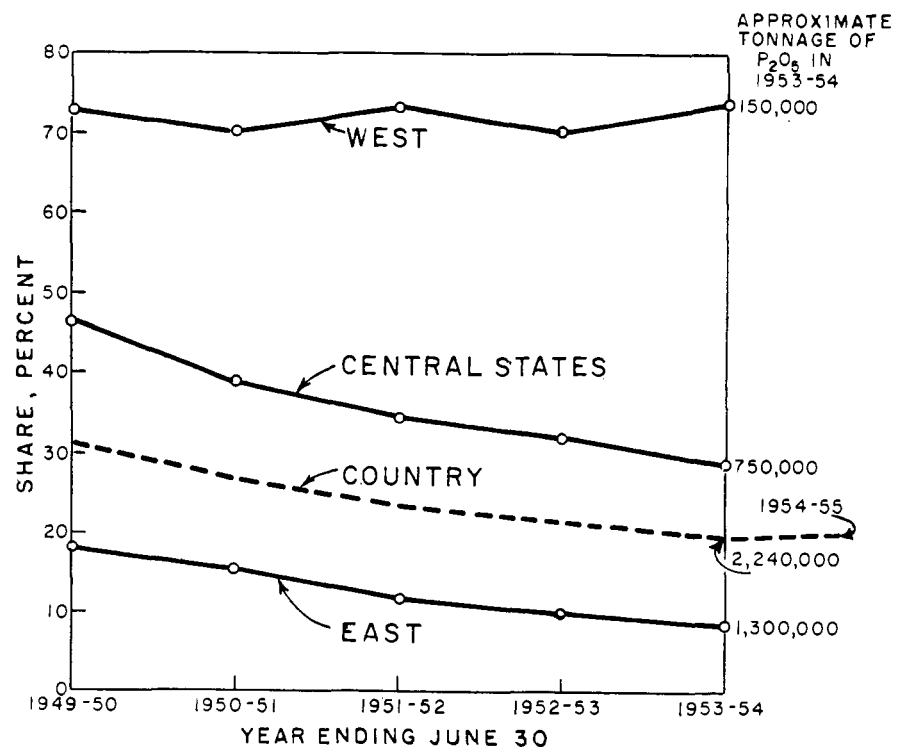


Table I. Elements Essential for Plant Growth

Element	Approximate Amount in Whole Plant	Principal Function
1. Carbon	45%	plant structure
2. Oxygen	43%	
3. Hydrogen	6%	
4. Nitrogen	1-3%	vital-tissue structure
5. Potassium	0.3-6.0%	
6. Calcium	0.1-3.5%	regulator and carrier
7. Sulfur	0.05-1.5%	vital-tissue structure
8. Phosphorus	0.05-1.0%	vital-tissue structure
9. Magnesium	0.05-0.7%	regulator and carrier
10. Chlorine	100-300 p.p.m.	unknown
11. Iron	10-1500 p.p.m.	catalysts and activators
12. Manganese	5-1500 p.p.m.	
13. Zinc	3-150 p.p.m.	
14. Copper	2-75 p.p.m.	
15. Boron	2-75 p.p.m.	
16. Molybdenum	very minute	

use of the fertilizer. The performance of the fertilizer then becomes more sensitive to nature of soil and kind of crop. On neutral, alkaline, or calcareous soils high water solubility is to be preferred for most economic crops. Water solubility is less important on acid soils, especially with cereal and forage crops.

The reactivity of the phosphorus in a mixed fertilizer is influenced by (1) the nature and amounts of the phosphorus-bearing compounds, (2) associated salts, (3) fineness of constituents of the mixture, (4) their interdispersal, or intimacy of contact, and (5) fineness or granularity of the mixture. The first dimension of variability has already been discussed at some length. The rest, closely interrelated, can be effectively discussed in relation to fertilizer granulation.

Influence of Granulation On Phosphorus Reactivity

Fertilizer granules vary widely in composition, size, shape, compactness,

resistance to crushing, and retention of shape when wetted. Products may consist mainly of water-soluble compounds, or they may carry a large complement of insolubles. The size ranges from powders to about 4-mesh. The granules may be spheroidal or angular; they may be porous or non-porous; and they may present smoothed surfaces or surfaces of fracture. The ideal granule is an ellipsoid approaching a sphere, has a smooth surface, and dissolves as a granule instead of decomposing to a wet powder in moist surroundings. This kind of granule, being stable when wetted, is to be assumed in discussions bearing on the effect of granulation on fertilizer reactivity in use. Unstable granules influence fertilizer-placement effects without appreciable alteration of phosphorus reactivity from that of the parent powdered mixture.

Stability of a granule under moist conditions is determined largely by composition, interdispersal of components, and compactness. Potassium

sulfate, rather than ammonium sulfate or nitrate, and calcium sulfate contribute to stability. Also, stability is enhanced by compacting thoroughly-mixed, fine-grained components into dense granules. In these respects slurry mixing provides better granules than does semidry mixing. Shape and surface character, on the other hand, are determined mainly by the fineness of the component compounds and by the method of granule formation and recovery of the sized product.

Granulation of a fertilizer into stable granules necessarily lowers the over-all reactivity of the mixture. The net effect on individual nutrients is the resultant effect of interrelated factors—size, compactness, and associated salts. Very soluble salts lie in sharp contrast with slightly soluble ones. The former are very reactive even in large granules, whereas the latter, already relatively unreactive, may, by granulation to very moderate size, be made much too slow for good performance. In addition to the lowered reactivity of a slightly soluble compound like dicalcium phosphate, for example, granulation also imposes a localizing restriction on placement of the fertilizer in the soil.

Granularity and Fertilizer Placement

The kinds of fertilizer placement commonly used are listed in Table IV. The potential effect of granulation on the fertilizer-soil reaction is greatest in mixed placement and decreases with localization of the fertilizer in the soil. The size of the granules limits the extent to which the fertilizer can be dispersed in the soil in mixed placement, and thus, localization in mixed placement arising from granulation increases with granule size. The agronomic implications of this placement effect fol-

Table II. Possible Variability of a 12-12-12 Fertilizer

Type of Preparation	Input Nutrient Carriers KCl and		Resident Nutrient Carriers	Available Phosphorus, % of Total	Water-Soluble Phosphorus, % of Total
	N	P ₂ O ₅			
Unneutralized dry mix	(NH ₄) ₂ SO ₄ NH ₄ NO ₃	Super. ^a	NH ₄ H ₂ PO ₄ (NH ₄) ₂ SO ₄	KCl KNO ₃	90+ 85-95
Ammoniated dry mix, (Neutralizing N): P ₂ O ₅ = 0.1	NH ₃ NH ₄ NO ₃ (NH ₄) ₂ SO ₄	Super. ^a	NH ₄ H ₂ PO ₄ NH ₄ Cl (NH ₄) ₂ SO ₄	NH ₄ H ₂ PO ₄ CaHPO ₄ KNO ₃ KCl	90+ 40-60
Ammoniated dry mix, (Neutralizing N): P ₂ O ₅ = 0.2	NH ₃ NH ₄ NO ₃	Super. ^a	NH ₄ H ₂ PO ₄ NH ₄ Cl NH ₄ NO ₃ (NH ₄) ₂ SO ₄	NH ₄ H ₂ PO ₄ CaHPO ₄ KNO ₃ Basic Phos.	90+ 20-30
Nitric phosphates	HNO ₃ ^b NH ₃	Phosphate Rock	NH ₄ H ₂ PO ₄ NH ₄ NO ₃ NH ₄ Cl	NH ₄ H ₂ PO ₄ CaHPO ₄ Basic Phos.	90+ 10-30 5, or less ^c

^a Inclusive of triple superphosphate and mixtures of ordinary and triple superphosphates, the dominant phosphorus carrier being monocalcium phosphate.
^b H₃PO₄ (or H₂SO₄), or CO₂ are used as auxiliary acids.
^c When CO₂ is used.

Table III. Yield of Available Phosphorus in Wet Processes

Material	Available P ₂ O ₅ Content, %	Available P ₂ O ₅ per Ton of Sulfur, ^a tons	Sulfuric Acid Efficiency, %
Superphosphate	18-22	1.64	100
Superphosphate	44-48	1.47	90
Phosphoric Acid	50-54	1.19	73

^a Based on factors used in war allocation of sulfuric acid.

Table IV. Placements of Fertilizer in Soil

Increasing localization by placement ↓ Decreasing influence of granule size ↓		
	Mixed	Realized only under experimental conditions in greenhouse culture. Possible inter-dispersal with soil limited only by granule size. Mixed placement, so-called, under field conditions is necessarily either a sheet or a sheet of bands.
	Sheet	Used with sod and small-grain crops. Broadcast application on surface, with or without plowing under, and drilling.
	Band	Used with row crops.
	Hill	Used with hill crops, including checked corn.

low directly from the experimentally established rule—localization of fertilizer in the soil, in general, enhances the effect of water-soluble phosphates on crops and suppresses that of water-insoluble phosphates. A logical extension of this rule calls for fine grinding and mixed placement for water-insoluble phosphates.

Recognition of localization of fertilizer in the soil bed, rather than the mode of attaining it, as the basically important condition, leads at once to the supposition that a neighborhood of fertilizer influence can be established in the soil equally well with a water-soluble phosphate in either solid or solution form. A band of the solid soon dissolves, and the phosphorus is stored in the surrounding cylinder of soil, which expands gradually with the elapse of time. Banded application of a solution merely by-passes the dissolution step. One can hardly be expected to be superior to the other. This view is supported by experiment with vegetable crops.

Granularity and Associated Salts

The reactivity of the water-insoluble phosphate is increased somewhat in the presence of a soluble salt that does not present a common ion. The magnitude of this salt effect varies among the salts. In the case of a clump of fertilizer lying in moist soil, with insufficient water in the immediate vicinity for complete dissolution of the soluble salts, the salt solution in contact with the water-insoluble phosphate in the fertilizer is necessarily a saturated solution. Hence, the influence of saturated salt solutions on insoluble phosphates has primary interest in considerations of the fertilizer-soil reactions.

The salt effect in soil environments is enhanced by intimacy of contact between salt and phosphates. Thorough mixing of fine-grained ingredients with subsequent formation into compact stable granules is thus strongly indicated. The importance of the architecture of the granule needs emphasis in this connection, since it is amenable to more or less control in fertilizer making. For example, the use of coarse-grained potassium chloride in mixtures for granulation, a growing practice, is a turn away from interdispersal of potassium salts in the granule. This trend provides occasion for serious speculation as to the likely influence of the salt on water-insoluble phosphorus constituents. In the event the dominant granule type consists of a core of potassium salt inside a uniform coating that is also stable when wetted, enhancement of the salt effect is a reasonable expectation.

The salt effect, particularly in granulated fertilizers, can be altered markedly by the choice of salts. Under conditions of dissolution in the soil, moderate rather than high salt solubility is desirable. This is true because the amount of phosphorus dissolved in a saturated salt solution depends on both solubility and the amount of salt solution. Hence, on the basis of chemical equivalents, moderately soluble potassium sulfate produces a markedly greater effect on dicalcium phosphate than does either of the more soluble salts, potassium chloride and ammonium sulfate. The differences are registrable in growth response.

A special case of the salt effect that possesses great economic importance is presented by a mixture of monoammonium phosphate and dicalcium

phosphate. Apart from the nutritive benefit of water-soluble phosphorus, the highly soluble acid salt exerts a favorable influence on the reactivity of the water-insoluble phosphate. This effect has not been satisfactorily evaluated in experiments. Tests with the use of mixtures of P³²-tagged and untagged salts, however, show that each salt influences the other to a measurable extent.

Granule Size

Granulation of a fertilizer tends, on the one hand, to reduce effectiveness of a water-insoluble constituent as a consequence of a lowered reactivity and greater localization of fertilizer placement, and on the other hand, to increase effectiveness as a consequence of enhancement of the salt effect. All these effects are magnified by increasing the granule size. The experimental range in granule size for measurable effects varies with the reactivity of the nutrient. Agronomic advantage to granulated water-soluble phosphates becomes noticeable experimentally at about 28 to 32 mesh. Test materials of this size are rarely significantly different from powders in vegetation experiments. On the other hand, with water-insoluble phosphates the influence of fineness can be detected much farther down the scale of particle dimensions. The downward range extends the farther with the least soluble compounds and reaches 200 mesh, or perhaps finer, in the case of phosphate rock and some fused phosphates. In general, water-insoluble phosphates are ground finely, in order to speed up the fertilizer-soil reaction, which at best is relatively slow, whereas water-soluble phosphates are granulated, in order to slow down reaction in the soil, which in many cases is too fast for optimal crop response.

Upward extension of the experimental range in granule size is limited by use requirements. For example, in greenhouse culture the investigator would frown on an application of only one or two granules per culture. Actually a greenhouse pot of 7 to 8 pounds of soil, a size in common use today, requires only 4 or 5 granules of 4- to 6-mesh 20% superphosphate for an application of 75 pounds of P₂O₅ per acre. The problem of overlocalization in the soil bed arising from the use of granules larger than about 4 mesh is perhaps even more important in field application.

The technologically practical range in granule size, found by examining marketed mixed fertilizers, is about 4 to 35 mesh, which is very close to the range found useful in experimental work.