THE STATUS OF PLANT-GROWTH SUBSTANCES AND HERBICIDES IN 1945

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I. INTRODUCTION

During the past ten or twelve years, numerous investigations into the preparation, properties, and effects of plant-growth substances have been conducted. Many of the results obtained have been exceedingly interesting from a scientific point of view, as well as very valuable economically. In more recent years it has been observed that some of the growth-producing substances, when applied under different conditions of concentration and temperature, become effective herbicides for certain species of harmful plants.

In view of the importance of this line of work, a literature survey of the more important recent contributions has been made.

It has been known for many years that illuminating gas in the air, even in small amounts, is toxic to plants (30, 63, 64, 119, 120, 135, 153, 161), the damage depending not only on the amount of gas present but also on the species of plant involved. One of the most noticeable effects on the plant is epinasty, a bending or distortion caused by a differential growth rate, usually in the leaf petiole. In an investigation of this problem, Zimmerman *et al.* (172) found that ethylene, present in illuminating gas in small amounts and responsible for the epinastic effect, may enter the plant through the stem, petiole, or leaf blade and spread throughout the entire plant. Should but a single leaf be exposed to ethylene, the remainder of the plant will also show the epinastic response. It is not known exactly how this particular response is transmitted, but it is believed to be through the intercellular spaces. Ferri (34) has shown that growth substances applied to the base of cuttings are transmitted upward through the xylem. Beal (8) uses the word "telemorphic" to describe the effect, on one part of the plant, of a growth substance applied at another part.

Doubt (3) reported that when illuminating gas was passed through soil in which tomato plants were growing, there was a tendency for the roots to grow out of the soil. There was also an unusual development of the basal part of the stem. Zimmerman *et al.* (161) verified these results and, in so doing, came to the conclusion that the root stimulation was due to the presence of carbon monoxide in the illuminating gas. They therefore exposed portions of stems to concentrations of carbon monoxide (162) and found that, in addition to the epinastic and other effects usually produced, the gas induced definite rooting responses in twenty-seven species of plants. This was the first report to show that new organs could be induced by the application of a known chemical.

More work on carbon monoxide (163) and other gases (164) followed, and it was soon found that ethylene, acetylene, and propylene in the proper concentrations were also effective in stimulating root growth. The fact that more than one pure chemical substance was able to induce a formative response naturally raised the question as to how many other chemicals were capable of performing the same function. Went (149) reported a root-forming substance in plants which he called rhizocauline and which formed roots on treated cuttings of sweet pea. He also reported a test method by which the concentration of rhizocauline could be determined by the number of roots formed. Thimann and Went (146), using this assay method, determined the comparative amounts of the root-forming substance occurring naturally in plant and animal material. Laibach *et al.* (93), using concentrates from urine and pollen mixed with lanolin and applied locally, induced increased root growth of cuttings. Kogl *et al.* (87) were the first to isolate a growth substance as a pure chemical compound and identify it as β-indoleacetic acid.

Hitchcock (66), in testing many chemicals, found that, in addition to indoleacetic acid, indolepropionic acid, phenylacrylic acid, and phenylpropionic acid were effective in causing root initiation. Within a short time, eight new chemical compounds were found to have special effects on plants. These, as reported by Zimmerman and Wilcoxon (175), were α-naphthaleneacetic acid, β-naphthaleneacetic acid, acenaphthyl-5-acetic acid, indolebutyric acid, phenylacetic acid, fluoreneacetic acid, anthraceneacetic acid, and α-naphthylacetonitrile. It was also determined (68) that a rooting response would follow if any of these substances were added to the soil in which a plant was growing. At this point several papers appeared substantiating the findings concerning growth substances in inducing root initiation (16, 18, 67, 92, 101, 165), and numerous articles were published in semiscientific and popular magazines. β-Indoleacetic and β-indolebutyric acids appeared on the market as the powdered hormone in talc or other dry inert material for dusting on the ends of cuttings, and also dissolved in lanolin in the salve form.

