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Workshops on the Management of Urban Waste and on Wastewater Reuse in Agriculture

Staff Summary Report

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

This summary of the workshops on Management of Urban Waste and on Wastewater Reuse in Agriculture has been prepared by Carol Corillon, staff officer, Board on Science and Technology for International Development. The workshops were jointly sponsored by the Tunisian Ministry of Higher Education and Scientific Research and the Board on Science and Technology for International Development (BOSTID), National Research Council (NRC) of the United States. Participation by the NRC was made possible through funds provided by the U.S. Agency for International Development, under AID Contract AID/NE-C-1536.

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STAFF SUMMARY REPORT

BACKGROUND

The U.S. National Research Council's (NRC) Board on Science and Technology for International Development (BOSTID) helped organize and participated in two workshops in Tunis on Management of Urban Waste (April 12-16) and Wastewater Reuse in Agriculture (April 18-22). The workshops were held at the request of the Tunisian Ministry of Higher Education and Scientific Research. BOSTID participation was sponsored by the U.S. Agency for International Development (AID). Two American experts were selected by BOSTID for each workshop. Dr. Prakasam B. S. Tata, Project Manager in the Research and Development Laboratory of the Metropolitan Sanitary District of Greater Chicago, and Dr. Melvin Finstein, Professor of Environmental Science at Rutgers University, were the two experts selected for the Workshop on Management of Urban Waste. Dr. Herman Bouwer, Director of the U.S. Water Conservation Laboratory in Phoenix, Arizona, and Dr. Norman Kowal, Research Medical Officer at the Health Effects Research Laboratory of the U.S. Environmental Protection Agency in Cincinnati, Ohio, were selected for the Workshop on Wastewater Reuse in Agriculture. The experts participated in informal discussions with Tunisian scientists and engineers, both in academia and in industry, and gave formal lectures during working sessions at Tunisian academic institutions.

Before the arrival of the BOSTID experts, a meeting was held with the AID science staff, Richard Stevenson and Saida Zouiten, for briefings, to discuss organization of the workshops and meetings, and to review the agenda topics. The arrangements had been coordinated by Ms. Zouiten, whose assistance was invaluable.

A list of people with whom discussions were held is in Appendix I.

WORKSHOP ON MANAGEMENT OF URBAN WASTE

A meeting was held with Dr. M'Hamed Brini, of the National Agronomic Institute of Tunisia (INAT), who hosted the workshop on Management of Urban Waste. He was briefed on BOSTID's activities and given a number of publications on urban waste management that had been provided by the

BOSTID experts. Dr. Brini requested that he be sent duplicate copies of the materials provided by the BOSTID experts in wastewater reuse as well.

The BOSTID experts in the Workshop on Management of Urban Waste, Drs. Prakasam and Finstein, were briefed by Mr. Stevenson and Ms. Zouiten on the proposed program and by Dr. Brini on urban waste treatment in Tunisia. The group met with the four interpreters responsible for simultaneous translation during the workshops. They were provided with written material on the subjects of the workshops and, at Dr. Brini's suggestion, a list of technical vocabulary words was compiled to assist them in their work. A meeting was also held with the Director of Scientific Research, Mr. Ezzaddine Makhlouf, at the Ministry of Higher Education and Scientific Research. Mr. Makhlouf thanked AID and BOSTID for their assistance in organizing the workshops and expressed a strong desire that the workshops would be but the first step in a long and fruitful collaboration. He requested that the lectures given by the BOSTID experts be tape-recorded for future use.

The workshop was held at INAT. Dr. Brini, the chief moderator, was assisted by Jamila Bartaguiz and Hayet Belaid. The lectures were attended by about 40 professors and students, as well as scientists and engineers working in areas related to urban waste management. The BOSTID experts and workshop participants were welcomed by the Director of INAT, Mr. Abderrahmane Jerraya, and by the Executive Secretary of the Department of Public Works (Chef de Cabinet du Ministère de l'Equipement), Mr. Taoufik Aras Turki.

The lectures focused on the following topics:

- -- Overview of Urban Refuse Disposal Methods
- -- Underlying Concepts of Composting
- -- Scientific Principles of Composting
- -- Pilot-Scale Experimentation
- -- Heavy Metals and Pathogens
- -- Economic Considerations
- -- A General Overview of Anaerobic Digestion
- -- Sewage Treatment Processes and Sludge Disposal Methods
- -- Informal Discussions of Solid Waste Research at Bordj Cedria Research Center

Detailed information on this workshop is contained in a report by Drs. Prakasam and Finstein in Appendix II.

The participants asked many questions during the lectures as well as during the breaks and after the sessions. Many participants mentioned the need for more information on composting and methane generation from wastes and asked that AID and BOSTID help in any way possible. Several dozen copies of various relevant NRC publications, as well as copies of reprints and publications furnished by Drs. Prakasam and Finstein, were left for the INAT library and with many of the participants.

To get a clear understanding of the problems of urban refuse and wastewater disposal in Tunis, in the company of Dr. Brini, his assistants, Ms. Zouiten, and Mr. Melika Mehdi, Chief Engineer at the Department of Sanitation (ONAS), the BOSTID team visited one refuse disposal site (Figures 1 and 2) and two wastewater treatment plants--a conventional activated-sludge plant (Cherguia, Figure 3) and a Carrousel-type treatment plant in south Tunis (Miliane, Figure 4). The latter plant is also the site for a planned composting project.

WORKSHOP ON WASTEWATER REUSE IN AGRICULTURE

On Saturday, April 16, when all four BOSTID participants were in Tunis, Mr. Makhlouf arranged for an official dinner with the AID Science Office professional staff and the Tunisians who were directly involved in the workshops. The dinner provided a pleasant opportunity for discussion of general areas of interest.

To familiarize Drs. Bouwer and Kowal, the BOSTID wastewater reuse experts, with conditions and practices in Tunisia and to provide them and the Tunisian scientists working in areas related to wastewater reuse with an opportunity to exchange ideas, two or three meetings were held every morning with scientists working in the departments listed below. (See Appendix III-A, Workshop on Wastewater Reuse in Agriculture by Herman Bouwer, and Appendix III-B, Health Aspects of Wastewater Reuse in Agriculture by Norman Kowal, for details). Many of these meetings were set up by Dr. Noureddine Ennabli, Professor, INAT, and proved to be very informative.

- o U.S. Agency for International Development
  - -- Science and Technology Office
- o Ministry of Higher Education and Scientific Research
- o Ministry of Public Health
  - -- Department of Sanitation (ONAS). Also, ONAS Hygiene Section.
  - -- Environmental Protection Department
- o Ministry of Agriculture
  - -- Department of Hydrology
  - -- Department of Rural Engineering: Administrative Offices, Research Department

The BOSTID team visited the Miliane Carrousel sewage treatment plant in south Tunis in the company of Mr. Mehdi and Gunter Brox of German Technical Assistance. In addition, a one-day field trip was made to Kairouan with Dr. Tahar Gallali of the Faculté des Sciences de Tunis and his students. The visit included a briefing on a wastewater treatment plant and project to study the use of the effluent for irrigation of forage crops and, later, a tour of the plant and

REFUSE DISPOSAL SITE--TUNIS

FIGURE 1 Refuse being collected for market sale.

FIGURE 2 Livestock grazing on garbage.

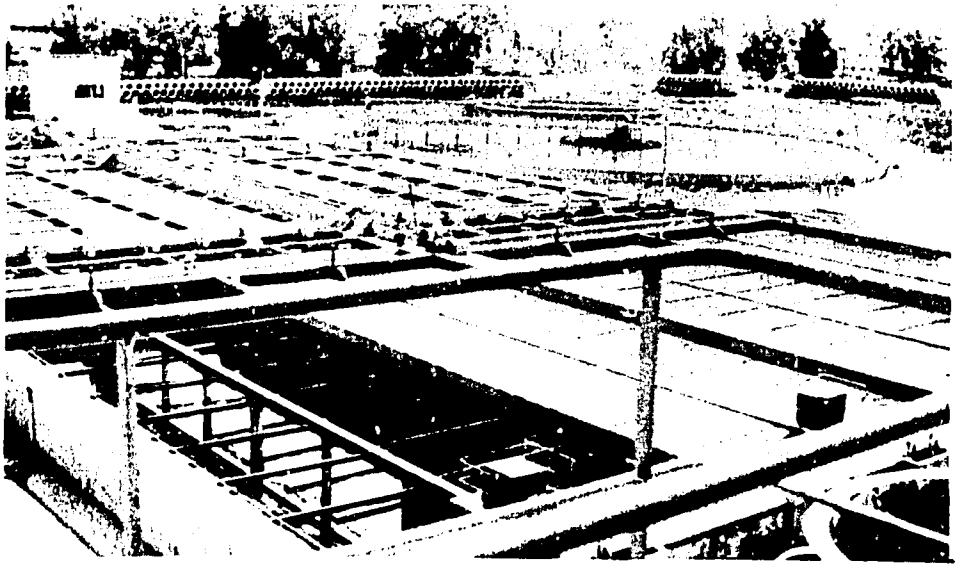

FIGURE 3 Cherguia Sewage Treatment Plant--Activated-Sludge System.

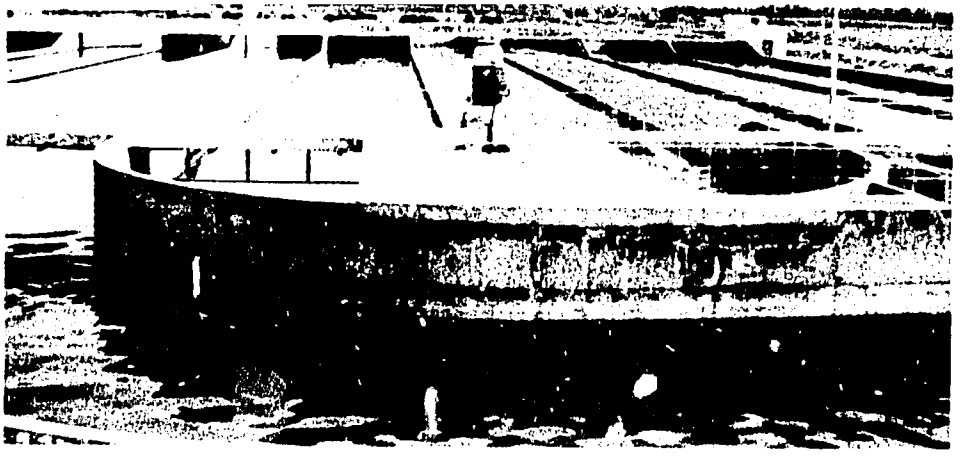

FIGURE 4 Miliane Sewage Treatment Plant--Carrousel System.

irrigation site. On the return trip from Kairouan to Tunis, the BOSTID team also visited a dam (Barrage de Nebhana) which stores water for agricultural irrigation.

The workshop on Wastewater Reuse in Agriculture was held at the Faculté des Sciences de Tunis. Lectures were given in the afternoons and were attended by about 30 professors and students as well as scientists and engineers working in wastewater-related areas. The lectures focused on the following topics:

- Quality requirements for the use of sewage effluent for irrigation
- Principles of sewage treatment and practical sewage irrigation in the United States
- Microorganisms in sewage effluent, and their health effects
- Standards for irrigation with sewage effluent in the United States
- Renovation of partially treated sewage effluent by soil-aquifer treatment with rapid infiltration groundwater recharge systems
- Toxic substances in sewage effluent, and their health effects

Copies of the publications and documents furnished by BOSTID and by Drs. Bouwer and Kowal were given to the library of the Ministry of Higher Education and Scientific Research. All available duplicates were given to the INAT library, ONAS, and to the workshop participants. Many of the students requested that BOSTID or its experts send them specific publications relating to wastewater reuse. Other students and scientists asked that BOSTID send them information on American universities that offer courses in wastewater reuse and on American institutions that offer training programs in the same field.

APPENDIX I

Contacts

Sadok Attalah, Director, Environmental Services and Protection of Public Health, Ministry of Public Health

Jamila Bartaguiz, Assistant, National Agronomic Institute of Tunis (INAT)

A. F. Bartsch, Environmentalist, Consultant to USAID Tunis, Corvallis, Oregon

Hayet Belaid, Assistant, INAT

Mohamed Ben Ahmed, Director of Pumping Station, Miliane Wastewater Treatment Plant

Mansour Bouraoui, Regional Commissioner for Agricultural Development, Kairouan

Abdelaziz Bouzaidi, Project Director, Department of Rural Engineering

M'Hamed Brini, Professor, INAT

Gunter Brox, Engineer, German Technical Assistance

Mohamed Chalala, Engineer, Kairouan

Touhami Chettaoui, Assistant Director, Office for the Improvement of the Medjerda Valley (OMVVM)

Rafik Ben Choug, Director, Industrial Wastes Laboratory, Miliane Wastewater Treatment Plant

Emilio Q. Daddario, Past President, American Association for the Advancement of Science, USA

Ali Djebali, Director, Department of Rural Engineering, Ministry of Agriculture

Yvon Dommergues, Office of Scientific and Technical Overseas Research, (ORSTOM), Senegal

Slaheddine Elamami, Director, Department of Rural Engineering, Ministry of Agriculture

Mohamed Ennabli, Professor, INAT

Noureddine Ennabli, Professor, INAT

Tahar Gallali, Professor, Department of Soil Sciences, Faculty of Sciences of Tunis

Ahmed Ghrabi, Chief Engineer, INAT

Ridha Hachicha, Engineer, INAT

Mekki Hamza, Director of Soil and Water Resources Division, Kairouan

Ameur Horchani, Director, Department of Hydrolic Projects, Ministry of Agriculture

Mohamed Jemli, Engineer, Department of Rural Engineering

Abderrahmane Jerraya, Director, INAT

Belgacem Khammari, Engineer, Kairouan

Mohamed Larbi Khrouf, Planning and Studies Director, Department of Sanitation (ONAS)

Abdel-Halim Koundi, Wastewater Treatment Plant, Cherguia

Julia Marton LeFevre, Central Secretariat, CISTOD, France

L. Gilles Lessard, Associate Director, Forestry Sciences, International Development Research Centre (IDRC), Canada

Franklin Long, Professor, Cornell University, USA

Ezzeddine Makhlouf, Director of Scientific Research, Ministry of Higher Education and Scientific Research

Youssef Marsit, Plant Director, Miliane Wastewater Treatment Plant

Melika Mehdi, Chief Engineer, ONAS

Bechir M'Rabti, Director, Municipality of Tunis

Mannouba Muzitouni, Engineer, Kairouan

Tawfik Nacef, Director, Department of Hygiene, Ministry of Public Health

A. Karim Oka, Forestry Advisor, IDRC, Kenya

Nacer Ouslati, Staff, Ministry of Higher Education and Scientific Research

Jean-Pierre Person, Chief Engineer, INAT

Warren Prawl, Agricultural Extension Specialist, D.E.R.V., Ministry of Agriculture

Richard Stevenson, Science and Technology Officer, USAID, Tunis

Monia Trad, Engineer, Department of Rural Engineering

Mahmoud Triki, Scientific Mission Director, Embassy of Tunisia, USA

Taoufik Aras Turki, First Secretary, Department of Public Works

Marsit Youssef, Plant Director, Miliane Wastewater Treatment Plant

Saida Zouiten, Assistant Science and Technology Officer, USAID, Tunis

APPENDIX II

Workshop on Management of Urban Waste

Prakasam B. S. Tata and Melvin Finstein

Our activities during the mission to Tunis fell under the following categories:

1. Familiarization with the problem of urban refuse and wastewater disposal in the city of Tunis by visiting a refuse disposal site and wastewater treatment plants.

2. Presentation of a series of seminars on state-of-the-art of urban refuse disposal technology and methods of wastewater treatment, disposal, and utilization.

3. Discussion of public health and socioeconomic considerations pertaining to composting systems for the disposal of refuse in Tunis.

4. Participation in a round table discussion:

   a. To identify guidelines for the formation of a collaborative team consisting of key individuals from various agencies in Tunis to study the problem of urban refuse disposal.

   b. To determine how USAID and NRC could assist in the formulation and implementation of a research and training facility to alleviate the problem of urban refuse disposal in Tunis.

5. Visit to Naples, Italy, for discussions with Dr. Franco Zucconi regarding composting and to promote contact with Tunisians on problems of mutual concern.

Dr. Prakasam is Project Manager in the Research and Development Laboratory of the Metropolitan Sanitary District of Greater Chicago, Chicago, Illinois, USA. Dr. Finstein is Professor of Environmental Science at Rugers University, New Brunswick, New Jersey, USA.

1. Urban Refuse Disposal and Wastewater Treatment in Tunis

Refuse Disposal Site Currently the refuse from households and commercial establishments such as shops and restaurants is disposed of at two major dump sites located in Tunis. We visited one of these sites at around 11:00 a.m. The dump was a beehive of activity with hand-drawn and motor vehicles bringing in and dumping garbage in an uncontrolled fashion at the site and returning to bring in more garbage during the day. We were told that about 500 tons of garbage is produced in Tunis per day and that organic content is more than 80 percent. There were scores of people, young and old alike, sorting the garbage to collect bottles, cans, rags, etc. which have a cash value on the market. We were told that many of these people earn a part or all of their livelihood by salvaging such articles from the city dump sites. We smelled an odor characteristic of decomposing garbage. There were also smoldering, as well as open fires in various areas of the dump.

It is interesting to note that rubble collected from the various construction sites in Tunis is disposed of in several locations in the dump in a discrete fashion and is not unduly combined with the refuse. Hence, due to its highly organic nature, opportunities exist for stabilization of the refuse deposited at this dump site by composting. It is also interesting to note that while we saw piles of rubble and other inert materials along the roadside at various places, we did not see any domestic refuse indiscriminately disposed of on the shoulders or other adjacent sites along the main and secondary streets on which we traveled. This suggests that there is an awareness in the community of the potential consequences of the indiscriminate disposal of domestic refuse. In consequence, any scheme of treatment and disposal of urban refuse to be implemented in the future must be thoroughly studied so that problems such as odors, emissions that cause air pollution, and any other ecological and sociological repercussions associated with the new scheme are minimized.

The current mode of handling and processing the refuse at the dump sites involves covering a heap of refuse with soil when it reaches a height of about 4 m. Additional quantities of refuse are then dumped over it or along side it and the process of piling it to a height of 4 m and covering it with soil is repeated. However, by no stretch of the imagination could this operation be called a sanitary landfill. Rather, it is correctly described as a dump.

Wastewater Treatment Plants We visited two wastewater treatment plants serving the city of Tunis. One is a conventional activated sludge plant (Cherguia) and the other is a Carrousel plant (Miliane) which is a multi-channel oxidation ditch system.

The activated sludge plant was designed to process about 65,000 m^3 of sewage/day. The sewage received at this plant is domestic in origin. The plant consists of screens, an aerated grit chamber, an oil and scum skimming tank, rectangular primary settling tanks, diffused aeration tanks, secondary clarifiers, anaerobic digesters, and sand beds for the dewatering of anaerobically digested sludge.

The anaerobic digestion of the combined primary and water-activated sludge is carried out at 35°C. It consists of two stages. The first stage digester is mixed by gas recirculation and has a detention time of seven days. The second stage digester is not mixed and it has a detention time of about four days. The gas produced in the digesters is completely utilized in the plant to heat the digesters and for the generation of electricity.

We were told that the final effluent is not disinfected and is discharged into a canal which eventually discharges to the sea. The Carrousel-type plant was put into operation six months earlier. It processes wastewater from both residential and industrial sources. About half of the flow processed is from domestic sources whereas the remainder is from industrial sources. The average daily flow of the wastewater required at this plant is 37,000 m^3/d, of which 50 percent is from domestic sources and the remainder is from industrial sources. Major industries contributing to the wastewater are a battery manufacturing plant, a tannery, and a textile dying plant.

The Carrousel system is designed to achieve nitrification and denitrification of the wastewater. At this plant there is no primary settling. The detention time of the system is about 2.5 days. The sludge from this plant will be dewatered and dried on sand beds when the plant is fully operational.

Currently, no detailed analyses of the wastewater are made routinely for heavy metals and their concentrations, cyanides, phenols, fats, oils and grease, etc., at the Carrousel plant. The industries do not analyze the quality of the wastes they discharge either. While we did not visit the laboratory at the activated sludge plant, we did visit the laboratory at the Carrousel plant and it appears to be adequate for daily monitoring of selected parameters such as pH, conductivity, total solids, suspended solids, volatile suspended solids, and BOD.

During our brief visits to these treatment plants, we smelled a distinct, offensive odor on the premises and in the surrounding areas. This odor is presumably due to deficiencies in plant operation. In the activated sludge treatment plants, the waste-activated sludge is returned to the primary settling tanks with an expectation on the part of the operator that such a procedure will improve the settling characteristics and enhance the thickening of the sludge. The recycling of waste activated sludge solids to the primary settling tank would obviously increase the solids loading to these clarifiers. The primary effluent may have more suspended solids and biochemical oxygen demand with the current practice than if waste-activated sludge is not recycled through the primary clarifier. The odor problem may be partially due to overloading of these clarifiers and may also be due to inadequate aeration. It would be advantageous to thicken the waste-activated sludge and primary sludge. In the absence of records pertaining to the dissolved oxygen profiles in the aeration tanks and to the effects that recycling waste-activated sludge through primary clarifiers has on odor production, it is difficult to ascertain what is causing the odor problem. It should also be ascertained whether the anaerobic digestion is stabilizing the sludges adequately and whether it is causing the odor.

In the Carrousel system the nitrification-denitrification mode of processing is not necessary if the effluent will be used for irrigation. In fact, it would be counterproductive since operating the treatment plant via the nitrification-denitrification mode yields an effluent with almost no inorganic nitrogen, which otherwise can be utilized as a nutrient for crops. Operating the treatment plant for secondary treatment objectives only, via suspended solids and carbonaceous BOD removal, will increase the capacity of the treatment plant to process more flows than are currently received provided the aeration requirements are satisified.

If irrigation of effluent is implemented in the future, disinfection may be necessary. A routine monitoring program to monitor the bacteriological and chemical quality of the final effluent will be necessary. Also, the analyses of sludges generated at the treatment plants should be made on a routine basis to determine the concentration of heavy metals and toxic organic compounds in order to assess their impact on phytotoxicity and public health. Such analyses would also assist in the evaluation of the quality of compost, if composting of sewage sludge and urban refuse is undertaken as a method of treatment and stabilization and for the production of a soil conditioner and fertilizer.

2. Presentation of Seminars

During the week, seminars on the following topics were presented:

(a) State of the art of urban refuse disposal. The techniques that are available for the disposal of refuse such as sanitary landfills, incineration, pyrolysis, composting, and anerobic digestion and their advantages and disadvantages were discussed.

(b) Problems of heavy metals and pathogens in composting and sludge disposal systems.

(c) Factors to be considered in the economic analysis of composting systems.

(d) A discussion of primary, secondary, and tertiary processes for the treatment of wastewater and the place of composting and anaerobic digestion in treating and stabilizing sludges derived from these processes.

(e) Development of the background to composting: its spontaneous nature; distinction between the process (composting) and one particular product (compost); distinction between process configuration (materials handling) and management of the process' underlying microbial ecosystem (process control strategy); the need to be wary of salesmen in the composting field whose primary interest is profit making; the need for Tunisians to understand the basic scientific and technical factors, so that they can devise a facility well suited to their particular conditions.

(f) Development of the scientific and technical basis of composting: the nature of self-heating; the key role of the interaction between microbial heat generation and temperature; the 60°C threshold to process deterioration; interactions among heat generation,

temperature, vaporization, and ventilation; ventilation mode (forced pressure preferred over vacuum-induced); the problem of matching the heat removal rate to the heat generation rate, in reference to the 60°C threshold; the time-variable nature of the above problem; the solution to the problem in temperature-feedback control; the components of the control system (thermistor, timer, temperature controller); the components of a monitoring system (event recorder, thermocouples, O_2-CO_2 measurement, moisture content measurement); peak demand for ventilation and overall demand; drying and its significance as an indicator of process performance; significance of drying for microbial activity; the rewetting problem; significance of curing and its possible need; resource recovery through production of compost, chicken litter, landfill cover material, biomass-derived (solid) fuel.

A number of reprints and reports in English dealing with the subject of composting and biogas production from various agricultural wastes, such as poultry wastes, were given to the chief moderator of the workshop, Dr. Brini.

During the course of the workshop, participants were encouraged to ask questions. In spite of the language barrier, many questions were asked by the Tunisian participants without hesitation. The participants were very receptive throughout the workshop and stayed beyond 6:00 p.m., in spite of the intensive schedule. Many participants expressed interest in obtaining more information on the subjects of composting and methane generation from wastes as such information is not readily available in Tunisia. We strongly recommend any assistance that the NRC and the USAID can provide in this regard.

3. Public Health and Socioeconomic Considerations Pertaining to Composting Operations

An overview of the potential public health problems associated with wastewater treatment and sludge disposal in general, and with composting systems in particular, was presented. The fate of pathogenic bacteria, viruses, fungi, helminthic ova, and protozoan cysts was discussed. The importance of maintaining aerobiosis and thermophilic activity during the active composting period to avoid nuisance odors and to achieve a well-stabilized compost was stressed.

The fate of heavy metals in composting operations was discussed after presenting an overview of the potential risks associated with spreading wastes containing heavy metals on land used for agriculture. In this discussion a general summary of how various heavy metals affect plant, animal, and human health was also presented.

The factors that should be considered in arriving at the capital, operating, and maintenance costs of composting urban refuse were enumerated. In order to make an economic analysis of a composting facility, the importance of maintaining good records on the daily quantities of incoming refuse, compost produced, and compost sold, if any, costs pertaining to equipment, labor, energy, land, maintenance of equipment, and any other overhead and contingencies were stressed. The maintenance of satisfactory records during the research and demonstration phase of the proposed composting experiments in Tunis should yield

valuable information on how a full-scale facility would perform when it is established.

If and when the existing dumps are closed and the refuse is processed by composting and/or by any other process, such as incineration, the people who are salvaging refuse for their livelihood will be disturbed. Thus, any streamlined refuse disposal process poses a sociological problem. The importance of opening a dialogue now among the various agencies and people concerned with refuse disposal and public welfare activities and its continuation during the research and demonstration phase of the composting experiments was stressed. Such dialogues would keep all of the concerned parties well informed so that they could work in a concerted fashion when the full-scale operations are in place.

The necessity of educating the public with regard to the advantages of composting urban refuse, the problems that might possibly occur, and how they could be rectified were also discussed. By the use of extension education programs, the public in general and the farmers in particular can be made aware of the value of the compost. Such programs would not only enhance the chances of acceptability of composting as a method to treat and stabilize refuse but can also create a market for the finished compost as a soil conditioner and fertilizer.

4. Round Table Discussion

The round table discussion, which was attended by about a dozen people representing ONAS, INAT, USAID, and the visiting BOSTID team, focused primarily on how an interdepartmental team can be set up. In this discussion, the participants were told by Dr. Brini that the Government of Tunisia has decided to implement composting and incineration for the treatment and disposal of urban refuse. Information on the feasibility of composting urban refuse in Tunisia is lacking. Because of the decision to use composting as a method of stabilizing urban refuse in Tunis, it has become imperative that a research and demonstration study be started very quickly.

Funds have already been allocated for the construction of a research and demonstration facility at Bordj Cedria to study the process of composting. However, adequate resources are not available in Tunisia to initiate research on composting. Dr. Brini said that a grant from the USAID mission could be used to provide some technical expertise to evaluate the progress of work, to buy some research equipment for the study, and to support the training of Tunisians at a university such as Rutgers if such training can be arranged. He also sought the assistance of Drs. Finstein and Prakasam to review a research proposal that he is writing on composting of the refuse collected in Tunis with or without mixing wastewater residuals and other agricultural wastes such as poultry wastes.

During the round table discussion, as well as during informal unstructured discussion, the following promising possibilities emerged for integrating the management of solid waste of Tunis with the waste generated by the substantial poultry industry nearby.

-- The laying hens are housed in cages; hence the excreta are available for anaerobic digestion for methane (biogas) production. The digested residue might be acceptable for direct land application, or it might be preferable to combine it with refuse for composting. Alternatively, the component of the poultry waste could be combined with refuse for composting, without prior digestion. The question hinges on the cost of anaerobic digestion and the value of the gas.

-- The broilers are housed in the "loose housing" mode, which involves the use of absorbant material such as litter. Straw, the main material used, is costly (approximately 35 dinars (US $55.00) per ton) and in short supply locally.

Municipal refuse can be composted for the specific purpose of producing chicken litter. This is done in Altoona, Pennsylvania, and the product is trucked to Del Mar Va, Pennsylvania, for use in the broiler industry. The potential in Tunisia is evident in that the estimated price for refuse-derived compost is 6 dinars per ton. Dr. Brini and Dr. Prawl (Extension Service, University of Kansas - USAID, Tunis) agreed that Dr. Brini should visit the Altoona facility during his forthcoming trip to the United States.

Regardless of its origin (straw, refuse, etc.), spent chicken litter does not lend itself to anaerobic digestion. If it is not acceptable for direct land application, it might be composted by itself to make it acceptable. Alternatively, the spent litter can be combined with refuse for composting. Again, numerous economic and environmental factors are at play, and the issue requires detailed consideration.

Another point stressed in the round table discussion was the importance of having channels of communication open at all times among members of the various Tunisian Ministries which will be responsible for the treatment of waste residuals, urban refuse, and agricultural wastes and for public welfare. Such a practice will accelerate the collection and dissemination of information among the concerned individuals and facilitate the successful implementation of projects dealing with urban refuse disposal in Tunisia.

Finally, considerable time was spent developing an overall framework for setting up a waste management scheme centered on composting. This framework is outlined here.

A. Pre-Composting Operations

1. Salvage. This involves removal by hand of valuable material from the waste, for direct reuse or for upgrading through non-biological processing. Materials that can be reused directly might include bottles, leather goods, clean vegetable discards (on-site animal feeding), and bricks. Materials requiring further processing include glass, metals ("tin" cans), paper, and rags.

In determining the exact arrangement for this phase of the projected facility, representatives of the people currently salvaging material at the existing dumps should be consulted extensively. To avoid conflict, and to maximize the chance for success, the new arrangement should be senitive to their modes (e.g., apportionment of salvage rights, informal means of settling disputes).

Judging from our brief visit, the present arrangement seems to be that of "multipoint inputs," or "parallel flow." That is, load a is picked over by group a, while load b is simultaneously picked over by group b. This arrangement tends to disperse among a large number of people the opportunity to pick out the best items. A more formal system involving a single-point input (a series-like pattern of waste flow) would drastically alter the existing arrangement. All groups would vie for the upstream point closest to input to get the first chance at the best pickings. If this analysis is correct, then the most "efficient" system from a strictly engineering, materials handling, viewpoint might upset social structure. Arrangements sensitive to the existing modes can undoubtedly be devised.

Concerning salvage, two other comments can be made. First, the material salvaged from the day's operation should be removed from the facility by the end of the same day. If left overnight, the material might attract rodents and other pests. Similarly, before day's end the post-salvage material should be formed into piles to initiate composting. Second, the maximum feasible amount of material should be salvaged. This is because salvage represents the highest form of resource recovery, creates the most jobs, and decreases the burden on the downstream unit operations (composting, etc.).

2. Size reduction. Breaking up the larger pieces of material might or might not be indicated at this stage. It might possibly be indicated as a post-composting operation. The exact role of size reduction, if any, will become clearer as pilot experience accumulates. Regardless, size reduction can be accomplished by thorough use of a hammer mill, flail, or rotating drum.

3. Mixing. It is probably desirable to mix the material prior to composting. If refuse and sludge are co-composted, this further indicates mixing. Mixing is accomplished in a rotating drum, with a pug mill, with a "window machine", etc.

4. Moving. At various points in the operation, material must be moved. Aside from hand operations associated with salvage, moving is usually accomplished using conveyors and front-end loaders. Alternatives compatible with local circumstances might exist.

B. Composting *per se*

1. High rate stage. The high rate stage of composting is the centerpiece of the entire scheme in that it is responsible, in part or whole, for odor control, stabilization, weight and volume reduction, water removal, and pathogen kill, and results in a product suitable for resource recovery (possibly after curing). As suggested by the term "high rate," the objective is to maximize the rate of microbial decomposition so as to promptly destroy the daily input of putrescible material. The importance of maximizing the rate of decomposition at the earliest possible stage of composting cannot be exaggerated. This

requires strict application of the process control strategy known to accomplish this end.

Field-scale pilot studies are needed to (1) develop among the Tunisian personnel a comfortable familiarity with the high rate stage, and (2) acquire the information needed to economically design the full-scale facility. These two purposes are best served by studies insulated from the demands of routine operation and should be initiated as soon as possible. The studies should be designed to determine some or all of the following characteristics of the waste to be composted:

- -- Peak demand for ventilation
- -- Overall demand for ventilation
- -- The pattern of moisture content decrease
- -- Temperature pattern, especially in reference to time-temperature exposures needed to ensure pathogen kill
- -- Response to rewetting
- -- Approximate mass balance
- -- Effect of pile height on performance

Material obtained from these studies should be evaluated for use as rough compost and as chicken litter.

2. Curing stage. The output of the high rate stage can be further composted, if indicated, without strict process control, as the material is now partially stabilized. Hence, its tendency to become excessively hot, or anaerobic, or to produce malodors is greatly decreased.

For curing, the material is removed from the high rate area, rewetted if necessary, and formed into piles. The curing pile might be formed over a "passive duct," but no mechanical ventilation is applied.

Whether curing is needed depends on the end use of the process residue. The output of the high rate stage will probably be suitable for use as rough compost or chicken litter. (Prior screening to remove large inert particles might be desirable.) However, if a highly stabilized, finished compost is the intended product, a curing stage is necessary.

It is not possible to predict all of the modes of operation and the types of end-uses that might become advisable over the years of operation. Waste management processes are, if anything, changeable. Therefore, a range of options should be explored to define the possibilities. Some questions that might be addressed in curing studies follow:

a. How might rewetting the post-high rate material be accomplished?

b. Determine the O_2 content in the interior of pile as curing progresses.

c. Determine the end-point of curing, as judged through nitrification (disappearance of NH_4+, appearance of NO_2- and NO_3-).

d. Involve agronomists in evaluation of the finished compost. (This should also be done for the rough compost.)

C. Post-composting operations

These operations might or might not include size reduction, screening, and storage.

D. Final comments

1. Need for a backup repository (e.g., landfill) for the process residue. When a sewage treatment plant experiences a processing failure, or a period of poor performance, the evidence quickly flows away downstream. The residue of the composting process is less obliging, it accumulates on site. Therefore, it is essential (1) to optimize design and operation from the outset, and (2) to have a preexisting emergency plan for disposing of residue that is either substandard, or otherwise not easily disposed of through deliberate use. This is especially important during the early "break-in" period of operation. Moreover, power failure or other unanticipated events can always result in a temporary need for an alternative mode of final disposition.

2. Lack of a "canned formula" and flexibility. The lack of a standard formula for development of a composting facility should not be viewed as a liability; indeed, it represents an opportunity for Tunisians to develop a model procedure, and facility, for others in the developing and developed countries to emulate.

Similarly, the composting process is extremely flexible, provided that the underlying scientific and technical principles are understood. Thus, a well-designed facility can respond to changing conditions of waste input and changing demands for product type.

5. Visit to Naples

We had useful discussions with Professor Franco Zucconi in Naples regarding the problem of solid waste disposal in Italy, possible contacts with Tunisians, and his work on composting. We also discussed the agricultural use of compost and the impact of heavy metals on plants, animals, and human health. Dr. Zucconi gladly agreed to send Dr. Brini and Mr. Mlika reprints of his relevant papers, and to send announcements of the forthcoming international conference (October 1983, in Naples) on composting and waste management. Moreover, Dr. Zucconi might be in a position to help evaluate Tunisia's application for Italian foreign aid in connection with solid waste management in Tunis.

APPENDIX III-A

Wastewater Reuse in Agriculture

Herman Bouwer

The one-week visit in Tunis included visits with university, government, and municipal agencies in the mornings (usually about two or three visits per day) and lecturing to students, faculty, and technical people at the Faculté des Sciences in the afternoons.

The morning discussions indicated that the Tunisians have a great interest in irrigation with sewage effluent. Research is being planned at a number of locations. The proposed sewage irrigation research projects range in size from a few hundred ha to a few thousand ha. Some are already functioning. The crops to be irrigated are mainly forage crops and corn.

Tunisia has a shortage of water. The rainfall is about 600 mm per year in the north, 300 mm in the center, and 100 mm or less in the south. Almost all of the rain in the Mediterranean climate of Tunis falls in the winter. There are many water-deficient areas. Groundwater is the main water source. However, the groundwater often is of poor quality. In the north, about 10 percent of the groundwater pumped has a total salt content of more than 3,000 mg/L. In the center, 20 percent contains more than 3,000 mg/L, and in the south, 50 percent contains more than 3,000 mg/L salt. Thus, irrigation and farming have to be managed for salinity (use of salt-tolerant crops such as barley, dates, and cotton; adequate leaching; and planting on the side of the ridges in furrow irrigation). The total area irrigated in Tunis presently is about 180,000 ha, which can readily be expanded to 220,000 ha. The maximum area is about 250,000 ha.

Along the northeast coast, hotels demand more water, groundwater levels are diminishing, and there are problems of seawater intrusion. The larger towns and cities have sewage treatment plants. Tunis has three main plants; one is an activated sludge plant; another has an oxidation pond system; and the newest one is a Carrousel treatment plant. Soon there will be 100 million m^3/year of sewage effluent, which at an average irrigation of about 60 cm/year could irrigate about 16,000 ha. Officials take a practical view of the situation,

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i.e., there are water shortages; the cities and people require the best quality water; agriculture is necessary to produce food and fiber for the population; thus, sewage water must be used increasingly for irrigation. There is no other choice. Health risks will be minimized, but some are hard to avoid completely (including the abuse of sewage irrigation by irrigating small patches of vegetables). However, these are risks that have to be taken.

A lot of research on irrigation with sewage effluent is being planned. The Rural Engineering Program previously concentrated its efforts on salinity. However, these efforts have now been redirected into sewage irrigation. Crops and irrigation management are going to be tested with sewage, and the yields that can be obtained and the health effects, including effects of heavy metals, will be studied. Tunisia's program is part of a three-country international water research project (project RAB 80/011) in which Morocco will study groundwater recharge; Algeria, erosion; and Tunisia, irrigation with sewage water. One engineer (Mr. Mohamed Jemli of the Department of Rural Engineering) has studied sewage irrigation in California. As a whole, the groups with which we met could benefit from the standards that have been formulated by various states, and from U.S. literature on the subject, as described in the book Water Reuse edited by E. Joe Middlebrooks (Ann Arbor Science Publishers, 1982), and various design manuals on land treatment systems.

The Carrousel treatment system in south Tunis which we visited was operating far below design capacity because the sewage from the residential areas had not yet been hooked up. It was primarily treating waste from a textile dyeing plant, a battery manufacturing plant, and a tannery.

During a field trip to Kairouan, about 150 km south of Tunis, we were briefed on a new dam (the Bourguiba Barrage) for flood control (at one time a peak flow of 17,000 m^3 second had been recorded) and water storage. We were also briefed on a sewage treatment plant (activated sludge) and on a project to study the use of the effluent for irrigation of forage crops. The experimental field was 200 ha in size and was located about 2 km from the sewage treatment plant. The main crop irrigated with the effluent was oats (oats was selected because it is eaten only by animals). Next to the project were some barley fields which were not irrigated and hardly looked worth harvesting.

Water consumption in Kairouan is about 120 L/person/day, which is about one-third the in-house water use in the United States. The sewage effluent is quite concentrated, and nitrogen concentrations of 60 mg/L and more can be expected. Depending on amounts of water irrigated and the nitrogen requirements of crops, overapplication of nitrogen could be a problem. Rainfall in the area is 330 mm/year and occurs mostly in the winter. On the way back to Tunis we visited a dam (Barrage de Nebhana) with a storage capacity of 100 million m^3, storing water for an irrigation pipeline. The reservoir was about half full.

In some areas such as the east coast, groundwater recharge could be used for winter storage of the effluent. The effluent could then be pumped out in the summer for irrigation. This would have the

additional benefit of purification of the sewage effluent by soil-aquifer treatment, so that the effluent water could then be used for unrestricted irrigation. Currently, sewage is used mainly on forage and citrus crops where there is no contact between the crops or fruit and the effluent.

Tunisia's Department of Hydraulic Projects could be compared with the U.S. Bureau of Reclamation since it constructs dams and other large water projects. However, it is now quite involved with the construction of a canal to the northwest of Tunis that will carry sewage effluent to a new area of 2,670 ha which will be used for sewage irrigation. There will be a small reservoir for regulation but not for winter storage. The soils are relatively poor in this area, and only forage crops and maize will be grown for beef cattle. The area currently is not irrigated, so irrigation will increase productivity. The Pasteur Institute will regulate the use of the sewage effluent. According to law, if people are caught growing vegetables, the vegetables are to be destroyed. The sewage flow in 1981 was about 30 million m^3/year and by 2000 it is expected to increase to 108 million m^3/year.

We also met with Mr. Sadok Attalah, the director of an EPA-like agency within the Ministry of Public Health. This agency checks sewage effluent quality and the efficiency of treatment plants. There is ongoing research in different regions in Tunisia on irrigation with sewage effluent. Several regions now use untreated sewage water on vegetables because the vegetables grow well with sewage irrigation. This practice poses a threat to public health. Therefore, the agency cooperates with different departments within the Ministry of Agriculture and other agencies on pilot projects with treated sewage water. Where farmers already irrigate vegetables with raw sewage, it will be difficult to get them to change. In consequence, the agency plans to do research on how safe it is to use treated sewage effluent for vegetables. There are now about 28 sewage treatment plants in Tunisia and more must be built. The main concerns are with large towns and hotels, which represent the largest percentage of the population. The effluent from treatment plants in these areas must be used.

For the tourist area of Sousse, the price of water has increased and hotels want to use wastewater to irrigate their gardens and landscaped areas. The agency has a blueprint of what should be done. It lists the responsibilities of the hotel owners, the Department of Agriculture, and the Public Health Department. A golf course is also irrigated, but there are problems with salt effects on the grass. Apparently the grass used on the greens and fairways is not very salt tolerant. Under the present and proposed projects, the farmers will receive the sewage effluent at no cost, but the hotels pay a small amount for the infrastructure necessary to regulate the use of sewage water for golf courses and landscaped areas. The agency plans to do more bacteriological and parasitic tests where sewage is used for irrigation. It also plans to study the effects on groundwater, which is at a depth of about 10 to 15 m, including nitrate contamination.

Farmers using sewage effluent will receive typhoid injections. Operators of treatment plants also get these injections. There is

concern about standing sewage water in the irrigated fields, the proliferation of insects, and the danger of the spread of schistosomiasis. If there is stagnant water, the agency will work with larvicides and fish to keep mosquitoes under control. It is planning an educational program to acquaint farmers with the dangers of using sewage effluent. There is also an ongoing effort to improve the quality of the drinking water, because this will reduce outbreaks of typhoid, hepatitis, and other waterborne diseases, which in turn will make the wastewater safer to use for irrigation.

About 68 percent of the population presently has piped drinking water available. In rural areas, 25 percent of the population has access to piped water but must walk some distance to reach the pipeline. The main challenge is to provide small communities with good quality water, because they are the main source of disease outbreaks. In areas where people live in individual houses, the danger to public health of drinking contaminated water is not as serious because the chances that an infectious disease will spread are minimal.

RECOMMENDATIONS FOR SEWAGE IRRIGATION IN TUNISIA

Because of the great interest in Tunis in using sewage effluent for irrigation, experiments are planned to study agronomic, health, and environmental aspects. The main treatment processes used in the country are oxidation pond, oxidation ditch (Carrousel system), and activated sludge. Since the effluent from the treatment plants is not disinfected, it should be used primarily to irrigate crops not consumed by humans, such as forage, fiber, and seed crops. Tree crops (citrus) could be irrigated if there is no contact between the fruit and the sewage water. Crops that are cooked prior to human consumption may be considered. To avoid secondary contamination, however, this should be limited to crops that are not brought raw into the kitchen (wheat, for example), where they could contaminate other food stuffs. In view of the low per capita water use, nitrogen concentrations in the effluent will be high. Thus, the irrigation should be managed (and the effluent diluted or treated to lower nitrogen concentrations if necessary) to make sure that excessive amounts of nitrogen are not applied to the crops.

Nonchlorinated or otherwise nondisinfected effluent for irrigation can best be used at carefully managed and controlled sewage farms, operated by a city or a government entity. When farmers use nondisinfected effluent for irrigation, there is a real danger of outbreaks of infectious diseases, especially in countries where hepatitis, typhoid, cholera, and other waterborne diseases are still common. Contamination can result from handling of the effluent water by irrigation workers and others such as children coming into direct contact with the water, or from consumption of vegetables or other crops deliberately or inadvertently irrigated with the effluent. Unless irrigation is very strictly controlled and an education program is set up to teach workers and others how to handle the water, irrigation with nonchlorinated effluent could cause health problems.

As a guide, the Tunisians may wish to consider the standards for irrigation with sewage effluent developed in various states of the United States. Arizona, for example, allows the use of primary effluent for irrigation of fiber and seed crops if the irrigation is done by a sewage plant or a government entity. If the irrigation is done by private farmers, secondary treatment is required plus disinfection or other such treatment, even on fiber and seed crops, to reduce the fecal coliform concentration to less than 1,000 per 100 ml (nondisinfected sewage effluent may have 1-10 million fecal coliforms per 100 ml). Forage crops, food crops cooked before consumption, and golf course irrigation require secondary treatment of the effluent and disinfection to keep fecal coliforms below 1,000 per 100 ml. The suspended solids content may be below 30 mg/L. Irrigation of vegetables and other crops consumed raw requires tertiary treatment and disinfection to keep fecal coliforms below 25 per 100 ml. Also, turbidity, roundworm eggs, tapeworm eggs, and entamoeba must be nondetectable. The same standards apply to park and playground irrigation, with the additional requirement that the virus content must be below 3 plaque-forming units per liter.

An inexpensive, simple method to treat sewage so that it can be used to irrigate all crops without danger to the public health is to use the self-purification power of soil materials (vadose zones and aquifers) in a groundwater recharge system with recovery of the water from the aquifer. With this system, sewage effluent, after some pretreatment (primary, secondary, overland flow, oxidation pond, etc.), is spread into infiltration basins (or infiltration furrows if the land is rolling) from where it seeps into the soil and down to the groundwater. The filtered or "renovated" water is then collected from the aquifer a distance away (about 100 m, for example) from the infiltration basins. The renovated water can be collected in wells or subsurface drains for reuse or disposal, or it can seep naturally into streams or other surface water (Figure 1). The latter systems are used to minimize pollution of streams or other receiving waters by giving the wastewater soil-aquifer treatment rather than discharging it directly into the surface water.

The recharge of "rapid-infiltration" systems requires permeable soils (fine sands to sandy loams). However, they are simple to operate and give a lot of treatment for the cost. The soil-filtered water can then be used to irrigate vegetables or other crops. Since such systems would permit a higher economic return from irrigation with sewage effluent than would be possible with direct irrigation of forage crops, and would also safeguard the public health, they should be considered wherever sewage is to be used for irrigation.

The infiltration basins or furrows must be regularly dried to allow atmospheric oxygen to enter the soil for decomposition of organic matter, nitrification of ammonium, and other aerobic processes. Drying also helps restore infiltration rates which normally decrease during infiltration due to accumulation of solids, algae, etc., on the soil surface. Infiltration schedules may range from 8 hours wet to 16 hours dry each day to flooding/drying periods of several weeks each. The optimum schedule depends on the local conditions of soil, climate, and

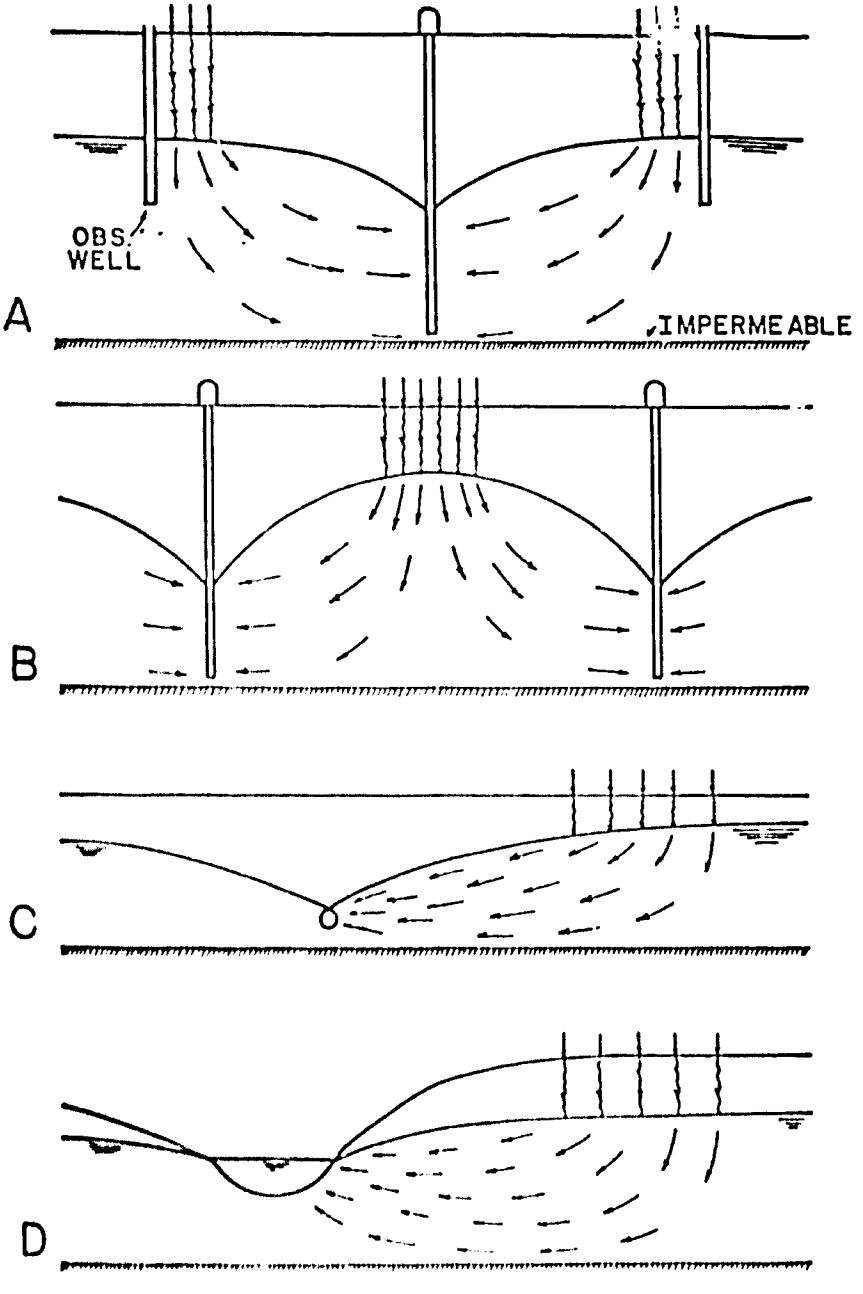

FIGURE 1 Soil-aquifer treatment systems with infiltration areas in two parallel rows and line of wells midway in between (A), infiltration areas in center surrounded by a circle of wells (B), collection of renovated water by subsurface drain (C), and natural drainage into surface water (D).

wastewater characteristics (suspended solids, biochemical oxygen demand), and whether the system is to be operated for maximum hydraulic capacity or for maximum removal of nitrogen from the water. Hydraulic loading rates of rapid-infiltration systems typically are in the range of 50 to 500 m/year (0.5 to 5.0 million m^3/yr/ha of basin area). Mechanical removal of accumulated solids from the soil surface may be periodically required to maintain high infiltration rates.

Because the bottom of infiltration basins is usually covered by a clogging layer of accumulated solids, infiltration rates are reduced, soil-water pressure heads beneath the clogged layers are negative, and the soil below the clogged layer is unsaturated. Infiltration rates for soils flooded with secondary sewage effluent typically are about one-half of the rates for clear water, which in turn are about equal to the hydraulic conductivity of the upper soil layers. In warm, arid climates, drying periods are about as long as flooding periods, so that the long-term infiltration rate, or hydraulic loading rate, will be about one-quarter of the hydraulic conductivity of the top soil expressed for the same time period. For primary effluent and/or more humid, colder climates, the ratio between hydraulic loading rate and saturated hydraulic conductivity of the soil can be much less, for example 0.1.

To allow flexibility in scheduling flooding and drying in a rapid-infiltration system, a relatively large number of basins is better than only a few basins. Since overloading of the infiltration system must be avoided, a few reserve basins should always be included to absorb the wastewater during times of low infiltration rates (rainy or cold periods, for example) or when part of the system is undergoing repair. Draining the basins by gravity at the end of a flooding period hastens the drying and gives greater hydraulic loading rates than when the basins are dried by stopping the inflow and letting all the water go into the ground by infiltration.

Suspended algae (for example, Carteria klebsii) in the wastewater should be minimized. Such organics can clog the soil and cause calcium carbonate to precipitate due to the pH increase of the wastewater as the algae absorb CO_2 from the water for photosynthesis. Growth of filamentous algae (for example, Oscillatoria sp.) on the bottom of the infiltration basins is not as serious and can actually increase infiltration rates as oxygen bubbles form in the algal mat. This causes portions of the algal mat to float to the surface, carrying suspended materials up with them and exposing fresh, "rejuvenated" basin soil.

As the wastewater (partially treated sewage effluent, for example) moves through the soil and down to the groundwater, suspended solids, bacteria, viruses, and biodegradable carbon will be almost completely removed. Some residual organic carbon, including synthetic materials, can be expected in the renovated water. Heavy metals and phosphate concentrations will be greatly reduced during passage through the unsaturated zone and aquifer, especially in calcareous materials. For secondary sewage effluent where nitrogen is mostly in the ammonium form, the nitrogen will be almost completely converted to nitrate if short, frequent infiltration periods are held. It will stay as

ammonium if infiltration periods are long and the cation exchange complex in the soil has become saturated with ammonium, and it will be partially converted to nitrogen gas and nitrogen oxides if infiltration periods are intermediate so that ammonium is absorbed in the soil during flooding and nitrified and denitrified during drying. Most of these quality improvements take place in the top meter of the unsaturated zone. However, for additional polishing treatment and safety, the travel distance of the water through the vadose zone and aquifer should always be as long as possible.

The suitability of treated sewage for irrigation of crops also depends on how well the sewage water meets the quality criteria for irrigation from an agronomic standpoint, as determined by the chemical composition of the sewage water. The chemical composition is then compared to accepted water quality standards for irrigation, such as those shown in Tables 1 and 2. If the sewage water does not meet these standards, extra treatment may be applied to remove the chemicals that exceed maximum permissible concentrations, but this is often costly. Excessive concentrations of certain chemicals (total salt content, for example) can also be reduced by mixing the sewage water with regular irrigation water. Nitrogen is one of the elements in sewage water whose concentration may have to be reduced. The concentration of heavy metals and other minor elements, which can enter the sewage water by industrial waste discharges or by the use of certain houschold products, can be reduced by control of these materials at the source.

Table 1.
Guidelines for Interpretation of Water Quality for Irrigation.

Potential Irrigation Problem	Units	Degree of Problem: No Problem	Slight to Moderate	Severe
Salinity (affects crop water availability)				
EC_w 1/	dS/m (mmhos/cm)	<0.75	0.75-3.0	>3.0
Permeability (affects infiltration rate of water into soil. Evaluate using EC_w and SAR in combination)				
SAR 2/ = 0-3	and EC_w	=>0.9	0.9-0.2	<0.2
= 3-6		=>1.3	1.3-0.25	<0.25
= 6-12		=>2.0	2.0-0.35	<0.35
= 12-20		=>3.1	3.1-0.9	<0.9
= 20+		=>5.6	5.6-1.8	<1.8
Specific ion Toxicity (affects sensitive crops)				
Sodium (Na) 3/ 4/				
Surface irrigation	SAR	<3	3.9	>9
Sprinkler irrigation	meq/ℓ	<3	>3	
Chloride (Cl) 3/ 4/				
Surface irrigation	meq/ℓ	<4	4-10	>10
Sprinkler irrigation	meq/ℓ	<3	>3	
Boron (B)	mg/ℓ	<0.75	0.75-3.0	>3.0
Heavy metals	see Table 3			
Miscellaneous Effects (affects susceptible crops)				
Nitrogen (NO_3-N or NH_4-N)	mg/ℓ	<5	5-30	>30
Bicarbonate (HCO_3) (overhead sprinkling only)	meq/ℓ	<1.5	1.5-8.5	>8.5
pH		(normal range 6.5-8.4)		

1/ EC_w means electrical conductivity (EC) of infiltrated irrigation water plus rainfall, reported in decisiemens per meter (millimhos per centimeter); dS/m x 640 ≅ mg/ℓ TDS.

2/ SAR means Sodium Adsorption Ratio. It is calculated from the equation

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

where Na, Ca, Mg respectively represent sodium, calcium, and magnesium reported in milliequivalents per liter (meq/ℓ). Within a given range of SAR, permeability problems are less likely to occur at the higher salinity than at lower. Evaluate by SAR and EC_w in combination.

3/ Most tree crops and woody ornamentals are sensitive to sodium and chloride - use values shown. Most annual crops are not sensitive - use crop tolerance tables for salinity (1, 2, 12).

4/ With overhead sprinkler irrigation during periods of low humidity (<30-40%), sodium or chloride greater than 3 meq/ℓ has frequently resulted in excessive leaf absorption and crop damage to sensitive crops.

From: R. S. Ayers and K. Tanji. Water Forum '81, Am. Soc. Civil Engineers, Vol. I, 578-586, 1981.

Table 2. Recommended maximum limits in milligrams per liter for trace elements in irrigation water (National Academy of Sciences-National Academy of Engineering, Report No. 5501-60520, Washington, D.C., 1972)

	Permanent irrigation of all soils	Up to 20 year irrigation of fine-textured, neutral to alkaline soils (pH 6.0-8.5)
Aluminum	5	20
Arsenic	0.1	2
Beryllium	0.1	0.5
Boron: sensitive crops	0.75	2
semitolerant crops	1	
tolerant crops	2	
Cadmium	0.01	0.05
Chromium	0.1	1
Cobalt	0.05	5
Copper	0.2	5
Flouride	1	15
Iron	5	20
Lead	5	10
Lithium: citrus	0.075	0.075
other crops	2.5	2.5
Manganese	0.2	10
Molybdenum	0.01	0.05[a]
Nickel	0.2	2
Selenium	0.02	0.02
Vanadium	0.1	1
Zinc	2	10

[a] For acid soils only

APPENDIX III-B

Health Aspects of Wastewater Reuse in Agriculture

Norman E. Kowal

TUNISIAN PLANS AND RECOMMENDATIONS

For several years the Tunisian government has been making plans for the application of treated municipal wastewater to agricultural land. Such reuse of wastewater is, of course, a perfectly natural operation for an arid or semiarid country with a strong agricultural economy. Construction of many of the land application systems is well under way, and several are already in operation (e.g., La Soukra, an area of about 800 ha on the northern outskirts of Tunis, soon to be followed by an additional 2,600 ha).

From a public health viewpoint, the two major concerns are protection of the drinking water supply and prevention of adverse health effects occurring through consumption of food products. The Government of Tunisia appears to be totally committed to the protection of public health in its planning and regulations and seems to have the engineering aspects well in hand. The effort appears to be well coordinated, even though several government agencies are involved (e.g., Department of Rural Engineering (DER), Department of Sanitation (ONAS), National Agronomic Institute of Tunisia (INAT), Ministry of Public Health, Department of Hydraulic Projects, and the Ministry of Higher Education and Scientific Research).

There appears to be a consensus among all the people and agencies visited that the land application of wastewater in Tunisia must be done properly and safely from the start. This attitude is to be commended, and I hope that it will be translated into actual practice and enforcement.

The most important recommendations for the success of this project concern illicit use of wastewater. Discussions during the field trip to Kairouan, a site of agricultural land application of secondary effluent, made it evident that illicit use of effluent by local farmers is likely to be a problem in future projects. The farmers see the effluent as a cheap source of badly needed irrigation water and probably do not understand the health consequences of its improper use,

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particularly on vegetables. Such use must be prevented, since it will circumvent the public health measures planned by the government.

Another recommendation concerns the disposal of wastewater by the tourist hotels along the coast. Most of these hotels presently treat their wastewater in some fashion and then pipe the effluent to the coast for ocean disposal. Since these areas are often areas of saltwater intrusion due to the heavy pumping of groundwater, it would seem more reasonable for the hotels to treat their wastewater on site and use the effluent for land irrigation. Besides ameliorating the groundwater problem, this solution would help decrease the pollution of the coastal waters as well, which is particularly important in a seaside resort.

Present plans and/or practices call for the irrigation of forage, grain, or tree crops. I recommend that the use of wastewater be restricted to such crops, since the growth of a crop whose edible portion might come into contact with the wastewater is likely to lead to health problems.

Discussions with Messrs. Ameur Horchani and Sadok Attalah suggested that of Tunisia's 28 sewage treatment plants, the stabilization ponds appear to be among the best operating plants. Other experience in warm areas of the world suggests that wastewater stabilization ponds are simple to operate and maintain and can treat wastewater efficiently (see, for example, Duncan Mara's Wastewater Treatment in Hot Climates, John Wiley & Sons, London, England). Such ponds can be recommended for Tunisia, if land values permit and if good sealing is prepared during construction.

Finally, several people have emphasized the importance of public health education for the populace as a whole but especially in areas where wastewater irrigation is used. I can only second this recommendation.

FORMAL PRESENTATIONS

The material for the formal presentations was selected from my publication, Health Effects of Land Treatment: Microbiological (EPA-600/1-82-007, May 1982, U.S. Environmental Protection Agency, Cincinnati, Ohio), and the first draft of its sequel, Health Effects of Land Treatment: Toxicological, to be published in 1984. The general areas covered are presented in the outline below; the specific material is presented in the attached lecture, which consists of sections from the two reports cited above.

INTRODUCTION

BACTERIA

- Types and Levels in Wastewater
- Aerosols
- Surface Soil and Plants
- Movement in Soil and Groundwater
- Animals
- Conclusions

VIRUSES

Types and Levels in Wastewater
Aerosols
Surface Soil and Plants
Movement in Soil and Groundwater
Animals
Conclusions

PROTOZOA

Types in Wastewater
Soil and Plants

HELMINTHS

Soil and Plants

EPIDEMIOLOGICAL STUDIES OF LAND TREATMENT SITES

ORGANICS

Types and Levels in Wastewater
Soil and Groundwater
Plants
Animals

TRACE ELEMENTS

Types and Levels in Wastewater
Soil and Plants
Groundwater
Animals

NITROGEN

Groundwater

LECTURE

Introduction

In 1978, the U.S. General Accounting Office concluded that greater use of land application as an alternative wastewater treatment technique is needed because it provides the benefits of (1) the elimination of point discharge to surface waters, (2) higher levels of treatment than generally provided by conventional secondary treatment, and (3) recharge of groundwaters.

There are three types of land treatment systems in general use: slow rate ("irrigation"); rapid infiltration ("infiltration-percolation"), and overland flow. Slow rate is the most commonly used

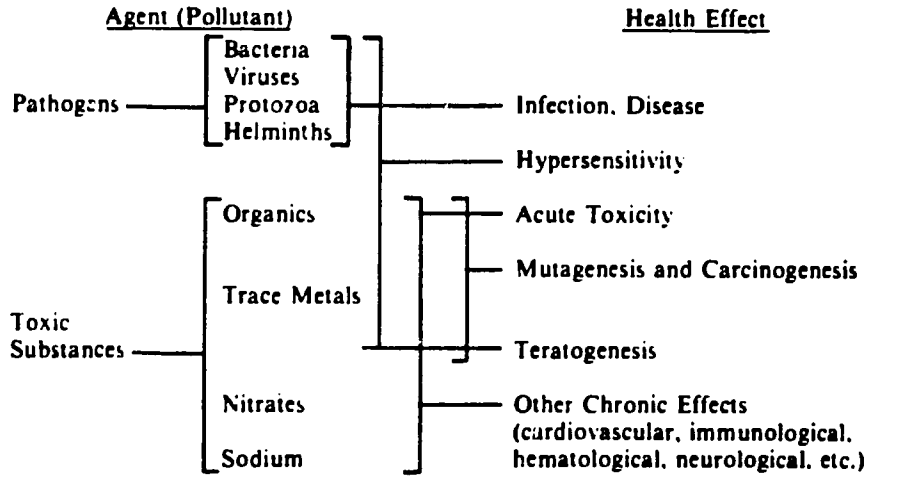
land treatment system. Wastewater, usually pretreated by some process, is applied by sprinklers, surface flooding, or ridge-and-furrow irrigation, at a rate of 2-20 feet (0.6-6.0 m) per year. Soils are usually medium- to fine-textured with moderate permeability, and percolated water is either collected by drainage tile or reaches the groundwater. Surface vegetation has included lawns and golf courses (for highly treated wastewater), pastures, and forests, but is most commonly crops, usually for animal consumption. Climatic constraints often require some winter storage of wastewater (Reed 1979). Recycling benefits include moderate groundwater recharge and the utilization of wastewater nutrients in crop production.

In rapid infiltration, wastewater is flooded, usually intermittently, into shallow basins at a rate of 20-600 feet (6-183 m) per year. Soils are usually coarse-textured with high permeability, and percolated water moves to groundwater, recovery wells, or underdrains. Surface vegetation is usually absent, and climatic constraints are not of concern (Reed 1979). Groundwater recharge is a recycling benefit.

Overland flow is the least commonly used land treatment system. Wastewater is applied to the top of gently sloping (2-4 percent) fields at a rate of 10-70 feet (3-21 m) per year, and moves by sheet flow down the slope to collection ditches at the base. Soils are usually fine-textured with very low permeability. Climatic constraints may require some winter storage of wastewater (Reed 1979). Recycling benefits may include the utilization of wastewater nutrients in harvested grass for animal forage.

With the application to land of large volumes of minimally pretreated wastewater, it is evident that considerable potential for adverse health effects exists (see Table 1).

TABLE 1 Major Health Effects of Pollutants



Bacteria

Campylobacter jejuni (formerly C. fetus subsp. jejuni) is a recently recognized cause of acute gastroenteritis with diarrhea. It is now thought to be as prevalent as the commonly recognized enteric bacteria Salmonella and Shigella, having been isolated from the stools of 4-8 percent of patients with diarrhea (MMWR 1979) (see Table 2). The total bacterial content of raw wastewater, as recovered on standard media at 20°C (Carnow et al. 1979), is about 10^6-10^7 organisms/ml. The presence and levels in wastewater of any of the pathogens listed in Table 2 depend, of course, on the levels of infection in the contributing population.

TABLE 2 Pathogenic Bacteria of Major Concern in Wastewater

Name	Nonhuman Reservoir
Campylobacter jejuni	Cattle, dogs, cats, poultry
Escherichia coli (pathogenic strains)	--
Leptospira spp.	Domestic and wild mammals, rats
Salmonella paratyphi (A, B, C)*	--
Salmonella typhi	--
Salmonella spp.	Domestic and wild mammals, birds, turtles
Shigella sonnei, S. flexneri, S. boydii S. dysenteriae	--
Vibrio cholerae	--
Yersinia enterocolitica, Y. pseudotuberculosis	Wild and domestic birds and mammals

*Correct nomenclature: Salmonella paratyphi A, S. schottmuelleri, S. hirschfeldii, respectively.

Where wastewater is applied to the land by spray equipment (e.g., impact sprinklers, fan sprinklers, rain guns, and fixed-aperture rocker-arm sprayers), aerosols that travel beyond the wetted zone of application will be produced (Shaub et al. 1978a). These are suspensions of solid or liquid particles up to about 50 μm in diameter, formed, for example, by the rapid evaporation of small droplets. Their content of microorganisms depends on the concentration in the wastewater and the aerosolization efficiency of the spray process--a function of nozzle size, pressure, angle of spray trajectory, angle of spray entry to the wind, impact devices, etc. (Schaub et al. 1978a).

Although aerosols represent a means by which pathogens may be deposited on fomites such as clothing and tools, the major health concern with aerosols is the possibility of direct human infection through the respiratory route, i.e., by inhalation.

When aerosols are generated, bacteria are subject to an immediate "aerosol shock," or "impact factor," which may reduce their level by one log within seconds (Schaub et al. 1978a). There is some evidence that this might be caused by rapid pressure changes (Biederbeck 1979). Their survival is subsequently determined primarily by relative humidity and solar radiation (Carnow et al. 1979, Teltsch and Katzenelson 1978).

More recent data from Kibbutz Tzora in Israel allow a more accurate estimate of human exposure (Teltsch et al. 1980). During a period of time in 1977-1978, when the wastewater total coliforms were 2.4×10^6 to 1.4×10^7/100 ml and Salmonella was 0-60/100 ml, the density of aerosol Salmonella at 40 m, the maximum distance found was 0-0.054/m^3, with a mean of 0.014m^3. This would result in an inhalation rate of 0.017/hr at 40 m, higher than the previous estimate, but still an extremely low rate of bacterial exposure.

The survival time of bacteria in surface soil and on plants is only of concern when deciding how much time must be allowed after the last application before permitting access to people or animals, or harvesting crops.

The factors affecting bacterial survival in soil (Gerba et al. 1975, USEPA 1977) are:

1. Moisture content. Moist soils and periods of high rainfall increase survival time. This has been demonstrated for Escherichia coli, Salmonella typhi, and Mycobacterium avium.

2. Moisture-holding capacity. Survival time is shorter in sandy soils than those with greater water-holding capacity.

3. Temperature. Survival time is longer at lower temperatures (e.g., in winter).

4. pH. Survival times are shorter in acid soils (pH 3-5) than in neutral or alkaline soils. Soil pH is thought to have its effect through control of the availability of nutrients or inhibitory agents. The high level of fungi in acid soils may play a role.

5. Sunlight. Survival time is shorter at the surface, probably due to desiccation and high temperatures, as well as ultraviolet radiation.

6. Organic matter. Organic matter increases survival time, in part due to its moisture-holding capacity. Regrowth of some bacteria (e.g., Salmonella) may occur in the presence of sufficient organic matter. In highly organic soils, anaerobic conditions may increase the survival of Escherichia coli (Tate 1978).

7. Soil microorganisms. The competition, antagonism, and predation encountered with the endemic soil microorganisms decrease survival time. Protozoa are thought to be important predators of coliform bacteria (Tate 1978). Enteric bacteria applied to sterilized soil survive longer than those applied to unsterilized soil.

The survival of bacteria on plants, particularly crops, is especially important since these may be eaten raw by animals or humans, may contaminate hands of workers touching them, or may contaminate equipment contacting them (see Table 3). Such ingestion or contact would probably not result in an infective dose of a bacterial pathogen, but if contaminated crops are brought into the kitchen in an unprocessed state they could result in the regrowth of pathogenic bacteria (e.g., Salmonella) in a food material affording suitable moisture, nutrients, and temperature (Bryan 1977).

It is generally believed that the removal of bacteria at land treatment sites occurs primarily by filtration, or straining, with most bacteria retained within about 50 cm of the soil surface. Under optimum conditions 92-97 percent of coliforms have been observed to be trapped in the first centimeter of soil (Gerba et al. 1975). Coarse sandy or gravelly soils or fissured subsurface geology would, of course, allow the bacteria to penetrate to great depths. Adsorption of bacteria also plays a secondary role, being increased by the presence of clay-sized particles, high cation concentration, and low pH. This adsorption is reversible, and the bacteria can be released and moved

TABLE 3 Contamination Periods for Soil and Plants.

	Soil		Plants	
Pathogen	Absolute maximum	Common maximum	Absolute maximum	Common maximum
Bacteria	1 year	2 months	6 months	1 month
Viruses	6 months	3 months	2 months	1 month
Protozoa	10 days	2 days	5 days	2 days
Helminths	7 years	2 years	5 months	1 month

down the soil profile by distilled water or any water with low conductivity, such as rainfall (Sagik et al. 1978).

It is evident that most slow-rate sites pose little threat to the groundwater but that the combination of high bacterial densities and shallow water table, resulting in seeping, such as that at the San Angelo site, should be avoided. The data suggest that bacteria at rapid-infiltration sites may penetrate about 10 m vertically and variable distances laterally. These distances are, of course, highly site-specific, and the vertical distance may be more than 10 m but is usually much less.

The major bacterial concerns with respect to animals grazing at land treatment sites are Salmonella infections and bovine tuberculosis (Mycobacterium bovis and M. tuberculosis); both can be passed on to man. On the basis of Salmonella measurements in wastewater and sludge in England, Jones et al. (1980) concluded that a 4-week waiting period would prevent salmonellosis in grazing animals.

Several investigations on tuberculosis infection of cattle grazing on wastewater-irrigated land have been undertaken in Germany, with the conclusion that if application is stopped 14 days before pasturing, grazing cattle will not contract bovine tuberculosis (Sepp 1971).

Viruses

Viruses found in human wastewater include:

- Enteroviruses
  - Poliovirus
  - Coxsackievirus A
  - Coxsackievirus B
  - Echovirus
  - New Entero
- Hepatitis A virus
- Rotavirus ("Duovirus," "Reovirus-like agent")
- Norwalk-like agents (Norwalk, Hawaii, Montgomery County, etc.)
- Adenovirus
- Reovirus
- Papovavirus
- Astrovirus
- Calicivirus
- Coronavirus-like particles

The concentrations reported in the literature may be as little as one-tenth to one-hundredth of the actual concentrations because of the limitations of virus recovery procedures and the use of inefficient cell-culture detection methods (Akin et al. 1978, Keswick and Gerba 1980). (The use of several cell lines usually detects more viral types than a single cell line does, and many viruses such as hepatitis A virus and Norwalk-like agents cannot yet be detected by cell-culture methods.) Some representative levels of enteric viruses in raw U.S.

wastewaters are summarized by Kowal (1982). It is evident that reported concentrations are highly variable; Akin and Hoff (1978) have concluded that "...from the reports that are available from field studies and with reasonable allowances for the known variables, it would seem extremely unlikely that the total concentration would ever exceed 10,000 virus units per liter of raw sewage and would most often contain less than 1,000 virus units/liter."

The initial aerosol shock during the process of aerosolization may result in a half-log loss of virus level (Sorber 1976). The subsequent die-off, estimated to be about one log every 40 seconds (Sorber 1976), is determined primarily by solar radiation, temperature, and relative humidity (Lance and Gerba 1978).

The results obtained from these two studies are highly variable, but it appears reasonable to make use of the Pleasanton aerosol virus density (i.e., $0.014/m^3$), to make human exposure estimates.

From these data it can be calculated that an adult male, engaged in light work, breathing at a rate of 1.2 m^3/hr and exposed to 0.014 PFU/m^3 at 50 m downwind from a sprayer, would inhale approximately 0.13 PFU of enterovirus during an 8-hour work day. This is probably an insignificant level of exposure. However, since (1) the recovery of enteric viruses from environmental samples is not perfectly efficient, (2) isolation of viruses increases as more cell culture types are used, and (3) some enteric viruses cannot yet be isolated on cell cultures, the actual exposure to enteric viruses may be as much as 10-100 times the reported level (Teltsch et al. 1980). Thus, it might be prudent to recommend that a land treatment spray source be kept to a minimum exposure distance of 100 m or 200 m from the general public.

The factors affecting virus survival in soil are solar radiation, moisture, temperature, pH, and adsorption to soil particles. The soil microorganisms appear to have a less important effect on virus degradation.

Virus removal is almost totally dependent on adsorption. Thus, in contrast with bacteria, filtration plays a minor role in the removal of viruses in soils. Since adsorption is a surface phenomenon, soils with a high surface area (i.e., those with a high clay content) would be expected to have high virus removal capabilities. Although the physical-chemical reasons for virus adsorption to soil surfaces are poorly understood, it appears that adsorption is increased by high cation exchange capacity, high exchangeable aluminum, low pH (below 5), and increased cation concentration (Gerba and Lance 1980). As the flow rate, or application rate, increases, virus removal declines (Lance and Gerba 1980, Vaughn et al. 1981).

Upon application of wastewater to land, most viruses are adsorbed in the top few centimeters of the soil profile. After being adsorbed to the soil, viruses may remain infective and, under certain conditions, may be desorbed and migrate down the soil profile. As a result of such migration, viruses have been detected in the groundwater beneath several rapid-infiltration land treatment sites. It might be advisable, therefore, to site rapid-infiltration systems only on fine sandy soils, avoiding coarse gravelly or organic soils, and to apply the effluent intermittently, allowing the soil to dry between

applications. Drying should help to inactivate both viruses and bacteria and has recently been recommended by Hurst and colleagues (1980a) to prevent virus contamination of groundwater.

Protozoa

The protozoa and helminths (or worms) are often grouped together under the term "parasites," although biologically all pathogens are parasites. Because of the large size of protozoan cysts and helminth eggs, compared with bacteria and viruses, it is extremely unlikely that they will find their way into either aerosols or groundwater at land treatment sites; thus, these routes of exposure are not further considered here.

Only three species of protozoa are of major significance for transmission of disease to humans through wastewater: Entamoeba histolytica, Giardia lamblia, and Balantidium coli.

The types and levels of protozoan cysts that are actually present in wastewater depend on the levels of disease in the contributing human population and on the degree to which animals contribute to the system.

It should be noted that protozoan cysts are highly sensitive to drying.

Helminths

The presence and levels in wastewater of any of the helminth eggs from humans, or of those from animal feces (Ancylostoma, Toxocara, and Echinococcus), depend on the levels of disease in the contributing population, and the degree of animal contribution to the system.

Helminth eggs and larvae, in contrast to protozoan cysts, live for long periods when applied to the land, probably because soil is the transmission medium for which they have evolved and protozoa have evolved toward water transmission. Thus, under favorable conditions of moisture, temperature, and sunlight, the helminths Ascaris, Trichuris, and Toxocara can remain viable and infective for several years (Little 1980). Hookworms can survive up to 6 months (Feachem et al. 1978); and Taenia, a few days to 7 months (Babayeva 1966); other helminths survive for shorter periods.

Because of desiccation and exposure to sunlight, helminth eggs deposited on plant surfaces die off more rapidly. Thus, Rudolfs and colleagues (1951c) found Ascaris eggs, the longest-lived helminth egg, sprayed on tomatoes and lettuce, to be completely degenerated after 27-35 days.

The most serious threat to cattle at land treatment sites is the beef tapeworm, Taenia saginata (Feachem et al. 1978). The increased incidence of cysticercosis in cattle results in economic losses (because of condemnation of carcasses), as well as increased incidence of disease in man.

Epidemiology

Perhaps the largest epidemiological study of the health effects of land treatment was a retrospective study of 77 kibbutzim (agricultural cooperative settlements) in Israel practicing slow-rate land treatment with nondisinfected oxidation pond effluent, and 130 control kibbutzim (Katzenelson et al. 1976). The incidence of typhoid fever, salmonellosis, shigellosis, and infectious hepatitis was 2-4 times higher in the land-treatment kibbutzim than the controls. The study, however, did not rule out a number of pathways of infection other than aerosols (e.g., direct contact via clothing or bodies of sewage irrigation workers), and there were problems with the data reporting methods. Consequently, it is generally believed that no conclusive findings may be based on the report, and the study is currently being repeated, correcting for the deficits of the original study (Shuval and Fattal 1980). Preliminary results suggest little effect of land treatment on disease incidence.

Although these retrospective studies are reassuring, a better measure of the health effects of land treatment will come from well-planned prospective epidemiological studies. Two such studies are currently under way--at Lubbock, Texas, and in Israel. The results of these two projects may, in the future, modify the conclusions and recommendations made here.

Organics

The potential adverse health effects of toxic organic compounds are myriad. Systems affected range from the dermatological to the nervous to the subcellular, and effects produced range from rash to motor dysfunction to cancer. The degree of toxicity of organic compounds varies widely, from essentially harmless (e.g., most alcohols) to extremely toxic (e.g., dioxin).

A glance at the current edition of The Merck Index (Windholz et al. 1976) will reveal that the number of organic compounds described thus far is almost unfathomable. Almost any of these may appear in wastewater, depending on its sources. Thus, the discussion below must be rather general, and the presence of any particular toxic organic in high concentration in the wastewater may require a site-specific evaluation of potential adverse health effects.

Most common organics in domestic wastewater derive from feces, urine, paper products, food wastes, detergents, and skin excretions and contaminants (from bathing).

Although most of the organics found in domestic wastewater are probably harmless in a land treatment context, it has recently been found that fecal material commonly contains mutagens. Thus, there is evidence that one of the causes of colorectal cancer is the presence of carcinogens or co-carcinogens produced by the bacterial degradation, in the gut, of bile acids or cholesterol (Thornton 1981).

Ten domestic and industrial secondary effluents in Illinois were examined for mutagenicity by Johnston et al. (1982), with the results that all 10 effluents assayed showed significant mutagenicity.

There was no obvious influence of disinfection by chlorination on the effluent mutagenicity, in spite of the fact that one would expect many mutagens to be formed by the action of chlorine on humic substances and other organics found in wastewater.

The major contributors of toxic organics to municipal wastewaters are usually assumed to be industrial discharges. However, household wastewater discharge may represent an important contributor since many consumer products in daily use contain toxic substances. A recent study (Hathaway 1980) identified consumer products containing toxic compounds, on EPA's list of 129 priority pollutants, which may eventually end up in wastewater. The most frequently used products are cleaning agents and cosmetics, containing solvents and heavy metals as main ingredients. Next are deodorizers and disinfectants, containing naphthalene, phenol, and chlorophenols. Discarded into wastewater infrequently, but in large volumes, are pesticides, laundry products, paint products, polishes, and preservatives. The organic priority pollutants most frequently used and discharged into domestic wastewater were predicted to be the following. They are listed in order of importance.

benzene
phenol
2,4,6-trichlorophenol
2-chlorophenol
1,2-dichlorobenzene
1,4-dichlorobenzene
1,1,1-trichloroethane
naphthalene
toluene
diethylphthalate
dimethylphthalate
trichloroethylene
aldrin
dieldrin

Because of the difficulty of analysis of complex mixtures, it has only recently been possible to measure the actual levels of organics in wastewater, using advanced methods of extraction, gas and other chromatography, mass spectrometry, and computer analysis. The U.S. Environmental Protection Agency has sponsored two extensive surveys of the types and levels of priority pollutants in municipal wastewaters, which, of course, result from both domestic and industrial discharges.

Comparison of the results of the surveys, together with the list of organic priority pollutants most likely to be discharged into domestic wastewater, reveals considerable overlap and gives one some confidence that these two studies have yielded a reasonable characterization of the priority organics in municipal wastewater, at least of those identifiable by modern methods. The broad range of concentrations

detected among the samples, however, suggests that wastewater applied to land should be regularly monitored for toxic organics.

Organic compounds in wastewater may be volatilized, immobilized by adsorption, or transported through the soil column, possibly to reach the groundwater. Adsorbed organics may be subsequently chemically or photochemically degraded, microbially decomposed, or desorbed. A considerable body of research on the behavior of pesticides in soil has shown that the affinity of soil materials for pesticides, and presumably for organics in general, decreases in the following order (Chang and Page 1978):

1. Organic Matter
2. Vermiculite
3. Montmorillonite
4. Illite
5. Chlorite
6. Kaolinite

The potential of microbial decomposition for removal of organics is demonstrated by the experience at two rapid infiltration land treatment sites. At Flushing Meadows in Arizona, secondary effluent has resulted in no accumulation of organic carbon in the soil after 10 years of operation and 754 m of total infiltration (Bouwer and Rice 1978). The Lake George Village Sewage Treatment Plant in New York has been applying unchlorinated secondary effluent to natural delta sand beds by rapid infiltration since 1939 (Aulenbach and Cleceri 1978). After about 40 years of daily infiltration rates of 0.08 to 0.30 m/day, there were no indications that the soil's capacity to treat the applied effluent was approaching exhaustion. The greatest removal of constituents occurred in the top 10 m of the sand beds.

In view of the great variety of organic compounds, it is difficult to generalize about their biodegradation in soil. It appears, however, that most organics do become microbially decomposed in the soil, at least to some extent. This is especially true of naturally occurring compounds, or those resembling them, because of the eons of evolution that have developed effective microbial enzyme systems. The more structurally complex the molecule is (e.g., condensed rings or dense branching) and the more halogenated it is, the more difficult is biodegradation.

Data for the transport of organics to groundwater exist from two slow-rate land treatment sites, a prototype system operated by the U.S. Army Cold Regions Research and Engineering Laboratory in Hanover, New Hampshire (Jenkins and Palazzo 1981), and the Muskegon, Michigan system. The New Hampshire prototype site showed good removals for natural chloroform and toluene in the wastewater, and greater than 98 percent removal for four spiked volatile organics. At the Muskegon system (Demiyian et al. 1981) there was no evidence for slight accumulation of organics after 7 years of operation. In the drain tile effluent (at a depth of 5-12 feet) there was sporadic occurrence of approximately 1 μg/l levels of chloroform, 1,2-dichlorethane, and 2-chloroaniline, the latter probably from lagoon seepage. Also in the effluent were 1 μg/l levels of the herbicides simazine and atrazine.

At the low concentrations found in the soil at municipal wastewater land treatment sites, very few organic compounds are likely to be toxic to plants. In a review of data on over 130,000 chemicals, Kenaga (1981) found only 0.17 percent of the chemicals killed seeds or seedlings at concentrations of 0.1-0.99 ppm. These plants, although not injured themselves, may accumulate organics that may be toxic to animals to which they are fed or to humans who use them as food, either directly or through animal products.

Among the organics, the pesticides appear to be the most notorious accumulators in crop plants. Thus, heptachlor, dieldrin, and chlordane are absorbed at low levels from the soil (Brande et al. 1978). Most herbicides, of course, are readily taken up and translocated within plants, but there is no reason to think that herbicides would present more of a problem at land treatment sites than they do at ordinary agricultural sites.

In contrast with pesticides, most organic compounds are only poorly absorbed and translocated by plants, with much of the "absorption" probably accounted for by root adsorption. The literature, however, in this area is sparse.

At the operating land treatment site in Muskegon, corn crop samples for 1980 did not contain detectable levels of any of the chemicals tested, and it was concluded that plant uptake of irrigated organic chemicals does not occur to any measurable extent (Demirjian et al. 1981).

The low levels of toxic organics to be expected in the above-ground portions of plants growing at land treatment sites probably pose little hazard to animals feeding on them. Under certain site-specific conditions, however, high concentrations of particular organics in the wastewater may cause problems. For example, PCBs (polychlorinated biphenyls) in cabbage grown on sludge-amended soil have probably caused degenerative changes in liver and thyroid of sheep (Kienholz 1980), and one can extrapolate a similar phenomenon to a land treatment site.

A more serious route of exposure by animals to toxic organics is the soil itself. Most grazing animals ingest a certain amount of soil together with their food plants. Thus, dairy cows may ingest 100-500 kg of soil per year, with an average of about 200-300 kg/yr: expressed in other terms, dairy cows may consume soil up to 14 percent of dry matter intake when available forage is low and no supplemental feed is used (Kienholz 1980, Fries 1980). Lipophilic organics present in the soil may concentrate in animal fat. For example, feeding experiments with PCBs indicate that the steady-state milk fat concentrations are about 5 times the diet concentrations, which could result in milk fat levels of 0.7 ppm for each 1 ppm of PCBs in surface soil (Fries 1980). Body fat levels would be expected to be similar.

Trace Elements

The trace elements (including the "heavy metals") in wastewater of public health concern--that is, those for which primary drinking water standards (USEPA 1977) exist (but excluding silver)--are:

	Primary Drinking water Standard (mg/L)
Arsenic (As)	0.05
Barium (Ba)	1.0
Cadmium (Cd)	0.010
Chromium (Cr)	0.05
Lead (Pb)	0.05
Mercury (Hg)	0.002
Selenium (Se)	0.01

Cadmium, lead, and mercury are usually regarded as of most concern, and barium of minor concern. Chromium and selenium are essential elements in man; arsenic and cadmium have been shown to be essential to experimental animals and, thus, are probably essential to man as well (National Research Council 1980).

Arsenic is popularly known as an acute poison, but chronic human exposure to low doses, as might be expected for all trace elements as a result of land treatment, may cause weakness, prostration, muscular aching, skin and mucosal changes, peripheral neuropathy, and linear pigmentations in the fingernails. Chronic arsenic intoxication may result in headache, drowsiness, confusion, and convulsions (Underwood 1977). Epidemiological evidence has implicated arsenic as a carcinogen, but there is little evidence that arsenic compounds are carcinogenic in experimental animals (Sunderman 1977). Even with high concentrations in soil, however, plants rarely take up enough of the element to constitute a risk to human health (Underwood 1977, Council for Agricultural Science and Technology 1976).

Barium has a low degree of toxicity by the oral route. Because of its effect of intensely stimulating smooth, striated, and cardiac muscle in acute exposures, however, it may have cardiovascular effects in low doses, but this has not thus far been demonstrated (Brenniman et al. 1979).

Cadmium is widely regarded as the trace element of most concern from a human health effects viewpoint in the land application of sludge, and this status probably carries over into the land treatment of wastewater as well. The critical health effect of chronic environmental exposure via ingestion is renal tubular damage due to accumulation of cadmium in the kidney. The initial consequence of this damage is the loss of low molecular weight serum proteins in the urine, followed by loss of other proteins, glucose, amino acids, and phosphate. This kidney damage is often irreversible and constitutes a significant adverse health effect (Ryan et al. 1982). There is evidence that the absorption and/or toxicity of cadmium are antagonized by zinc, selenium, iron, and calcium (Sandstead 1977). The carcinogenicity of cadmium is controversial; the epidemiological evidence is tenuous, but the experimental evidence is more supportive of cadmium being a carcinogen (Sunderman 1977).

Chromium is much more toxic in its hexavalent form than its trivalent form, its predominant state in wastewater and soil. Chronic oral exposure in experimental animals has been associated with growth depression and with liver and kidney damage (Underwood 1977). Hexavalent chromium causes respiratory cancer on chronic exposure to chromate dust (Sunderman 1977). Most crops absorb relatively little chromium from the soil (Council for Agricultural Science and Technology 1976).

Lead chronic toxicity is characterized by neurological defects, renal tubular dysfunction, and anemia. Damage to the central nervous system is common, especially in children, who have low lead tolerance, resulting in physical brain damage, behavioral problems, intellectual impairment, and hyperactivity. At soil pH above 5.5 and high labile phosphorus content, common conditions at a land treatment site, little movement of lead from the soil into plant tops and seed would be expected (Council for Agricultural Science and Technology 1976, Stewart 1979).

Mercury in low levels can result in neurological symptoms such as tremors, vertigo, irritability, and depression, as well as salivation, stomatitis, and diarrhea. Mercury can enter plants through the roots and appears to be readily translocated throughout the plant (Council for Agricultural Science and Technology 1976), although there is some contrary evidence (Stewart 1979).

Selenium exposure in its chronic form is associated with dental caries, jaundice, skin eruptions, chronic arthritis, diseased fingernails and toenails, and subcutaneous edema. It has also been found to have an inhibitory effect against several types of cancer (Fishbein 1977). Selenium is readily taken up by plants and passed onto animals and has caused toxicity in livestock in high-selenium soils (Council for Agricultural Science and Technology 1976, Underwood 1977).

From ranges of levels of trace elements in untreated municipal wastewater in the United States, together with recommended irrigation water quality criteria, it is evident that the trace elements in wastewater most likely to violate agricultural irrigation criteria are cadmium and chromium. The high levels of these two elements found in certain municipal wastewaters are doubtlessly due to industrial sources, such as electroplating operations. Since chromium is poorly absorbed from the soil by crops, cadmium is probably the element of greatest public health concern.

Limits for the maximum cumulative application of trace elements to agricultural land have been recommended by various governmental agencies, for the protection of public health and the prevention of phytotoxicity. These limits have almost invariably been proposed in the context of the land application of sludge but should be just as valid for land treatment of wastewater, at least in the slow-rate mode. Limits for rapid infiltration and overland flow could be less restrictive because of the lack of production of crops for human

consumption and the greater depth of soil involved in treatment (in the former case). These limits have been used, together with typical wastewater levels of trace elements, by Page and Chang (1981) to predict the useful life of a typical land treatment site where crops are grown for human consumption. It is evident that cadmium, with a limit of 17-67 years, is the element most likely to restrict the use of wastewater for irrigation of crops for human consumption. In the case of crops not for human consumption, other elements may be limiting--in particular molybdenum because of its toxicity to livestock, and nickel because of its phytotoxicity. These latter elements yield limits of 47-48 years in Page and Chang's analysis.

Trace elements, of course, are conservative materials, in contrast to organics and pathogens, which may become inactivated and decomposed. Thus, one would expect cadmium to build up in the soil at a land treatment or irrigation site. Our major hope, from a health effects point of view, is that it will become immobilized in the soil and less available for plant uptake as time passes. There is some suggestion of this in Hinesely's data (Hinesley et al. 1979) on cadmium content of corn grain and leaves, grown during and after the termination of wastewater sludge application. It is of interest to note that the cadmium content of the grain approached that of control grain within 3 years after termination of sludge applications, even though the cumulative cadmium application was 58.3 kg/ha, almost 3 times the maximum recommended limit of 20 kg/ha. The issue of cadmium uptake by plants after annual vs. cumulative application limits and the effect of discontinuing application remain unsettled, however (Ryan et al. 1982).

That trace elements can increase in plants at land treatment sites is documented by results at Werribee Farm in Melbourne, Australia, where, after more than 70 years of primary effluent irrigation, trace element levels in both soil and plants have increased with cumulative input loads (Croxford 1978). Similar levels of cadmium, but lower levels of chromium, have been found in vegetables grown at a site in Santiago, Chile, where the city's untreated wastewater has been applied for over 40 years (Schalscha et al. 1978).

Slow-rate land treatment appears to stabilize trace elements, and prevent their entry into the groundwater. Thus, at the prototype land treatment system in Hanover, New Hampshire, trace elements were found to be removed quickly in the first several centimeters of soil and did not seem to move deeper into the profile, even after 5 years following termination of the trace element spiking into the wastewater (Jenkins and Palazzo 1981). After 18 years of slow-rate irrigation with wastewater at the San Angelo, Texas, site, concentrations of cadmium, chromium, and lead were below drinking water standards in seepage creeks, shallow ground walls, and deep walls within the sewage farm (Hossner et al. 1978).

Rapid-infiltration sites, in contrast, appear to present some threat to groundwater. After 30 years of primary wastewater infiltration at the Hollister, California, site, concentrations in shallow groundwater of cadmium (0.028 mg/L) and lead (0.09 mg/L) were above drinking water standards, but arsenic, barium, chromium, mercury, and selenium were below (Pound et al. 1978).

The accumulation of trace elements in cattle grazed on sludge-amended pastures has revealed raised levels in liver and kidney but not in muscle tissue (Bertrand et al. 1981a). No increases were seen when cattle were fed sludge-amended, soil-grown forage sorghum (Bertrand et al. 1981b). It may not be fair, however, to extrapolate from sludge-amended land, where high levels of trace elements in soil may be expected, to land treatment sites. Experience at Werribee Farm in Melbourne, Australia, where cattle are grazed on pastures irrigated by wastewater, has shown higher organ levels of cadmium and chromium than in farm cattle grazed on nonirrigated pastures, but comparable to nonfarm cattle. Organ levels of lead, however, did not increase, despite increases in both soil and pasture plants.

Since trace elements accumulate in very small quantities in animal muscle tissue, there is probably little concern about nonvisceral meats in the marketplace. Liver and kidneys of animals, however, do accumulate high levels of cadmium, just as they do in man, so that these meats may be of concern to people who consume large quantities of them.

Nitrogen

Inorganic nitrogen is normally quite innocuous from a human health point of view, although high ammonia levels can present an aesthetic problem. The major health concern is that infants who are less than about 3 months of age and consume large quantities of high-nitrate drinking water through prepared formula have a high risk of developing methemoglobinemia. The incompletely developed capacity to secrete gastric acid in the infant allows the gastric pH to rise sufficiently to encourage the growth of bacteria which reduce nitrate to nitrite in the upper gastrointestinal tract. The nitrite is absorbed into the bloodstream and oxidizes the ferrous iron in hemoglobin to the ferric state, in which form it is incapable of carrying oxygen. The relevance of land treatment, of course, centers on the possibility of highly soluble nitrates reaching groundwater that may be used as a potable water supply.

The threat of nitrates to groundwater is less at slow-rate than rapid-infiltration sites because of lower application rates and the presence of plant uptake. (Overland flow systems should not affect groundwater.)

It is evident that many rapid-infiltration systems result in groundwater nitrate concentrations above the 10 mg/L drinking water standard. Many of these systems could improve their performance by decreasing the loading rate (thus allowing more time for within-soil treatment), increasing the C:N ratio (particularly by using primary effluent instead of secondary), and/or optimizing the flooding-drying sequence.

REFERENCES

Akin, E.W., et al. 1978. Health hazards associated with wastewater effluents and sludge; Microbiological considerations. Pp. 9-26 in Proceedings of the Conference on Risk Assessment and Health Effects of Land Application of Municipal Wastewater and Sludges, B.P. Sagik and C.A. Sorber, eds. University of Texas at San Antonio, San Antonio, Texas, USA.

Aulenbach, D.B., and N.L. Clesceri. 1978. The Lake George Village (N.Y.) land application system. Pp. 27-35 in State of Knowledge in Land Treatment of Wastewater, Vol. 2, H.L. McKim, ed. U.S. Army Corps of Engineers, CRREL, Hanover, New Hampshire, USA.

Babayeva, R.I. 1966. Survival of beef tapeworm oncospheres on the surface of the soil in Samarkand. Med. Parazitiol. Parazit. Bolezn 35:557-560.

Bertrand, J.E., et al. 1981a. Metal residues in tissue, animal performance, and carcass quality with beef steers grazing Pensacola Bahiagrass pastures treated with liquid digested sludge. J. Animal Sci. 53:146-153.

Bertrand, J.E., et al. 1981b. Animal performance, carcass quality, and tissue residues with beef steers fed forage sorghum silages grown on soil treated with liquid digested sludge. Proc. Soil Crop Sci. Soc. Florida 40:111-114.

Biederbeck, V.O. 1979. Reduction of fecal indicator bacteria in sewage effluent when pumping for crop irrigation. J. Environ. Sci. Health B14:475-493.

Bouwer, H., and R.C. Rice. 1978. The Flushing Meadows Project. Pp. 213-220 in State of Knowledge in Land Treatment of Wastewater, