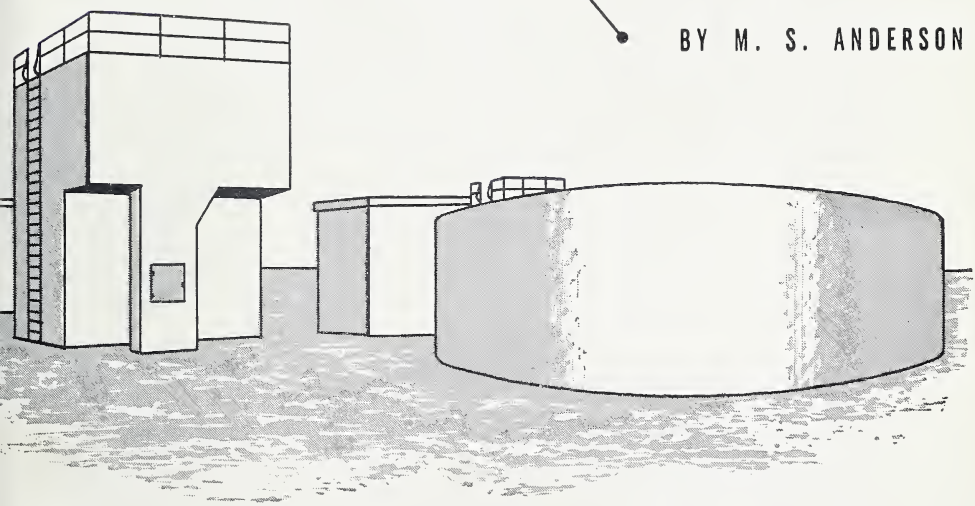
SEWAGE SLUDGE FOR SOIL IMPROVEMENT

BY M. S. ANDERSON



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SEWAGE SLUDGE
FOR SOIL IMPROVEMENT

By M. S. Anderson,[1] *senior chemist, Soil and Water Conservation Research Branch, Agricultural Research Service*

Sewage disposal plants are owned and operated by nearly all American towns and cities having populations greater than 2,500. A sizable expenditure of municipal funds is involved in the operation and maintenance of these disposal systems. There is thus considerable interest in any means by which the cost of such operations may be at least partly defrayed. It is the purpose of this circular to discuss the possible agricultural utilization of sewage sludges, whereby solid residues may possibly be processed for sale to agricultural consumers. Data of interest to farmers, soil and water conservationists, merchants selling sludges, and those concerned with waterway pollution abatement are also included.

Public sentiment is today strongly in favor of cleaner streams than now prevail. It is thus essential that more of the organic constituents present in raw sewage be removed in processing plants serving our centers of population. A few of the disposal systems in operation recover a large part of the plant nutrients, except potassium, present in raw sewage. Sludges of high quality recovered after heating often are used directly as fertilizers. The sludge output of a large number of disposal plants is of low grade as fertilizer but has some value when applied to land in the manner that farm manure is used. The better grades of sludge are often sold to defray a part of the expenses of operating a plant. The poorer quality materials that have lost a large part of the nutrients originally present may be given to users or sold for a very small price. As these low-quality sludges are being processed, sizable quantities of organic matter are lost in the form of gases, and plant nutrients are carried off in drainage water.

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[1] The wholehearted cooperation and assistance of many individuals and groups is hereby acknowledged. These include the representatives of several sewage disposal plants who furnished samples of their sludges, officials who made operational and design data available and who allowed inspection of disposal facilities during visits, persons associated with the Interstate Commission on the Potomac River Basin who supplied pertinent information, and staff members of the Soil and Water Conservation Research Branch and the Soil Conservation Service of this Department who provided most of the heretofore unpublished chemical data. Those having a part in the analytical work follow: Dorothy H. Carroll, L. J. Clark, A. J. Engel, V. L. Gaddy, W. M. Hoffman, B. M. Olive, Catherine B. Scott.

Processing of Sewage

Agriculturists recognize wide differences in the fertilizer value of sewage sludges. To a considerable extent these differences are associated with method of sewage treatment, but other factors influence the chemical composition of sludge (*31*).[2] Major differences in processing, as indicated by the terms "digested" and "activated," tend to connote wide differences in value of the sewage products as fertilizers.

In the parlance of sewage technicians, the terms "primary treatment" and "secondary treatment" are commonly used (*10*). Primary treatment refers to the separation of solids by gravity, with or without chemical treatment, often followed by anaerobic digestion of the somewhat concentrated sludges. The residues may be incinerated or may be used for soil improvement. Secondary treatment includes any one or more steps designed particularly to remove a relatively large amount of organic material from the effluent before it passes into a natural water body. Important secondary steps include: (1) Aeration of sewage and sludge with or without chemical treatment before settling; (2) heat treatment of damp sludge; (3) purification of effluent on trickling filters; (4) secondary treatment of effluent from primary digestion tanks by recycling into a primary or secondary system; (5) chlorination of the final effluent; and (6) certain other operations that might be useful for purification after primary treatment.

Digested Sludges

Sedimentation systems involving settling by gravity and subsequent anaerobic digestion of solids are extensively used. The equipment at the Agricultural Research Center, United States Department of Agriculture, Beltsville, Md., serves to illustrate several steps in the process. Different parts of the system are shown in figure 1. A conventional anaerobic digestion period of 10 to 14 days is used. Digested solids are then pumped to the glass house where solar heat and protection from rainfall hasten drying. The final step is removal of the dry material to a heap for storing outdoors or for application to land.

A short period of aeration is frequently used before raw sewage is allowed to settle prior to digestion. A system of this kind at Des Moines, Iowa, is very effective (fig. 2). Sludge from this plant is recovered on open sand-gravel beds (fig. 3). Much of the dry material is used as fertilizer after fortification with chemical nitrogen.

A rotary-vacuum filter is often used within a large plant for removal of much of the water from digested sludge. Figure 4 shows such a filter in the plant at Washington, D. C. The digested sludge as removed usually contains from 65 to 75 percent water. Use of such a filter system eliminates the need for sand-gravel beds.

A few medium-sized cities located in agricultural areas dispose of a part of their short-time activated and subsequently digested sludge in liquid form (*14*). This is delivered to farmers within a radius of about 10 miles and is used for direct application to land. A delivery tank is shown in figure 5. The sludge not delivered to farms is

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[2] Italic numbers in parentheses refer to Literature Cited, p. 25.

Figure 1.—Sewage disposal system, U. S. Department of Agriculture, Research Center, Beltsville, Md. *A*, An overall view shows serimentation tanks and trickling filters for improvement of effluent. *B*, The digestion chamber at the right is partly underground. The small pipe in the foreground is for escape of combustible gases. Digested solids are pumped to filter beds in a glass house at the left. *C*, Sludge that is nearly dry on a sand-gravel filter shows cracks caused by great shrinkage.

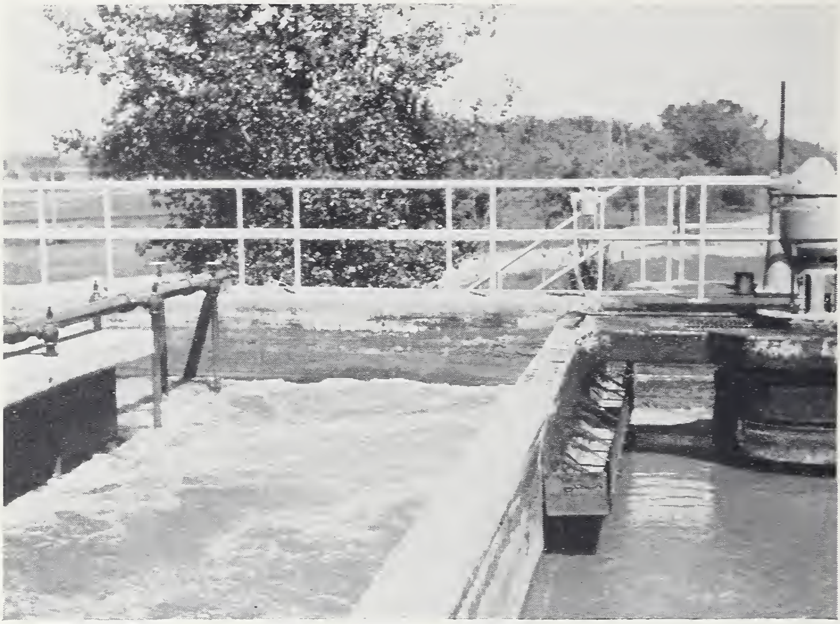

Figure 2.—Aeration of sewage previous to settling and subsequent digestion of the sludge, Des Moines, Iowa.

Figure 3.—Dried digested sewage sludge of the Des Moines, Iowa, plant is recovered for use as fertilizer.

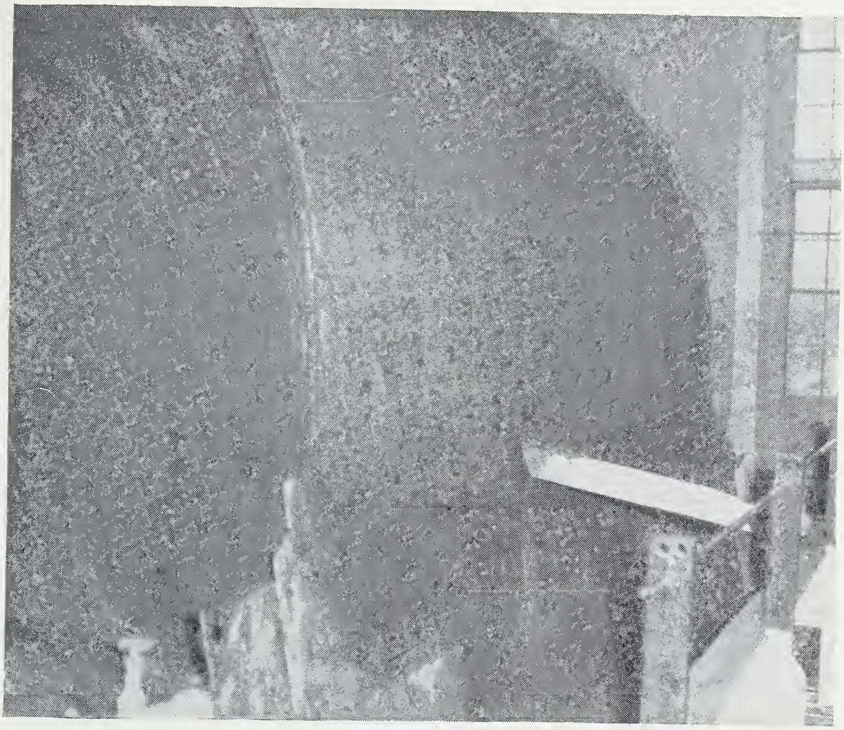

Figure 4.—Solids are removed from a digested sludge suspension by a rotary-vacuum filter.

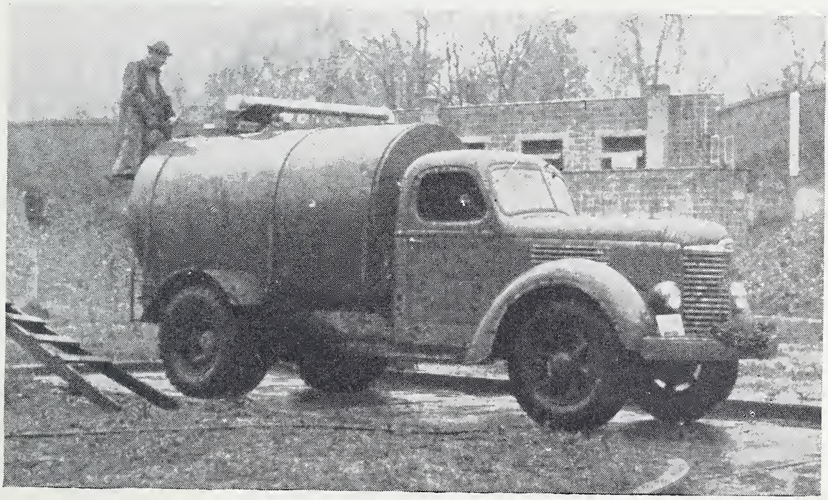

Figure 5.—Sewage sludge containing 6 to 10 percent of solids is transported to farms from the Richmond, Ind., disposal plant.

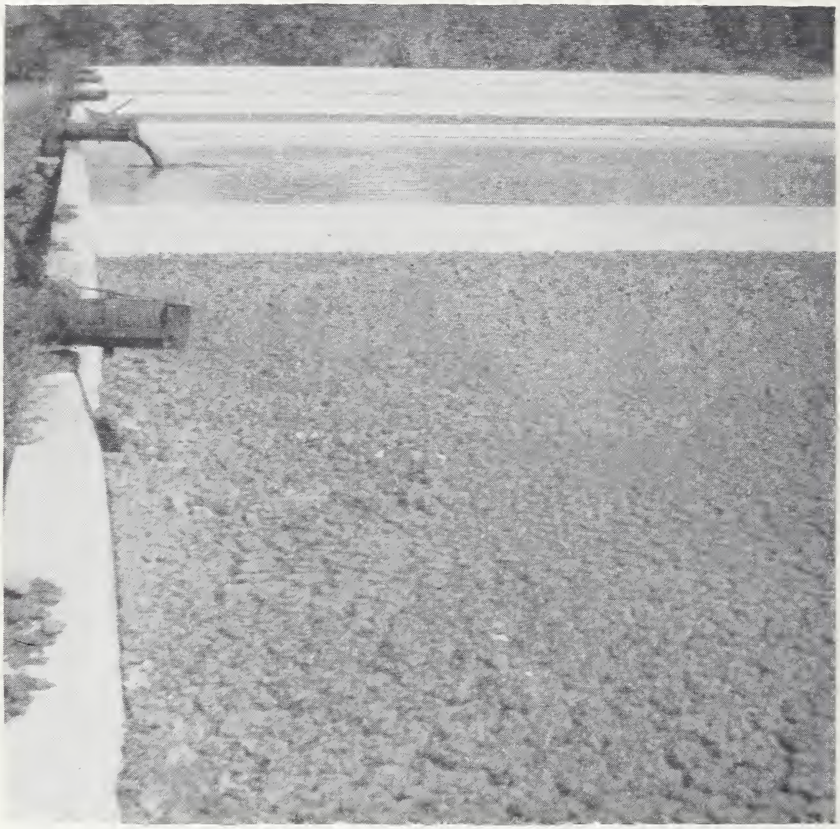

Figure 6.—Partly dried sludge is shown in the compartment in the foreground.

pumped onto filter beds for drying, as shown in figure 6. In some cases the evolved gas, essentially methane, from a digestion chamber is collected for use commercially or for consumption within the plant. Sometimes sludge is dried and sterilized by heat from this source. Gas may be consumed currently as produced or it may be stored in suitable containers. A storage sphere similar to the one at Richmond, Ind., is a type that is frequently used (fig. 7).

An Imhoff tank combines the functions of a settling tank and a digestion chamber. The system, named for its German designer (*6, 20*), consists of an upper and a lower chamber. The upper part serves as a settling tank where solids reach a sloping bottom, from whence they move into the lower, or digestion, chamber. The bottom plates are so arranged as to prevent rising gas bubbles from reaching the upper chamber where they might interfere with the settling of solids. A small Imhoff tank is shown in figure 8. Digested sludge is pumped onto a filter bed where solids are collected in a conventional manner.

Digested sludges usually have an offensive odor that persists for some time after application to a soil surface during cool weather. This odor differs greatly in character, however, from that of the raw sludge,

Figure 7.—The sewage disposal plant at Richmond, Ind., has a spherical storage tank for the combustible gases arising from the digestion chamber.

since drastic changes have taken place during digestion (*11*). The odor from digested sludges may be eliminated by storage in a heap during warm weather.

The lagooning of sludges refers to their digestion in field ponds, constructed by suitable excavation or by the making of levees or rims around suitable areas. The sludge is pumped into one of a series of these large ponds that may be several acres in area. Indianapolis, Ind., has followed this practice for a long time (fig. 9). A short period of activation is accomplished by pumping and subsequent fall of the water. After several years, the water of a lagoon may be drained to another similar body and the solid material allowed to dry. Farmers remove this residue for soil improvement. Since the solid materials have been essentially submerged most of the time, the action in the lagoon resembles to some extent that in the lower

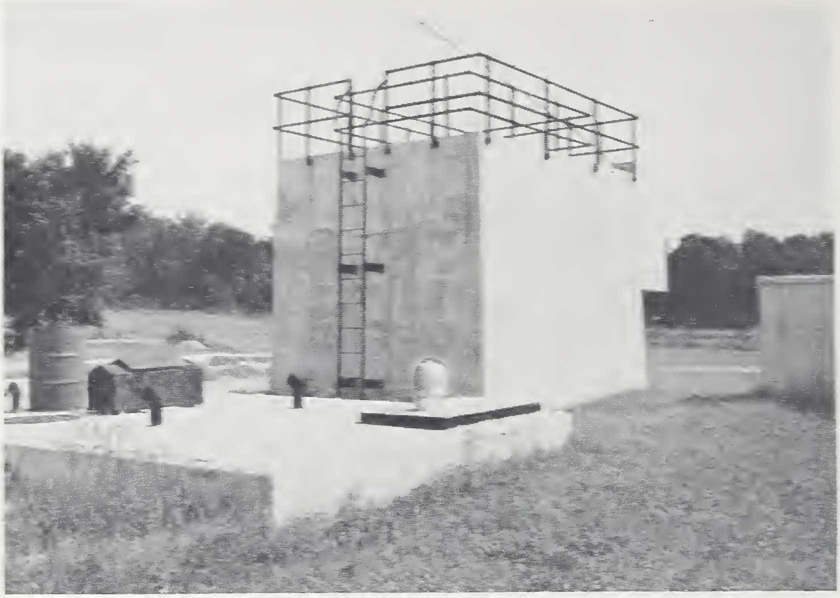

Figure 8.—An Imhoff tank consists of an upper and a lower chamber. This small plant serves the Plant Industry Station, USDA, Beltsville, Md.

chamber of an Imhoff tank. The lagoon material has somewhat more access to oxygen, however.

Waste water from industrial plants is often lagooned as a means of protecting small streams from undue pollution. Figure 10 shows a system of small lagoons serving a tannery at Luray, Va.

Activated Sludges

Activated sludge is prepared by passing air rapidly through raw sewage in the presence of large numbers of very active, aerobic bacteria and other organisms. Sometimes certain chemicals, such as ferric chloride, are added to the raw sewage or sludge to aid settling (*2, 52*). Biological, physical, and chemical changes that take place during a period of several hours greatly hasten the settling rate of solids.

The disposal plant at Milwaukee, Wis., serves to illustrate features of a modern plant for production of activated sludge (fig. 11). The daily output is approximately 160 tons. Sale of activated sludge sometimes serves to defray a moderate part of the expenses of such a plant.

In the case of Milwaukee, effluent is discharged into Lake Michigan from which the city gets its municipal water supply. Sanitary engineers seek to reduce the content of organic matter in raw sewage as much as practicable before the effluent waters are discharged. Biochemical oxygen demand (B. O. D.) is a conventional measure of

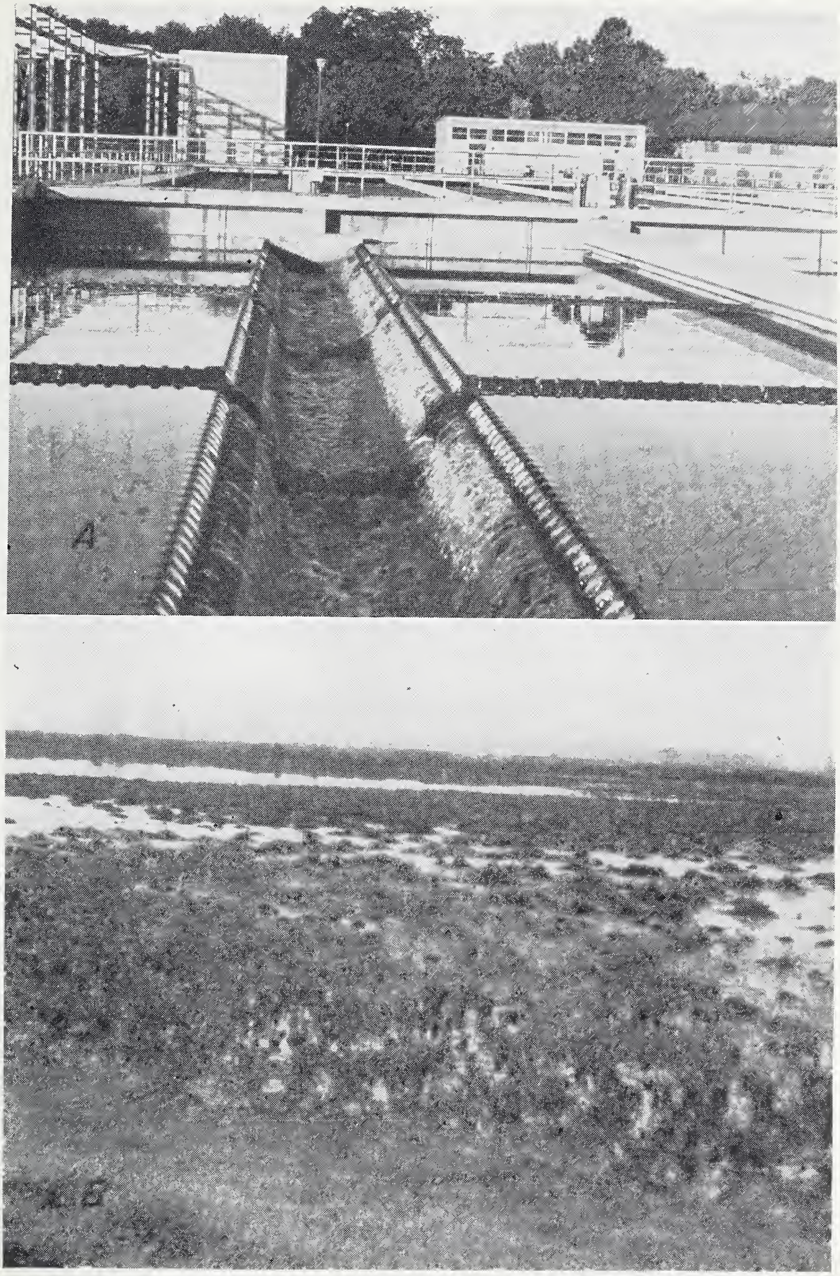

Figure 9.—Raw sewage is aerated in passing over a weir (*A*) before delivery to a lagoon (*B*) for digestion, Indianapolis, Ind.

Figure 10.—Waste materials of a tannery are processed in lagoons from which the water is allowed to seep slowly into a small local stream, Luray, Va.

the active organic matter present (*16*). Figure 11, *B*, illustrates the great effectiveness of a properly operated activation system. At least 90 percent of the organic matter as represented by B. O. D. in the raw sludge goes into the dried product prepared for commerce.

One of the objectives of an activation installation is maximum removal of organic matter from the raw sewage. This means delivery of the best quality water possible to streams or other natural water bodies. In the process of activation a group of bacteria forms a jellylike matrix called zoogloea. These masses increase in size until the material behaves as a floc and readily settles. Just what roles the various bacteria and protozoa play in floc formation are not well known. It is clear, however, that an abundant supply of oxygen is essential for effective coagulation and settling (*16*). As the flocs settle they presumably carry down various organisms in the liquid, together with an appreciable quantity of inorganic colloidal material.

Chemical Composition

Many chemical analyses have been made of dried sewage sludge prepared at different times and in different places. The Federation of Sewage Works Associations has taken the lead in supplying data regarding the chemical composition of municipal sludges prepared by particular systems. Data from this source are given in table 1. Activated sludges listed have an average nitrogen content of 5.6 percent, while a corresponding value for digested sludge is only 2.6 percent.

The range of composition found in certain plants preparing digested sludge in Ohio is shown in table 2. The average value for nitrogen is 1.77 percent and for total phosphoric oxide (P_2O_5) 2.4 percent. The range of nitrogen percentage in the 12 samples listed is 0.88 to 2.98, and for total phosphoric oxide (P_2O_5) 0.68 to 3.22. The ranges given would seem to lie within limits frequently found for the two types of

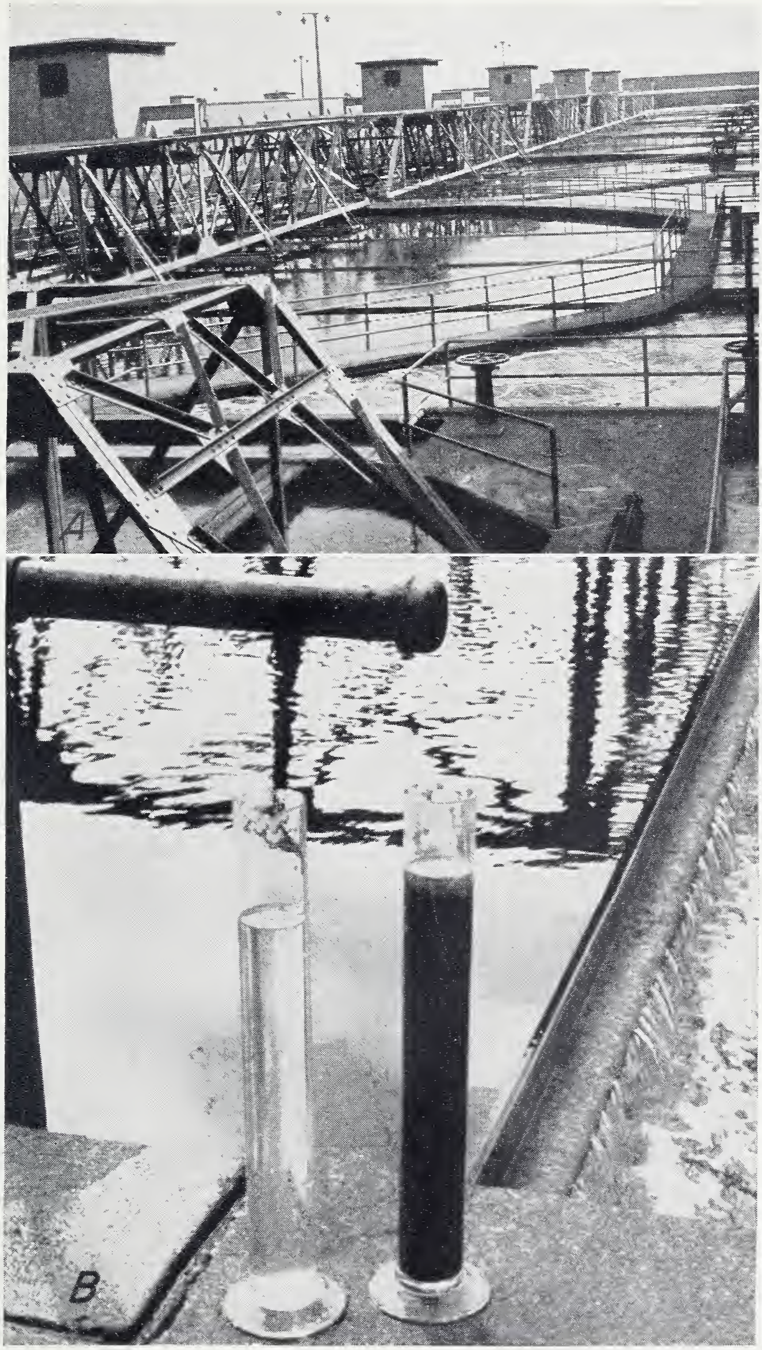

Figure 11.—The city of Milwaukee, Wis., processes its sewage by an activation system. *A*, Aeration occurs in a compartment at the right in the foreground. Settling takes place in the tanks on the left. *B*, Effectiveness of the activation process is shown by the clear supernatent liquid in the cylinder on the left as compared with sludge not activated in the cylinder on the right.

TABLE 1.—*Chemical composition of sewage sludges from different municipal plants (moisture-free basis)*[1]

DIGESTED SLUDGES, IMHOFF AND SEPARATE DIGESTION PLANTS

Municipality	Volatile matter	Nitrogen (N)	Phosphoric oxide (P_2O_5)
	Percent	*Percent*	*Percent*
San Diego, Calif	60	3. 0	1. 50
Greenwich, Conn	49	2. 38	----------
Grand Rapids, Mich	42	2. 80	2. 0
Middletown, N. Y	43	2. 4	. 81
Delphos, Ohio	33	1. 75	2. 0
Toledo, Ohio	48. 5	3. 0	2. 0
Racine, Wis	43. 2	2. 69	2. 32
ACTIVATED SLUDGE, DIGESTED OR LAGOONED			
Collingswood, N. J	60	4. 35	----------
Gary, Ind	48	1. 4	----------
Los Angeles, Calif	47	3. 0	3. 6
San Antonio, Tex	60	2. 8	1. 35
Springfield, Ill	35	2. 1	1. 06
ACTIVATED SLUDGE			
New York, N. Y. (Wards Island)	74	6. 4	3. 8
Milwaukee, Wis	78	6. 0	3. 3
Chicago, Ill. (Calumet, old)	61	4. 3	----------

[1] See citation (*12*).

TABLE 2.—*Plant nutrient contents of some Ohio sludges (moisture-free basis)*[1]

Source (city)	Total nitrogen (N)	Phosphoric oxide (P_2O_5)		Water-soluble potassium oxide (K_2O)
		Total	Available	
	Percent	*Percent*	*Percent*	*Percent*
Garfield	0. 88	1. 25	1. 05	----------
Barberton	1. 64	. 90	. 74	0. 45
Elyria	2. 98	3. 22	2. 10	. 08
Dayton	1. 96	1. 10	. 84	1. 60
Lakewood	1. 54	1. 61	1. 09	. 54
Wadsworth	2. 15	2. 00	----------	----------
Akron (first sample)	1. 64	. 68	. 42	. 45
Akron (second sample)	1. 48	1. 17	. 75	. 57
Kent	2. 20	1. 25	. 80	----------
Ashland (first sample)	1. 72	1. 18	. 76	. 05
Ashland (second sample)	. 89	. 91	. 70	. 30
Oxford	2. 14	1. 83	----------	. 25

[1] See citation (*7*).

material. Products from the Milwaukee disposal plant that are of high nitrogen content have been given considerable study. Both major and minor element contents have been considered. Rehling and Truog (*26*, *27*) determined the minor element contents of activated sludge from Milwaukee. Percentage contents of a few of the more important of these constituents were as follows: B_2O_3, 0.012; CuO, 0.043; MnO, 0.025; ZnO, 0.030. Niles (*23*) found somewhat higher minor element contents in digested sludge than those reported for the Milwaukee product.

Recent developments involving the use of individual garbage disposal units (*41*), citywide garbage disposal through a city sewage processing plant (*5*), and extensive use of synthetic detergents in urban areas sometimes increase the problems of sewage disposal. Possible change also in the composition of sludges may result from some of these modern disposal practices.

The inadequacy of present knowledge concerning the chemical character of the sludges made it desirable to collect for study some representative samples from different types of disposal plants located in various parts of the United States. A description of the sources of the various sludges, all produced in 1952, and the system by which each was produced are given below. These are the samples that have been analyzed for the present studies.

Kind of sludge and location of plant	*Remarks*
Activated sludges:	
Chicago, Ill	Heat-dried sludge from West-Southwest Works, Sanitary District of Chicago; sold to fertilizer companies.
Chicago, Ill	Heat-dried sludge from Calumet Plant; sold to fertilizer companies.
Houston, Tex	A part is prepared and sold commercially.
McKeesport, Pa	Sludge sold commercially.
Milwaukee, Wis	Milorganite; commercial product from a Washington, D. C., retail store.
Short period or fully activated sludges, subsequently digested:	
Des Moines, Iowa	Sludge from sand filters; material activated about 2 hours; at times much industrial material is in the sewage; a part of sludge is later applied to land.
Hagerstown, Md	Fully activated sludge from sand filter.
Hagerstown, Md	Dried residue of sewage sludge suspension from digesters; total solids approximately 2.7 percent.
Los Angeles, Calif	Partially activated sludge.
Digested sludges:	
Beltsville, Md	U. S. Department of Agriculture Research Center; anaerobic digestion; some laboratory and experimental plant products present in raw sludge, which is chlorinated on entrance.
Greenbelt, Md	Dried in glass houses.
Washington, D. C	Primary treatment only.
Imhoff tank sludges:	
Beltsville, Md	U. S. Department of Agriculture Plant Industry Station.
Rochester, N. Y	Widely used by apple growers of the area as a mulch; a substitute for farm manure.

Kind of sludge and location of plant	*Remarks*
Lagoon sludge:	
Indianapolis, Ind	Used to some extent by farmers and truck gardeners.
Industrial plant sludges:	
Luray, Va	Tannery waste.
Mercersburg, Pa	Tannery waste for disposal with sewage or for direct application to land.
Williamsport, Md	Sludge from leather goods manufacture.

Primary and Secondary Fertilizing Constituents

The chemical composition of various sewage and industrial sludges is given in table 3. In general the activated sewage sludges are more nearly uniform in composition and contain more nitrogen and phosphoric oxide than do the sludges produced by other treatment systems. The high phosphoric oxide contents of a number of the sludges from municipal plants may well be caused in part by soluble phosphates used as household cleaning agents. Although water-soluble when the product was used for cleaning, such constituents are absorbed by solid particles in suspension. The potash contents of sludges are low. This is to be expected, since the solids recovered have been suspended in large quantities of water, and potash associated with organic matter is normally water-soluble and therefore mostly in the effluent. The industrial plant sludges were found to be relatively low in nitrogen, phosphoric oxide, and potash contents.

Activated sludges tend to be more acid in reaction than those of the digested and industrial types. Perhaps one important factor is the inclusion of considerable quantities of ferric chloride as a flocculating agent in many of the plants producing activated materials. As the industrial sludges are of high lime content, pH values on the alkaline side are to be expected. In the case of the sample from Luray, Va., the very high pH value (11.6) indicates the probable presence of calcium hydroxide. The ash contents of activated sludges are usually lower than those of the digested materials. High quantities of ash mean low contents of organic matter.

The information at hand is not adequate to account for the high lime content of the one sample of lagooned sludge. The magnesium and sulfur contents of various sludges would seem to be of the expected order.

Minor Elements

Minor element contents of fertilizers are not usually included in a conventional analysis as made in the trade. Certain of these elements are occasionally included in mixed goods, however, and the percentage may be guaranteed. Of late, considerable importance has been attached to the place of minor elements in crop nutrition. The total quantities of several minor elements have been determined in the sludges considered here. These determinations include elements that are known to be essential for plant or animal growth and are usually present in plant tissues in detectable quantities. The quantities of certain of these elements found in soil are frequently less than are found in sludge (*19*). Data given in table 4 are calculated on two bases: (1) As the chemical element; and (2) as pounds per ton of a compound containing the element in a conventional form.

According to the data presented in table 4, a ton of digested sludge of average minor element content (average, 9 samples) would supply

TABLE 3.—*Chemical composition of certain sewage and industrial sludges, analyses on moisture-free basis*

Kind of sludge and location of plant	Primary fertilizing constituents			Acid-soluble secondary constituents				Ash	Reaction (pH)
	Nitrogen (N) total	Phosphoric oxide (P_2O_5) total	Potassium oxide (K_2O) acid soluble	Calcium oxide (CaO)	Magnesium oxide (MgO)	Sulfur (S)	Iron oxide (Fe_2O_3)		
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	
Activated sludges:									
Chicago, Ill	4. 81	6. 86	0. 30	1. 63	0. 82	0. 76	13. 87	39. 22	4. 6
Chicago, Ill	5. 60	6. 97	. 56	2. 22	1. 03	1. 14	7. 41	37. 39	5. 3
Houston, Tex	5. 77	3. 08	. 30	1. 26	. 50	1. 06	4. 36	30. 18	4. 5
McKeesport, Pa	5. 68	7. 38	. 61	2. 52	1. 43	. 98	7. 09	37. 93	5. 5
Milwaukee, Wis	5. 96	3. 96	. 41	1. 64	. 93	. 95	7. 13	27. 73	5. 0
Short period, or fully activated sludges, subsequently digested:									
Des Moines, Iowa	1. 81	3. 31	. 40	7. 37	1. 05	1. 10	3. 42	61. 44	7. 0
Hagerstown, Md	3. 13	2. 81	. 10	4. 68	. 86	. 96	2. 34	47. 06	5. 9
Hagerstown, Md	4. 71	4. 96	. 74	5. 07	1. 45	1. 00	1. 75	33. 34	6. 5
Los Angeles, Calif	2. 49	4. 07	. 21	3. 92	. 78	1. 00	6. 04	49. 11	6. 1
Digested sludges, primary treatment:									
Beltsville, Md	1. 89	1. 64	. 19	2. 22	1. 01	1. 17	3. 37	56. 22	5. 6
Greenbelt, Md	3. 12	. 91	. 24	1. 91	. 28	. 61	1. 53	38. 22	5. 5
Washington, D. C	2. 06	1. 44	. 14	2. 38	. 60	. 89	4. 44	52. 83	6. 0
Imhoff tank sludges:									
Beltsville, Md	. 97	. 56	. 18	. 69	. 44	. 33	2. 18	74. 28	6. 0
Rochester, N. Y	2. 54	1. 16	. 29	2. 14	. 87	. 91	3. 15	42. 79	5. 4
Lagoon sludge:									
Indianapolis, Ind	1. 71	4. 32	. 28	15. 69	1. 66	1. 50	4. 62	58. 56	7. 2
Industrial plant sludges:									
Luray, Va	1. 22	. 42	. 09	37. 98	1. 57	. 79	. 40	51. 27	11. 6
Mercersburg, Pa	2. 64	. 87	. 17	12. 96	1. 24	. 93	1. 33	38. 87	7. 2
Williamsport, Md	1. 45	. 50	. 18	18. 87	. 68	. 58	2. 13	55. 69	7. 6

TABLE 4.—*Minor element contents of sewage sludges calculated as parts per million and as pounds per ton of suitable compounds in dry sludge*

Kind of sludge and location of plant	Copper (Cu)	Equivalent copper sulfate ($CuSO_4 \cdot 5H_2O$) per ton	Zinc (Zn)	Equivalent zinc sulfate ($ZnSO_4$) per ton	Boron (B)	Equivalent borax ($Na_2B_4O_7 \cdot 10H_2O$) per ton	Manganese (Mn)	Equivalent manganese sulfate ($MnSO_4 \cdot 4H_2O$) per ton	Molybdenum (Mo)	Equivalent sodium molybdate ($Na_2MoO_4 \cdot 2H_2O$) per ton
Activated sludges:	*P.p.m.*	*Lb.*	*P.p.m.*	*Lb.*	*P.p.m.*	*Lb.*	*P.p.m.*	*Lb.*	*P.p.m.*	*Lb.*
Chicago, Ill	385	3. 0	3, 300	16. 3	6	0. 10	190	1. 54	45. 4	0. 23
Chicago, Ill	1, 225	9. 6	3, 050	15. 1	67	1. 18	135	1. 10	6. 5	. 03
Houston, Tex	1, 035	8. 1	950	4. 7	8	. 14	65	. 53	6. 7	. 03
McKeesport, Pa	1, 500	11. 8	3, 650	18. 0	74	1. 30	150	1. 22	6. 0	. 03
Milwaukee, Wis	435	3. 4	1, 550	7. 7	8	. 14	130	1. 06	13. 5	. 07
Short period, or fully activated sludges, subsequently digested:										
Des Moines, Iowa	315	2. 5	1, 350	6. 7	7	. 12	420	3. 41	4. 9	. 02
Hagerstown, Md	490	3. 9	3, 050	15. 1	7	. 12	70	. 57	3. 7	. 02
Hagerstown, Md	435	3. 4	3, 100	15. 3	12	. 21	60	. 49	4. 2	. 02
Los Angeles, Calif	1, 440	11. 3	3, 700	18. 3	15	. 26	265	2. 15	12. 0	. 06
Digested sludges, primary treatment:										
Beltsville, Md	480	3. 8	2, 050	10. 3	4	. 07	790	6. 41	6. 8	. 03
Greenbelt, Md	360	2. 8	1, 450	7. 2	8	. 14	120	. 97	2. 1	. 01
Washington, D. C	435	3. 4	2, 200	10. 9	8	. 14	140	1. 14	5. 4	. 03
Imhoff tank sludges:										
Beltsville, Md	100	. 8	610	3. 0	3	. 05	130	1. 06	118. 0	. 60
Rochester, N. Y	1, 980	15. 6	3, 400	16. 8	12	. 21	60	. 49	5. 1	. 03
Lagoon sludge:										
Indianapolis, Ind	755	5. 9	2, 750	13. 6	7	. 12	440	3. 57	9. 6	. 05
Industrial plant sludges:										
Luray, Va	90	. 7	75	. 4	74	1. 30	145	1. 18	. 4	. 002
Mercersburg, Pa	200	1. 6	220	1. 1	271	4. 78	260	2. 11	23. 6	. 12
Williamsport, Md	130	1. 0	260	1. 3	100	1. 76	760	6. 17	7. 2	. 04

the equivalent of 0.15 pound borax, 5.3 pounds copper sulfate crystals, 11.5 pounds zinc sulfate, 1.9 pounds manganese sulfate, and 0.09 pound sodium molybdate. Corresponding quantities of the five constituents in activated sludges are: Borax 0.57, copper sulfate 7.2, zinc sulfate 12.4, manganese sulfate 1.1, and sodium molybdate 0.08 pounds. In most cases it is not clear why the contents of different minor elements should vary so widely from place to place and why some of the values for contents of certain heavy metals are so high.

The sludge of the Imhoff tank at Beltsville no doubt reflects the influence of large quantities of molybdate residues from laboratory determinations of phosphorus discharged through the sewer. Several of the city disposal plants probably receive industrial wastes containing varying quantities of compounds of heavy metals. Such waste materials probably are responsible for the large and varying values found.

Zinc may be dissolved from certain galvanized metals, and copper from pipes that are commonly used in water systems. These materials in solution are quickly sorbed by solid particles to form essentially water-insoluble materials.

The boron present in municipal sludges varies widely from place to place, but at a low level comparable to the level in plants. Little is known, however, regarding the availabilities of the minor elements in sludges to growing plants or levels necessary to produce toxicity.

Comparison of Sludge With Farm Manure

The chemical composition of farm manure varies widely, depending upon kinds of animals kept, feed consumed, bedding incorporated, and methods of handling or storing (*4*). The average composition of damp stall manure with bedding included is approximately 0.50 percent nitrogen, 0.25 percent phosphoric oxide, and 0.50 percent potash. Digested sludges from a vacuum filter often contain about 65 percent water. The nitrogen and phosphoric oxide contents of such material approximate the values found in stall manure, while potassium is lower. Heck (*17*) and others (*21, 30*) have shown that the nitrogen of manure becomes available to plants much more slowly than that of ordinary chemical forms. The rates of nitrification and also the rates of availability to plants of the nitrogen in manure are somewhat similar to these properties of digested sludge. The two classes of materials differ widely, however, in various features of chemical composition.

Comparisons of the chemical composition of cottonseed meal and different classes of animal manures and sewage sludges are shown in table 5.

TABLE 5.—*Comparisons of the chemical composition of cottonseed meal, animal manures, and sewage sludges (moisture-free basis)*

Material	Nitrogen (N)	Phosphoric oxide (P_2O_5)	Potassium oxide (K_2O)
	Percent	*Percent*	*Percent*
Cottonseed meal	7. 0	2. 5	1. 5
Chicken manure	4. 1	3. 7	2. 3
Average farm manure	1. 2	. 6	1. 2
Average activated sludges	5. 6	5. 6	. 4
Average digested sludges	2. 0	1. 1	. 2

Economic Considerations

Quantities Involved

What are the fertilizer potentialities of sewage sludges in the United States? This question might be approached from several viewpoints—no one of these viewpoints furnishing definite information. The plant nutrients present in sewage sludges vary in their effectiveness to stimulate plant growth. Some of these materials applied to certain soils under certain climatic conditions may be as effective as chemical fertilizers of like total plant nutrient content. Frequently, however, they may be much less effective. However, an estimate of the primary nutrients available to agriculture through sludges of the United States gives some idea of the potentialities of such materials. The population of the United States is approximately 160 million: 60 percent live in cities of 2,500 or more (*37*), and many smaller towns deliver raw sewage to nearby city systems for disposal. Nearly all of the municipalities of 2,500 or more inhabitants have sewage disposal plants, but the effectiveness in producing sludge is highly variable.

Food eaten by the total population is reported to be about 1.7 pounds of dry matter daily per person (*38, tables 824, 825*). The nitrogen content of the dry matter is estimated at about 3.4 percent. The phosphoric oxide content is less definitely known, probably about 1.2 percent P_2O_5; and the potassium oxide, as K_2O, about 0.9 percent (*13*).

Varying percentages of the total quantities of nitrogen received from orignial food sources and from industrial wastes are recoverable in sludge, much depending upon the system of disposal used (*6*). The phosphoric oxide recovered in sludge may be even greater than the contents of this element consumed in foods. This is because of contributions from cleaning materials, ground bones, and materials from industrial sources. The potassium oxide of organic matter is essentially water-soluble.

Since many of the disposal systems of the United States are of the primary type with digesters, a brief review is listed below of pertinent data from the 1954 report of the Washington, D. C., disposal system.

Materials from city disposal systems:		*Total*
Raw sewerage (annual)	billion gallons	58
Volatile solids (annual)	tons	16, 900
Dry solids in recovered filter cake (annual)	do	7, 420
Suspended solids removed (annual)	percent	55. 6
Reduction of biochemical oxygen demand (B. O. D. average)	do	31. 0
Sludge gas per day	cubic feet	745, 000
Calorific value per cubic foot	net B. t. u.	590
Cost of operation per day	dollars	1, 000
Financial returns from sludge cake, moist condition, taken by users	do	0

If the data given above are projected to a national basis for city dwellers, about a million tons of dry digested sludge annually are indicated. If the composition of the whole is somewhat similar to that given in tables 3 and 4 for a Washington product, it would be equivalent to about 20,000 tons of total nitrogen. The phosphoric oxide resource is indicated as about 15,000 tons, and potash only about 2,000 tons. It is not practical to place a money value on plant nutrients in the form of sludge because they may be more or may be less effective than chemical forms, depending upon soil conditions and plants grown. If all disposal systems were of the activated type, the quantities of nitrogen and phosphoric oxide recovered would be expected to be much larger and the quality of the nitrogen better; the cost of recovery probably would be greater also.

Marketability of Sludges

Activated sludges are frequently marketed directly through jobbers and retailers. In other cases the sludges are sold to companies preparing mixed fertilizers. Other methods of marketing for certain sludge products are sometimes available. At Hagerstown, Md., a city of nearly 40,000 inhabitants, much of the sewage sludge in suspension from the digesters is delivered to farmers within a radius of 10 miles. The charge is $1 to $2 per tank truckload of 1,200 gallons. The price varies with distance from the plant. This material is usually added to land growing pasture or alfalfa. The rate of application is about 7,000 gallons per acre. The sludge that is not deliverable in suspended form because of weather and soil conditions is allowed to flow on to sand-gravel beds for dewatering. The dried product is then sold to farmers at a low price, varying somewhat with seasonal demand.

Fully activated, heat-treated sludge commands a good price in many markets. The price per pound of nitrogen usually lies between that of this constituent in cottonseed meal and that of chemical nitrogen such as ammonium sulfate, both of which are used as fertilizers. The use of most kinds of seed meals as animal feeds enhances their worth. At the same time, properly treated activated sludges are in demand for use on lawns and golf courses. These materials do not readily burn the vegetation and they serve as good quality nitrogen for plant growth.

The price that a user is willing to pay for sludge depends upon several factors, such as method of preparation of the product, type of raw materials entering the system, location with respect to place of application to soil, and kinds of crops or plants to be grown.

In order to provide some idea of the prices paid in retail stores for different forms of nitrogen, quotations from garden supply stores in the Washington, D. C., area have been compiled. For instance, the prices given in table 6 are for 100-pound lots delivered to homes.

TABLE 6.—*Approximate prices of certain organic nitrogenous materials and chemical nitrogen materials in stores of the Washington, D. C., area, 100-pound lots, 1954*

Material	Approximate analysis ($N-P_2O_5-K_2O$)	Price per 100 pounds of material	Price per pound [1] of nitrogen
		Dollars	*Dollars*
Cottonseed meal	7–2.5–1.5	5.75	0.76
Sludge from Milwaukee	5.4–2–0	3.90	.68
Ammonium sulfate	21–0–0	4.30	.205
Ammonium nitrate	33.5–0–0	5.85	.175

[1] Adjustments were made for the retail value of the P_2O_5 and K_2O in the material.

It is apparent that certain users are willing to pay a substantial premium for nitrogen in the form of good-quality sludge compared to that in chemical forms. The major use is for turf and certain other specialty purposes and not for production of most kinds of crops sold on a competitive basis. It is problematical how much greater tonnage of these sewage products could be marketed without a substantial drop in price.

The economics of production of high-grade sludge are intimately associated with the necessity for discharging good-quality water into natural waterways. No one would consider the preparation of commercial sludge aside from its value as a byproduct, even though the demand for conservation of our natural resources is strong. Certain disposal plants, however, are able to make economical recovery of the materials (*1*). This does not mean that such plants operate at a net profit. The cost to taxpayers may be high.

Digested sludges normally command only a low price, if any. The value is dependent essentially upon the proximity of the disposal plant to certain types of agricultural land. No charge is made to users who remove the materials from the plant at Washington, D. C.

If digested sludges are intended for garden or lawn use, heat-treatment or long-time storage is probably necessary in order to eliminate disagreeable odors and to render the material satisfactory from a sanitary standpoint. Sludges of this class are assumed to be of some value as soil conditioners in addition to serving as very low-analysis fertilizers. They are to some extent in competition with certain other organics of low value at point of origin. Table 7 lists a few of these materials.

TABLE 7.—*Prices of low-analysis nitrogenous organics and natural soil conditioners: Retail quotations 100-pound lots, Washington, D. C., 1953*

Material	Approximate fertilizer grade ($N-P_2O_5-K_2O$)	Price per 100 pounds of material	Price per pound of nitrogen [1]
		Dollars	*Dollars*
Cow manure	2–1–1	5. 25	2. 53
Sheep manure	2–1–1	5. 25	2. 53
Farm manure (poultry and sheep manure and peat).	2–1–1	5. 00	2. 53
Michigan peat	2–0–0	4. 50	2. 25
Cultivated peat, New Jersey (moist, often about 50 percent water).	1.3–0–0	2. 50	1. 92

[1] Adjustments were made for the retail value of the P_2O_5 and K_2O in the material.

Consideration has frequently been given to the economics of sewage sludge used as a fertilizer (*3*, *14*). The conclusions are not definite, however.

Digested sludges are of some value as soil conditioners, but this factor has not been well evaluated. The various sludges appear to have their greatest value when used in conjunction with chemical fertilizers of suitable grade.

Agronomic Evaluations

Data relating to the quality of nitrogen in organic ammoniates include (1) permanganate activities, (2) biochemical tests such as those from nitrification studies, (3) growth of selected plants in a greenhouse, and (4) field experiments or observations. Only the biochemical nitrification tests were made in the present evaluation. Other types of data have been obtained at different times and in different places.

Rubins and Bear (*30*) and Clark and Bear (*8*) used three types of evaluation of the usefulness of different sources of insoluble organic nitrogen. They compared results by the permanganate chemical methods, rates of nitrification, and vegetative tests. Their results for two types of sewage sludge, cow manure, and cottonseed meal are given in table 8. Results by these various methods are not in close agreement, but each provides relative values of some use in comparing the availabilities of nitrogen in compounds of organic materials.

TABLE 8.—*Comparison of the nitrogen activity of various organic materials as determined by several methods* [1]

Material	Permanganate activity [2]		Vegetative test (Sudan grass)[3]	Nitrification of added nitrogen (20 days)
	Alkaline method	Neutral method		
	Percent	*Percent*	*Percent*	*Percent*
Cottonseed meal	66.9	82.7	53.6	50
Milorganite	63.4	75.2	50.5	44
Sewage sludge (digested)	51.1	65.4	8.4	8
Cow manure (Bovung)	27.9	47.1	−15.6	−10

[1] See citations (*8*) and (*30*).
[2] Activity of the water-insoluble nitrogen.
[3] Added nitrogen recovered in tops and roots.

Crop Response Studies

Field and greenhouse experiments with sewage sludge as a fertilizer have been conducted in several States. Research in Texas led Fraps (*15*) to conclude that partly dried digested sludge should be handled in about the same manner as farm manure. It may be applied broadcast at the rate of 10 to 40 tons per acre, and then turned under or harrowed in before the crop is planted. It should not be applied to soil during the cultivation period of row crops. Reynolds (*28*), also in Texas, used activated sludge of 4.6 percent nitrogen for growing cotton and corn. The rates of application were 500 to 2,000 pounds per acre. Sludge applied at the rate of 1,000 pounds per acre increased the yields of lint cotton 37 to 47 pounds per acre. With the same rate of application corn yields were increased 13.9 percent, but the actual yield was small on this land of low productivity. No comparisons were made with chemical nitrogen, but the application of 200 pounds of superphosphate per acre with 1,000 pounds of sludge increased crop yields moderately over those with sludge alone.

Digested sludge from Baltimore, Md., was used alone and in combination with various commercial fertilizers in a series of field experiments, 1923–27 (*22*). Potatoes, sweet corn, and cabbage gave greatest response to sludge treatment, and spinach and tomatoes least. The rate of application was 20 tons of dry sludge or 40 tons of the wet material. The authors (*22*) felt that conclusions regarding the extent of benefits from sludge must be made with caution.

In Wisconsin (*34*) activated sludge was used for field and greenhouse trials with various crops. Applications of 500 to 1,000 pounds per acre increased greatly the yields of most crops. In one Milwaukee greenhouse the number of rose blooms showed an increase of 636 blooms per 1,000 square feet over those of an untreated plot.

Rehling and Truog (*26, 27*) used a carbonated-water extract of Milwaukee sludge as a medium for growing several kinds of crop plants in nutrient solution. The authors concluded that this sludge used as a constituent of mixed fertilizer may serve as a source of minor elements for plant growth.

Noer (*24, 25*), also of Wisconsin, obtained excellent field results from use of activated sludge in conjunction with commercial fertilizers of suitable phosphorus and potassium contents. The crops grown were cabbage, tomatoes, corn, and potatoes.

Barnes of Ohio (*7*) conducted greenhouse tests for an 8-month period with digested sludge, growing barley and Sudan grass. The treated pots received the equivalent of 45.8 pounds of P_2O_5, 66.7 pounds of K_2O, and from 16 to 81.7 pounds per acre of N. The average yield with sewage sludge was 17.9 percent greater than the yield with no fertilizer. The total yield of the series on which the same quantities of chemical nitrogen, phosphoric oxide, and potash were used as were present in the sludge was about 56 percent greater than that from unfertilized pots, and 33 percent greater than the total yield from sludge-treated pots.

The experiments cited here are only a part of the large number of plant-growth tests that have been made with sewage material as fertilizers or soil amendments (*3*). A general opinion often expressed in reports by those who have used sludge is that the digested materials are of some value for soil improvement but are definitely inferior to activated products (*9, 15, 20, 24, 29, 34, 39*).

Nitrification Characteristics of Sludges

Rate of conversion of nitrogenous compounds to nitrates in soil is widely recognized as a factor indicative of their usefulness to growing crops. Nitrification studies have been conducted recently in the laboratory at the Plant Industry Station, Beltsville, Md., by a standardized procedure in which a 20-mg. nitrogen equivalent of a sample is admixed with 100 gm. Morgnec silt loam soil and the mixture covered with 10 gm. soil. Before use, the pH of the soil is adjusted to the range 6.9 to 7.1 by addition of calcium carbonate. The moisture content of the soil-sample mixture is adjusted to the moisture equivalent of the soil, and the mixture is then incubated at 30° C. for the desired period with a periodic replacement of any water lost by evaporation. At the end of the incubation, the nitrate content of the mixture is extracted and determined photometrically by the phenoldisulfonic acid procedure. The nitrate found is corrected for the nitrate found in a soil blank, and the results are expressed in terms of the percentage of nitrogen content of the sludge that has been converted to the nitrate form. It is recognized that the organic materials must undergo ammonification before the nitrification step can take place. Slow action in the first step may delay nitrification.

The average nitrification data obtained from triplicate determinations for incubation periods of 4, 8, 12, and 16 weeks are given in table 9. The observed nitrifications of ammonium sulfate conducted under the same conditions and at the same time are included for comparison. The observed degree of nitrification of the sludge samples is very much less than that of ammonium sulfate for all incubation periods. Except for the activated sludges and one of the partially activated and digested sludges, less than 20 to 25 percent of the nitrogen of the sludge was converted to nitrate form in 16 weeks under substantially optimum conditions for nitrification. The nitrification patterns exhibited by activated sludges are in good agreement with generally observed patterns for other natural organic materials, such as processed tankage and seed meals.

TABLE 9.—*Nitrification characteristics of certain sewage and industrial sludges and ammonium sulfate*

Materials and sources	Total nitrogen (N) content, moisture-free basis	Portion of nitrogen converted to nitrate at 30° C. in—			
		4 weeks	8 weeks	12 weeks	16 weeks
	Percent	*Percent*	*Percent*	*Percent*	*Percent*
Activated sludges:					
Chicago, Ill	4.81	42.1	47.7	50.7	52.8
Chicago, Ill	5.60	48.8	54.8	57.1	57.4
Houston, Tex	5.77	51.1	56.7	58.7	57.6
McKeesport, Pa	5.68	51.7	54.4	57.8	56.0
Milwaukee, Wis	5.96	49.9	53.8	57.0	54.8
Short period or partially activated sludges, subsequently digested:					
Des Moines, Iowa	1.81	16.9	19.2	21.2	21.9
Hagerstown, Md	3.13	17.8	20.3	23.5	20.5
Hagerstown, Md	4.71	34.5	38.3	42.4	39.6
Los Angeles, Calif	2.49	14.0	17.8	20.8	20.9
Digested sludges:					
Beltsville, Md	1.89	17.5	21.5	22.1	22.4
Greenbelt, Md	3.12	9.5	14.3	20.4	18.9
Washington, D. C	2.06	14.2	18.5	18.4	19.0
Imhoff tank sludges:					
Beltsville, Md	.97	9.0	11.7	12.3	17.0
Rochester, N. Y	2.54	15.4	20.2	23.3	24.8
Lagoon sludge:					
Indianapolis, Ind	1.71	15.4	14.7	16.2	15.1
Industrial plant sludges:					
Luray, Va	1.22	−1.5	8.7	13.6	14.6
Mercersburg, Pa	2.64	1.9	3.0	5.0	3.2
Williamsport, Md	1.45	3.9	3.7	5.2	5.5
Ammonium sulfate	20.5	89.3	92.0	90.0	90.3

Sanitary Status

Many conflicting reports have been made regarding the sanitary status of digested sludges. This is not surprising in view of the varied factors involved from the time raw sewage is contributed to the system until the sludge is finally used for soil improvement (*33*, *35*). For example, numbers of pathogenic organisms present in raw sewage are sometimes greatly influenced by the numbers of persons in a community afflicted with certain communicable diseases and those who are carriers of a disease. Moreover, these organisms vary greatly in longevity after they enter a disposal system.

Insofar as digested sludges are concerned, it is apparent that all life is not destroyed in the disposal process. It is a very common sight to see tomato plants and weeds growing in a bed of dry sludge. This indicates that the more resistant life survives. The 10 to 14 days of anaerobic microbiological action effected in the digestion chambers produce drastic changes in the biology of the sewage solids, but destruction of pathogenic organisms is not necessarily achieved. Studies on the fate of the bacteria causing typhoid fever (*8*) gave highly variable results but indicated that the organism is more readily destroyed than the tubercle bacillus, which has a waxy protective outer surface. Examinations of the longevity of disease-producing unicellular protozoa (*3*, *11*, *18*, *36*, *40*) also gave variable results and produced conflicting interpretations.

Widely differing opinions prevail regarding the biological safety of digested solids for general garden use as a fertilizer. Drying subsequent to digestion further reduces the numbers of organisms of types originally present in digested sludge. Incorporation with soil provides another set of conditions usually unfavorable for organisms that thrive in the human body.

Carefully conducted tests of the sanitary condition of sludge from a particular system may show differences in biological status from time to time. This means that definite answers to questions regarding features of sludge are difficult to supply.

Activated sludges need heat-treatment before use as fertilizer. Such treatment is normally provided for material to be marketed. The heat used for drying normally accomplishes the destruction of dangerous organisms. This means that properly heat-dried activated sludges may be used with confidence regarding their safety from a sanitary standpoint.

A poll of health departments of the 48 States shows that only 6 have issued regulations regarding application of sewage sludge, raw sewage, or effluents for use with growing horticultural crops. These 6 States are Arizona, Arkansas, California, Connecticut, Mississippi, and Oregon. Certain States recommend that sludge be used only as an application to soil before crops are planted. It seems that States have generally accepted the conclusions of the Committee on Sewage Disposal of the American Public Health Association (*3*) that heat-dried activated sludges are satisfactory from a sanitary standpoint, and that digested sludges are satisfactory except where vegetables are grown to be eaten raw. All danger is thought to be removed by action in the soil after a period of about 3 months during a growing season.

Summary

Two widely differing general types of sewage-disposal systems are commonly used. These are (1) primary treatment with anaerobic digestion and (2) systems activated by injection of air. Digested sludge is usually of relatively low quality as a fertilizer compared with products from an activation system.

Dried activated sludge properly heat-treated normally commands a good price in fertilizer markets. Digested sludges, on the other hand, are often obtainable without cost or at a low price.

Determinations have been made of the chemical compositions of sludges variously prepared in different parts of the United States. The analyses include primary and secondary fertilizing constituents and several minor elements.

The nitrogen contents of activated sludges are normally much higher than those found in digested products. The phosphorus contents of sludges vary widely, presumably dependent upon local conditions. Potassium is always low. The secondary elements—calcium, magnesium, and sulfur—in the quantities present probably are of little importance from a fertilizer standpoint. Several of the minor elements are present in quantities usually much higher than are frequently found in soils. The fertilizer importance of the minor elements present in sludges collected has not been determined. It is presumable that certain soil deficiencies might be corrected by adequate applications of sludges known to contain minor elements.

Laboratory tests of the various sludges show that only 18 to 25 percent of the nitrogen present in digested sludges is normally nitrified during a period of 16 weeks. The activated sludges, on the other hand, show nitrification values ranging from 50 to 60 percent in this period.

Activated sludges are widely used as fertilizers for lawns and golf courses. Digested sludges are used as mulches around certain kinds of plants not requiring acid conditions. They are also spaded into flower and vegetable gardens.

Heat-treated sludges are normally safe for use from a sanitary standpoint. Digested sludges, not heat-treated, should be used with some caution. One way this is accomplished is by incorporation with soil several months before vegetables to be eaten raw are grown. The health departments of several of the States have issued regulations specifying the conditions under which unheated sludges may be used as garden fertilizers.

Literature Cited

(1) ALLEN, W. A.
1938. CONDITIONING AND SALE OF SLUDGE FOR FERTILIZER. Sewage Works Jour. 10: 945–948.

(2) AMERICAN PUBLIC HEALTH ASSOCIATION COMMITTEE ON SEWAGE DISPOSAL.
1935. CHEMICAL TREATMENT OF SEWAGE. Sewage Works Jour. 7: 997–1108.

(3) ———
1937. UTILIZATION OF SEWAGE SLUDGE AS FERTILIZER. Sewage Works Jour. 9: 861–912.

(4) AMES, J. W., and GAITHER, E. W.
1912. BARNYARD MANURE. PRODUCTION, COMPOSITION, CONSERVATION, REENFORCEMENT, AND VALUE. Ohio Agr. Expt. Sta. Bul. 246, pp. 725–753.

(5) BABBITT, H. E.
1935. THE POSSIBILITIES OF THE DIGESTION OF GARBAGE IN A SEWAGE TREATMENT PLANT. Sewage Works Jour. 7: 658–662.
(6) ———
[1953.] SEWERAGE AND SEWAGE TREATMENT. Ed. 7, 674 pp., illus. New York and London.
(7) BARNES, E. E.
1941. FERTILIZING VALUE OF GARBAGE TANKAGE AND SEWAGE SLUDGE. Ohio Agr. Expt. Sta. Bimonthly Bul. 26: 39–44.
(8) CLARK, K. G., and BEAR, F. E.
1948. USE OF NATURAL ORGANICS IN MIXED FERTILIZERS. Amer. Fert. 108 (3): [7]–10, 24, 26, 28, 30, illus.
(9) DETURK, E. E.
1935. ADAPTABILITY OF SEWAGE SLUDGE AS A FERTILIZER. Sewage Works Jour. 7: 597–610.
(10) FAIR, G. M., GEYER, J. C., and MORRIS, J. C.
[1954.] WATER SUPPLY AND WASTE-WATER DISPOSAL. 973 pp., illus. New York and London.
(11) FEDERATION OF SEWAGE WORKS ASSOCIATIONS.
1938. MODERN SEWAGE DISPOSAL. Ed. by L. Pearse. 371 pp., illus. [New York.]
(12) ———
1946. UTILIZATION OF SEWAGE SLUDGE AS FERTILIZER. Fed. Sewage Works Assocs. Manual of Pract. 2. 120 pp. Champaign, Ill.
(13) FORBES, E. B., BEEGLE, F. M., and MENSCHING, J. E.
1913. MINERAL AND ORGANIC ANALYSES OF FOODS. Ohio Agr. Expt. Sta. Bul. 255, pp. 211–231.
(14) FOSTER, W. S.
1950. SEWAGE SLUDGE—ITS INCOME POTENTIAL. Amer. City 65 (12): 87–89, 184, illus.
(15) FRAPS, G. S.
1932. THE COMPOSITION AND FERTILIZING VALUE OF SEWAGE SLUDGE. Tex. Agr. Expt. Sta. Bul. 445, 23 pp.
(16) GAINEY, P. L., and LORD, T. H.
[1950.] AN INTRODUCTION TO THE MICROBIOLOGY OF WATER AND SEWAGE FOR ENGINEERING STUDENTS. [2d] rev. ed. 319 pp., illus. Minneapolis. [Processed.]
(17) HECK, A. F.
1931. THE AVAILABILITY OF THE NITROGEN IN FARM MANURE UNDER FIELD CONDITIONS. Soil Sci. 31: 467–481, illus.
(18) HEUKELEKIAN, H., and SCHULHOFF, H. B.
1935. STUDIES ON THE SURVIVAL OF B. TYPHOSUS IN SURFACE WATERS AND SEWAGE. N. J. Agr. Expt. Sta. Bul. 589, 32 pp., illus.
(19) HOLMES, R. S.
1943. COPPER AND ZINC CONTENTS OF CERTAIN UNITED STATES SOILS. Soil Sci. 56: 359–370.
(20) IMHOFF, K., FAIR, G. M., and MOORE, E. W.
1940. SEWAGE TREATMENT. 370 pp., illus. New York and London.
(21) JENSEN, H. L.
1931. THE MICROBIOLOGY OF FARMYARD MANURE DECOMPOSITION IN SOIL. I. CHANGES IN THE MICROFLORA, AND THEIR RELATION TO NITRIFICATION. Jour. Agr. Sci. [England] 21: [38]–80, illus.
(22) KEEFER, C. E., and ARMELING, G. K.
1928. FERTILIZING VALUE OF BALTIMORE SEWAGE SLUDGE. Engin. News-Rec. 101: 837–840, illus.
(23) NILES, A. H.
1944. SEWAGE SLUDGE AS A FERTILIZER. Sewage Works Jour. 16: 720–728.
(24) NOER, O. J.
1925. ACTIVATED SLUDGE: A NEW SOURCE OF ORGANIC NITROGEN. Amer. Fert. 62 (12): 24–27, illus.
(25) ———
1926. ACTIVATED SLUDGE: ITS PRODUCTION, COMPOSITION, AND VALUE AS A FERTILIZER. Amer. Soc. Agron. Jour. 18: 953–962.
(26) REHLING, C. J., and TRUOG, E.
1939. ACTIVATED SLUDGE—MILORGANITE. CONSTITUENTS, ELEMENTS, AND GROWTH-PRODUCING SUBSTANCES. Indus. and Engin. Chem., Analyt. Ed., 11: 281–283.

(27) REHLING, C. J., and TRUOG, E.
1940. "MILORGANITE" AS A SOURCE OF MINOR NUTRIENT ELEMENTS FOR PLANTS. Amer. Soc. Agron. Jour. 32: 894–906, illus.
(28) REYNOLDS, E. B.
1930. ACTIVATED SLUDGE AS A FERTILIZER FOR COTTON AND CORN. Amer. Soc. Agron. Jour. 22: 537–539.
(29) ROST, C. O.
1950. THE MANURIAL VALUE OF SEWAGE SLUDGE. Minn. Univ. Soil Ser., No. 33, 7 pp. [Processed.]
(30) RUBINS, E. J., and BEAR, F. E.
1942. CARBON-NITROGEN RATIOS IN ORGANIC FERTILIZER MATERIALS IN RELATION TO THE AVAILABILITY OF THEIR NITROGEN. Soil Sci. 54: 411–423.
(31) RUDOLFS, W.
1928. SEWAGE SLUDGE AS FERTILIZER. Soil Sci. 26: 455–458.
(32) ———
1930. ANNUAL REPORT OF THE DEPARTMENT OF SEWAGE DISPOSAL FOR THE YEAR ENDING JUNE 30, 1929. N. J. Agr. Expt. Sta. Bul. 502, 40 pp., illus.
(33) ——— and GEHM, H. W.
1942. CHEMICAL COMPOSITION OF SEWAGE SLUDGES, WITH PARTICULAR REFERENCE TO THEIR PHOSPHORIC ACID CONTENTS. N. J. Agr. Expt. Sta. Bul. 699, 15 pp.
(34) RUSSELL, H. L., MORRISON, F. B., and EBLING, W. H.
1926. FERTILIZER VALUE OF ACTIVATED SLUDGE. Wis. Agr. Expt. Sta. Bul. (Ann. Rpt. 1924–26) 388, pp. 50–52, illus.
(35) SMIT, J.
1948. MICROBIOLOGY OF DRINKING WATER AND SEWAGE. *In* Ann. Rev. Microbiol. 2: 435–452. Stanford, Calif.
(36) TANNER, F. W.
1935. PUBLIC HEALTH SIGNIFICANCE OF SEWAGE SLUDGE WHEN USED AS A FERTILIZER. Sewage Works Jour. 7: 611–617.
(37) UNITED STATES BUREAU OF THE CENSUS.
1952. [U. S.] CENSUS OF POPULATION: 1950. VOLUME 1, NUMBER OF INHABITANTS. Sections by State, Territory, etc.; illus. Washington.
(38) UNITED STATES DEPARTMENT OF AGRICULTURE.
[1954.] AGRICULTURAL STATISTICS 1953. 777 pp. Washington.
(39) WEAVER, B. L., and SOMERS, L. A.
1942. AN ILLINOIS GARDEN GUIDE. Ill. Agr. Col. Ext. Cir. 522, 31 pp. illus.
(40) WOLMAN, A
1924. HYGIENIC ASPECTS OF USE OF SEWAGE SLUDGE AS FERTILIZER. Engin. News-Rec. 92: 198–202.
(41) WRAIGHT, F. D.
1954. PROS AND CONS OF HOUSEHOLD GARBAGE GRINDERS. *In* University of Pittsburgh, Local Govt. Conf. on Refuse Disposal Methods Proc. 1954: 14–17. [Processed.]

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