Haagen-Smit and Went (57) and Thimann (141) criticized the work of Zimmerman and his associates on the grounds that the experiments had been carried out on green hormone-rich material in light, and that the acid effect of the compounds, which might interfere with the transport of the growth hormones already in the plant, had not been considered. In answer to this criticism, Zimmerman *et al.* (174) reported that nine esters must be added to the list of growth substances, and that some of these were more effective than the original "hetero-auxin", β-indoleacetic acid, isolated from plant tissue. The nine esters included methyl and ethyl α-naphthaleneacetates, methyl and ethyl phenylacetates, *n*-butyl and isobutyl phenylacetates, methyl β-indoleacetate, methyl β-indolebutyrate, and methyl β-indolepropionate.

With esters of the indole and other acids as effective as the acids themselves, it was a natural step to try the effect of their salts. Not all tests were successful, but in a number of cases certain of the salts were more potent in initiating root growth than were the corresponding acids (45, 166). The salts known at this time to be effective were the potassium, sodium, calcium, barium, strontium, ammonium, trimethylammonium, and tetramethylammonium salts of naphthaleneacetic acid; the potassium, sodium, ammonium, trimethylammonium, and tetramethylammonium salts of β-indoleacetic acid; the potassium, sodium, ammonium, trimethylammonium, and tetramethylammonium salts of γ-indolebutyric acid; the potassium and sodium salts of indolepropionic acid; and potassium phenylacetate. Zimmerman and Hitchcock (167) in 1939 reported twenty-six new growth substances[1] in an article describing the effect of growth substances used in the vapor form. They also noticed that some of these caused parthenocarpic development of holly berries, of Fuschia and orchid ovularies, and the enlargement of the receptacle of strawberries.

This additional effect of a growth substance, whereby the development of the ovulary is stimulated in the absence of fertilization, leads to an entirely new use for these synthetic organic acids and their esters and salts. It becomes necessary to go back again in the literature and lead up to this point, inasmuch as the parthenocarpic development of fruit by plant extracts had been known for some time.

The observation that pollen contains substances which stimulate the enlargement of the ovulary, apart from the fertilizing function of the pollen nucleus, was made in 1902 by Massart (107) and in 1909 by Fitting (35, 36). In 1918 Morita (112) repeated some of Fitting's experiments and attempted the stimulation of ovulary development with several organic chemicals. In 1932, Laibach (90) further verified Fitting's work and also found that in animal tissue there were hormones that would induce development of the plant ovulary. In 1934 and 1935 Yasuda (155, 156, 157) injected aqueous pollen extracts into plant ovularies and obtained, in some cases, normal-sized but seedless fruit. Gustafson (49) also achieved parthenocarpy by means of pollen extracts applied to the pistil. He later (52) showed that the growth-promoting substance content in the ovularies of flower buds from parthenocarpic varieties of oranges, lemons, and grapes is higher than in the ovularies from corresponding varieties that do

[1] Ethyl α- and β-naphthoxy-α-butyrates, methyl and ethyl α- and β-naphthoxyacetates, α- and β-naphthaleneacetic acid picrates, butyl and isobutyl phenylacetates, β-naphthoxyacetamide, β-naphthoxy-α-butyric acid, α-naphthoflavone, α-naphthylamine, methyl ethyl phenylethylmalonate, phenylbutyric acid, phenylethylacetic acid, *N*-phenylglycine ethyl ester, irradiated methyl *m*-nitrocinnamate, methyl α-trimethylamino-β-(3-indole)propionate iodide, ethyl α-bromoacetoacetate, homopiperonylic acid, nicotinic acid nitrate, pimelic acid, and *m*-tolyl-β-napthoxyacetate.

not produce fruit parthenocarpically. In 1936 Gustafson (48) caused fruits to develop parthenocarpically in several species of plants by treating the pistils with known chemical compounds already found effective in stimulating the formation of roots. He thereby opened another field to the investigators of growth-promoting substances.

The following year, Gardner and Marth (40) induced parthenocarpy in holly and strawberries by spraying with growth-promoting chemicals, and in a similar manner Hagemann (58) and Schroeder (126) brought about parthenocarpy in gladiolus and tomatoes, respectively. Since 1937 research on the practical application of growth substances to greenhouse and truck crops has been carried on by many workers, including Gustafson (50, 51). Wong (154) produced parthenocarpic watermelons, cucumbers, and peppers, and Burrell and Whitaker (14) parthenocarpic muskmelons, but it has been only with the tomato that much success has been obtained (81, 82, 83, 115, 124, 137). This, however, has been phenomenal, and the use of growth-promoting chemicals on greenhouse tomatoes has increased to such an extent that in 1945 in Ohio, approximately 1,800,000 plants were treated, or about half the tomato plants grown in greenhouses in the state (85).

Closely associated with commencement of ovulary growth is the prevention of the formation of an absciss layer between it and the pedicel. Preventing this absciss layer from forming may even be the first step in fruit formation. Abscission may take place at any time between the withering of the flower and the maturation of the fruit. To horticulturalists it is a well-known fact that many fruits which have started in their development, drop before maturity. Dorsey (29) and others associated this with the lack of seed development. Laibach (91), La Rue (94), and Myers (118) have shown that if the debladed petioles of many plants are treated with growth substances, they will not drop nearly so soon as those not treated. Gardner *et al.* (41, 42) demonstrated that spraying nearly mature apples with growth-promoting substances prevents them from dropping. The subject of a pre-harvest spray for apples and other fruits was then taken up by several of the agricultural experiment stations (3, 12, 15, 19, 31, 32, 33, 38, 39, 46, 65, 73, 74, 76, 77, 98, 113, 116, 117, 122, 123, 129, 131, 132, 133, 134), with the result that the pre-harvest spray now is recommended to the fruit grower, especially for early apples. However, so much varietal difference has been found in the response of apples to treatment that recommendations vary in different parts of the country, and the grower is advised to consult his own state agricultural experiment station for spraying directions.

In addition to the stimulation of root formation, fruit formation, and petiole growth to prevent premature fruit drop, one other type of plant-tissue stimulation due to organic chemicals occurs which can be put to practical use. This is the stimulation of bud or shoot development. Although, according to Howlett (85), results are quite pronounced, this phase at present has not been exploited commercially, because in general there appears to be no particular benefit in stimulating the growth of buds. It has been shown that potato tubers can be induced to send out shoots at a time when normally they would be inactive, owing to the rest period. Experiments (21, 22, 24, 27, 28, 138, 151, 167) conducted over a number of years with the vapor of ethylene chlorohydrin and with sodium, potassium, and ammonium thiocyanates, and a few other chemicals have demonstrated that these have an unusual physiological effect on dormant potato tubers and will shorten the normal rest period.

It would seem paradoxical that growth substances which exert a promotive effect on the growth of stems and petioles, and initiate root formation, should in concentrations of the same order of magnitude exert exactly the reverse effect on the growth of roots. However, it has been shown by Bonner and Koepfli (10) that the chemical specificity of the growth substance that will promote stem growth is closely similar to the chemical specificity that will inhibit root growth. The inhibition of root growth has been recorded several times (87, 141, 142, 150).

There are other suppression or growth-prevention effects, all of which have an important utilitarian future. First is the removal of superfluous flowers and fruits, as opposed to the prevention of the pre-harvest drop of fruit. Second is the prevention of early bud development in stored potato tubers, as opposed to the breaking of the normal rest period. Third is the delay in the development of flower and leaf buds of early flowering trees and shrubs to prevent early frost damage, lengthen the period of time over which they blossom and fruit, and lengthen the period during which it is possible to plant shrubs in the spring, as opposed to the stimulation of flower and bud growth. Fourth is the differential herbicide. In this case, broad-leaved plants are stimulated to proliferate themselves to death while grasses are unaffected when both are treated with several times the concentration of growth substance that will cause the wanted stimulation of fruitfulness, petiole growth, or root formation.

Spraying apples to reduce the number of flowers setting fruit, and therefore making it unnecessary to thin by hand later in the season, was first shown to be feasible by Auchter and Roberts in 1933 and 1935 (1, 2). A number of articles have since been published on this subject, almost entirely from state agricultural experiment stations (4, 11, 13, 37, 44, 72, 75, 78, 79, 80, 84, 84a, 99, 100, 114, 125). In the first experiments on the thinning of fruit by spraying, tar oil distillates such as Reico were used. MacDaniels and Hildebrand (99) suggested the use of dinitro compounds, and Elgetol (sodium dinitro-*o*-cresylate), which acts as a pollenicide, Dow D-41 (dinitro-*o*-cylohexylphenol), and Dow D-145 (dinitro-*o*-cresol) gave promise of successful use. However, naphthaleneacetic acid, naphthaleneacetamide, and indoleacetic acid may be used for the same effect. Staymone and Hormex are now on the market to be used as a thinning spray or dust. Schneider and Enzie (125) found that naphthaleneacetic acid and naphthaleneacetamide as a 0.01 per cent spray at full bloom were too severe, nearly eliminating the crop; they recommended 0.002 per cent as a more favorable concentration. As in the case of the pre-harvest spray to prevent drop, the thinning spray is still in the advanced experimental stage and varietal, seasonal, and climatic differences exert such an influence that the general public has not been advised to use the thinning spray except under the supervision of an agricultural experiment station. Whether or not growth substances will be used commercially as thinning sprays depends upon what "follow-up" there is to the findings of Gardner (43), who sprayed apple trees with a wax emulsion only and found that it functioned as a thinning agent by providing a coating to the stigma, preventing the pollen from functioning. The obvious advantage of this is the lack of any possibly deleterious effect on the young foliage.

One of the first inhibition effects of indoleacetic acid noted was that of the retardation of bud growth (127, 141, 143, 144, 145). One practical side of this effect was made use of by Guthrie and others (23, 25, 26, 53, 54, 55, 56), who showed that potato tubers could be kept dormant by the use of the vapors of methyl α-naphthaleneacetate and other growth substances. A second practical use occurs in the treatment of rose bushes (102, 103), so that the period over which they may be shipped in the spring is considerably lengthened, and so that they will not sprout in winter storage. Another practical use for such growth substances is for retarding buds on fruit trees in order to prevent their being killed by late frosts, and to extend the fruiting season of certain varieties (69). In the latter case, the spray containing the growth substance (potassium α-naphthaleneacetate) is applied the summer before the effect is desired.

Prior to 1939, the known growth substances, excluding carbon monoxide, ethylene, and the other gases previously mentioned, consisted of the acids, esters, and salts of the naphthalene and indole compounds. A new growth substance, β-naphthoxyacetic acid, was first described as physiologically active in 1938 (86). In 1939 Bausor (5) detailed its synthesis and described its effects, and those of its potassium and sodium salts, on plants as compared to the known growth substances. They were found to be similar, but β-naphthoxyacetic acid was more powerful. In observing its effects on tomato plants (6,7), it was found to act in as short a period as 2 hr. and was able to produce detrimental formative effects at low concentrations. Zimmerman and Hitchcock (168) also reported the synthesis of β-naphthoxyacetic acid and described its formative effects on several plants.

Inasmuch as new growth substances were being found, there was a natural curiosity as to the minimum molecular structural requirements. Koepfli, Thimann, and Went (88) went so far as to give what they believed to be the minimum requirement as follows: (*a*) a ring system as nucleus, (*b*) a double bond in this ring, (*c*) a side chain, (*d*) a carboxyl group (or a structure readily converted to a carboxyl) on this side chain at least one carbon atom removed from the ring, and (*e*) a particular space relationship between the ring and the carboxyl group. These specifications would eliminate benzoic acid as an active compound, since the carboxyl group is not one carbon atom removed from the ring. Results by Zimmerman and Hitchcock (169) have shown that phenoxy compounds and substituted benzoic acids are active when bromine atoms and nitro groups are substituted in the proper positions in the ring. These substitutions do not change the space relationship between the carboxyl and the ring. However, the biological activity of hormone-like substances extends from simple molecules like carbon monoxide gas to complex structures like naphthaleneacetic acid. In spite of the minimum requirements laid down by

Koepfli *et al.*, a comparison of the molecular structures of active and inactive compounds shows that a satisfactory understanding of what constitutes a growth substance has not yet been reached.

Hitchcock and Zimmerman (70) also found the root-inducing activity of the phenoxy compounds to vary from low to very high, depending on the kind, number, and position of substituents in the ring, and on the relative length of the side chain. They had a relatively narrow effective range below that which is toxic, and overtreatment produced swelling, proliferation, and retarded growth of roots, which became extremely fasciated. An unusual result was found in the case of triiodobenzoic acid (170), which induced leafy shoots to grow flower clusters.

A leaf modification similar to that in virus-diseased plants was obtained when plants were treated with some of the active phenoxy (xylenoxy) acids having two methyl groups substituted in various positions in the ring (173). The effects, however, could not be transmitted by grafting or inoculation, as is true of virus diseases, and after the chemical influence had disappeared, the treated plants reverted to normal. Stoutmeyer (136) found that the addition of methyl, hydrogen, or isoprene groups in various positions on a growth substance does not interfere with the action in aiding root formation, and may even enhance it in some cases.

The use of growth substances as differential herbicides is recent, although chemicals have been used for killing weeds for many years. Iron sulfate and sodium chlorate are very effective in killing plants when applied as a spray but show little or no differential quality, grasses being killed nearly as readily as weeds. Ammonium sulfate and ammonium nitrate have also been used and, where applied in sufficient concentration, kill the weeds by osmotic action. The grass, because of its narrower leaves and internodal method of growth, often recovers from not too heavy applications and later is stimulated by the residual action of the nitrogen in the case of the ammonium sulfate and nitrate. Some differential effects have been obtained by the use of oil sprays in onion, carrot, and parsnip fields where, because of the waxy or finely divided character of the foliage, the vegetables suffer little injury (17, 89, 139, 159). Oil sprays have also been recommended for lawns (95, 96, 97), but control in this case is a matter of degree only; too concentrated an application injures the grass and too light an application does not give an effective kill of the broad-leaved weeds.

Westgate and Raynor (152) recommended Sinox (sodium dinitro-*o*-cresylate) as a non-corrosive, relatively non-hazardous, differential herbicide used for controlling annual weeds of cereals, flax, onions, alfalfa, corn, roadsides, and pastures. It will kill bent grass and therefore will not be used to any extent on lawns. It kills young crab-grass seedlings but does not prevent later germination. It is non-effective against deep-rooted perennials. On the other hand, one of the most effective chemicals for use against deep-rooted perennials, but of no use on lawns, is ammonium sulfamate (ammate).

When applied in concentrations of $\frac{3}{4}$ pound per gallon of water, ammonium sulfamate is found to be most effective for killing poison ivy (147, 158). The chemical penetrates to the roots, preventing sprouting after the top has been killed. The soil is not severely sterilized, as is the case with sodium chlorate, and grass may recover. Applications to ivy on trees will eradicate the ivy and not damage the tree, if the tree leaves are not sprayed. Grigsby (47) found that ragweed was destroyed by spraying with dinitro-2-butylphenol and with pentachlorophenol. Water solutions kill more slowly than kerosene solutions.

Formative effects were noticed to a greater or less extent in the earlier experiments on plant-growth substances, but with the synthesis of β-naphthoxyacetic acid (5, 6, 7, 86, 168) and the phenoxy compounds (70, 169) it was found that a slight increase in the concentration of these substances multiplied the formative effects to such an extent that a sprayed plant seemed to exhaust or destroy its food reserves and collapse in its entirety (61). The use of the more effective growth substances as herbicides naturally suggested itself (109). Hamner and Tukey (61) sprayed 2,4-dichlorophenoxyacetic acid (2,4-D) and 2,4,5-trichlorophenoxyacetic acid on bindweed and obtained a complete kill down to the root tips. At approximately the same time similar articles by Hamner and Tukey (62) and by Marth and Mitchell (105) appeared, describing the effect of 2,4-dichlorophenoxyacetic acid as a differential herbicide on lawns. All plants growing on the lawns, with the exception of grasses, were destroyed with no noticeable ill effect on the grasses. Soon others corroborated these findings (9, 121, 128). Warm weather accelerated the rate at which the weeds were killed, but Marth and Davis (104) found that lawn weeds which had been sprayed in cold weather with little apparent effect died when the weather became warm.

2,4-Dichlorophenoxyacetic acid and 2,4,5-trichlorophenoxyacetic acid are almost equally effective, according to Snyder (130), and 2,4,6-tribromophenoxyacetic acid, although not a plant hormone because of the fact that it causes no growth reaction, will kill poison ivy. Snyder, quoting a representative of the American Chemical Paint Company of Ambler, Pennsylvania, states that even more effective weed killers are to be put on the market. The present commercial product of the company is Weedone, which is very effective on a weedy lawn but at present commands a price that makes it impractical for use on a large area.

A rather unexpected reaction of 2,4-dichlorophenoxyacetic acid is its effect on the ripening of fruit (110). Ethylene has been used commercially for this purpose, but the plant hormone has several advantages over ethylene. The ripening period of bananas, apples, and pears was shortened by treatment with 2,4-D, but tomatoes, peppers, and persimmons were not affected.

Although plant-growth substances and related chemicals show great promise in ridding lawns of broad-leaved weeds, unfortunately some of the worst lawn weeds are grasses themselves, and show the same tolerance to 2,4-D as do the wanted lawn grasses. Crab grass, Nimble Will, goose grass, foxtail, and orchard grass are probably the worst offenders, with crab grass giving more trouble than the others combined. Weed seed, including that of crab grass, may be destroyed by cyanamid or chloropicrin prior to the seeding of a lawn, but these chemicals are not so useful on established turf, as they are toxic to all grasses (111, 148).

De France (20) found that when crab grass was treated at the time of seed formation with any of the following chemicals and preparations—sodium arsenite, sodium fluoride, sodium chlorate, Lawn Sinox, Milarsenite, "Gone with the Wind", and Zotox—there was a very substantial decrease in the percentage of germination of crab-grass seed. Control is largely a matter of the prevention of seed formation for reinfestation. If the season's crop of crab grass would germinate at one time, instead of having a prolonged period of germination from April until September, the plants could be killed in the seedling stage by one treatment which would not greatly harm the mature grasses, but many treatments are necessary if the successive crops of seedlings are to be eliminated. The logical time for treatment appears to be during the period of seed formation.

No one growth substance can be considered best for all purposes, although there is considerable overlapping. For convenience the different groups are taken separately and their values, as considered by Zimmerman (160), summarized.

II. PLANT-GROWTH SUBSTANCES

A. *Naphthalene compounds*

When properly applied, α-naphthaleneacetic acid and its derivatives inhibit bud growth, induce roots on cuttings, and prevent abscission layers from forming. An important use of α-naphthaleneacetic acid is for the prevention of preharvest drop of apples. Naphthalene compounds are frequently important in preventing the buds of tubers, bulbs, corms, cuttings, and trees from growing. After treatment with α-naphthaleneacetic acid, potatoes may be stored indefinitely without much shrinkage, and fruit trees can be prevented from flowering until danger of frost is past. The same treatment may be important in delaying the flowering of trees, so as to spread the fruit crop over a longer harvest period. This would apply particularly to tropical species, such as the mango and avocado. The flowering period of ornamental shrubs can be regulated to some extent. Wherever inhibition is desired, the α-naphthalene compounds appear to be the most effective. The β-isomers, as well as the higher homologs of α-naphthaleneacetic acid, are inactive.

B. *Indole compounds*

Indolebutyric acid appears to be of the most practical importance in this group. Its main use is in the propagation of plants, where it is used on cuttings to induce root growth. Although mixtures of naphthaleneacetic acid, chlorophenoxy compounds, and indolebutyric acid are now favored over a single substance for this purpose, indolebutyric acid remains the most important component of the mixture. Indolebutyric acid is also important in inducing fruit set and parthenocarpy in the tomato. Most commercial preparations now use for this purpose a mixture of indolebutyric acid and β-naphthoxyacetic acid.

The latter is much more active than the indolebutyric acid but has a tendency to induce unwanted formative effects.

C. Naphthoxy compounds

β-Naphthoxyacetic acid and its active higher homologs induce adventitious roots, cause plants to grow with modified organs, and induce seedless fruit. They are not so favorable for propagating plants from cuttings as indolebutyric acid, but for some species can be used effectively. β-Naphthoxyacetic acid is twenty to thirty times as effective as indolebutyric acid but not as active as dichlorophenoxyacetic acid in inducing parthenocarpy. From a scientific point of view the naphthoxy compounds are interesting because they induce formative effects when applied to growing plants. The growth which develops after treatment frequently shows leaves, stems, flowers, and fruit modified in size, shape, venation, and pattern. The similarity of the formative effects produced by naphthoxy compounds, substituted phenoxy compounds, and substituted benzoic acids to the effects produced by a plant virus brings up an interesting and untouched research problem as to the connection between the two. Plants with formative effects produced by the growth substances resume a normal habit of growth when the growth substance is no longer applied. It is not known whether or not formative effects produced by a plant virus are due to the production of growth substances by the virus.

D. Substituted phenoxy compounds

Substituted phenoxy compounds are proving to be perhaps the most effective of all growth substances. Zimmerman (160) gives the molecular configuration of eighteen such halogen-substituted phenoxy compounds which he found to be active in producing cell elongation and curvature. Bromo-substituted phenoxy compounds showed approximately the same activity as the corresponding chloro-substituted compounds.

Phenoxyacetic acid as such is but slightly active, but halogen-substituted phenoxy compounds are activated according to the positions and the number of substituted groups in the nucleus of the molecule.

The higher homologs of substituted phenoxyacetic acid are also very active. Nitro substitutions do not act in the same way as halogen atoms. The most active substituted phenoxy compounds for cell elongation are 2,4-dichlorophenoxyacetic acid and 2,4,5-trichlorophenoxyacetic acid. The former has now come into commercial use as a differential herbicide, since it causes the death of broad-leaved weeds with little or no detrimental effect on the surrounding grasses.

Substituted phenoxy compounds are important for propagating plants, preventing pre-harvest fruit drop, inhibiting bud development, and inducing seedless fruit. For the latter response dichlorophenoxyacetic acid is the most effective compound yet discovered. For example, 10 mg. per liter of water as a spray is approximately optimum for inducing parthenocarpy and seedless fruit of tomatoes. This is in contrast to 3000 mg. per liter for indolebutyric acid and 100 mg. per liter for naphthoxyacetic acid.

When used as a vapor in a greenhouse with a volume of 2500 cubic feet, 5 mg. of methyl dichlorophenoxyacetate is sufficient to induce fruit set throughout the house.

For the propagation of plants, halogen-substituted phenoxy compounds are effective when used alone or in a mixture of other growth substances. A mixture extends the effectiveness of a preparation to include more species of susceptible plants. So far, no one substance used alone has been found effective on all species. Not all of the substituted chlorophenoxy compounds have the same formative influence on plants, and it has not yet been possible to determine what part of the molecule is responsible for a given response.

E. Substituted benzoic acids

The possible practical applications of the substituted benzoic acids have not been thoroughly investigated. It would seem, however, that any substance as active as the substituted benzoic group for regulating the growth of plants is certain to be useful. Enough has been done to show that when various combinations of halogen and nitro groups are substituted in the nucleus, the molecule is activated. Benzoic acid is physiologically inactive, but 2,3,5-triiodobenzoic acid has a pronounced formative influence on plants. 2-Bromo-3-nitrobenzoic acid is mildly active for cell elongation and very active for modification of organs. 2-Chloro-5-nitrobenzoic acid is inactive for cell elongation but modifies organs. Triiodobenzoic acid, as has already been stated, has a pronounced effect on the flowering habit of tomato plants, producing flower clusters at the end of the main branches in addition to those along the stem.

Synerholm and Zimmerman (140) gave directions for the preparation of substituted phenoxyalkylcarboxylic acids with details for testing them as plant-growth substances. They found that halogen atoms or methyl groups are of the most importance in lending activity to the phenoxyalkylcarboxylic acids. The 2-, 3-, and 4-positions in the benzene ring are those in which the substituents exert their greatest influence.

The activity of growth substances is usually detected by curvatures resulting from induced cell elongation, or by formative effects on later growth. The former response occurs within a comparatively short period of time, considered in terms of minutes or hours. Formative effects appear within a few days or weeks after the plant has had time to grow and produce new organs. If a chemical compound does not induce curvatures, cell elongation, or formative effects, it is considered inactive. Hitchcock and Zimmerman (71) published a method by which the effectiveness of growth substances could be measured.

Active chemicals are referred to by various investigators as growth regulators growth substances, auxins, or plant hormones. The latter term must be considered incorrect, since the synthetic substances, with the exception of cinnamic acid, ethylene, and indoleacetic acid, are not known to be identical with naturally occurring hormones.

Methods of treating plants with growth substances are varied. To induce roots on cuttings, the basal ends are dipped into powder preparations or solutions of the substance. The concentration requirements vary with the species, and for general use more than one strength is desirable. To prevent pre-harvest apple drop, a water solution containing 10–50 mg. of naphthaleneacetic acid per liter is sprayed on the entire tree at the time apples begin to fall prematurely.

To inhibit the growth of buds on tubers, bulbs, corms, rhizomes, trees, and shrubs, the plants or plant parts are exposed to vapors, dipped into solutions, sprayed with solutions, dusted with powder preparations, or otherwise treated with naphthaleneacetic acid or its derivatives. For inhibition by vapor treatments, methyl and ethyl naphthaleneacetates are particularly effective. The esters of the halogen-substituted phenoxy compounds are very volatile and can be used effectively for inhibiting growth by means of vapor treatments. The same substances which accelerate growth with low concentrations will inhibit growth when the concentration is great enough.

Several methods are used for inducing seedless tomatoes. The most common method is spraying the open flowers with water solutions or emulsions. The most effective concentrations for five chemicals used in treating tomatoes are as follows:

SUBSTANCE	CONCENTRATION
	mg. per liter
Indolebutyric acid	3000
β-Naphthoxyacetic acid	100
β-Naphthoxypropionic acid	50–100
β-Chlorophenoxyacetic acid	50–100
2,4-Dichlorophenoxyacetic acid	10

To apply vapors in a greenhouse, the esters are warmed over a hot plate and the air is circulated by an electric fan. For vapor treatments the esters of β-naphthoxyacetic, β-naphthoxypropionic, β-chlorophenoxyacetic, dichlorophenoxyacetic, and trichlorophenoxyacetic acids are most effective. The milligrams required per 1000 cubic feet vary with greenhouse conditions, the amount of heat applied, or other conditions, but 1–10 mg. of the dichlorophenoxyacetic acid ester, or 25–50 mg. of the β-naphthoxyacetic acid ester, would ordinarily be sufficient. Indolebutyric esters are only slightly volatile and can not be used successfully as vapors. The use of the aerosol bomb for distributing the vapors of a growth substance in a greenhouse has been successfully demonstrated (61, 62, 171), and undoubtedly will be the preferred method of treatment in the future.

In treating lawns with 2,4-dichlorophenoxyacetic acid and other similar growth substances to kill weeds, spraying the area with a mist spray is the usual procedure.

III. SUGGESTED PROBLEMS FOR INVESTIGATION

When organic growth substances first became known, and the indole compounds were the only ones of importance, some investigators of plant hormones—or auxins as they are better known—strongly suggested that the synthetic compounds had counterparts in living tissue, and that what few new growth substances might come to light would eventually be found in plants by analysis. As a matter of fact, β-indoleacetic acid is the only organic growth substance known to be synthesized by plants from among the many score and constantly increasing number of effective organic growth substances. Possibly some of these will eventually be detected in plant tissue, and undoubtedly there will be generic and specific variation in the hormones occurring in plants; but the point is that, at present, even the most confirmed "vitalist" must admit the impossibility that all growth substances can be naturally produced by plant tissue.

It is beyond the purpose of this article to suggest any new classes of organic compounds which possibly would equal or excel those already known, but inasmuch as the substituted phenoxy compounds and benzoic acids have shown such promise within the past few months, there is no reason to doubt that there are many more compounds, as yet unsynthesized, which would have increased potency.

There is need for a growth substance to induce setting of fruit without the unwanted, but usually present, formative effects. Growth substances vary greatly in their ability to set fruit and to distort the growth of leaves and stems. The ideal growth substance for the setting of fruit has not been discovered, and at present combinations of several are used because no one is entirely satisfactory.

A dependable growth substance to induce parthenocarpy in watermelon, muskmelon, and other cucurbits is not yet known. An occasional seedless watermelon has been produced, and there is no reason why some growth substance could not be effective for this purpose.

The Boyce Thompson Institute is working at present on a growth substance that can be depended on to delay the flowering of early peaches and apples. α-Naphthaleneacetic acid is used for this purpose but is not entirely effective.

No spray is yet on the market which could be used on newly purchased Christmas trees and holly wreaths to prevent the dropping of leaves.

The only really effective differential herbicides are 2,4-dichlorophenoxyacetic acid (Weedone) and 2,4,5-trichlorophenoxyacetic acid. Others equally or more effective will undoubtedly be discovered.

A plant-growth substance that will break the rest period of crab-grass seed, causing it to germinate in the fall and succumb to frost, is not beyond possibility.

A growth substance that will accelerate the growth of stems and leaves without the distortion of epinasty has unlimited uses if developed.

The field of plant hormones is still new and holds much for the future.

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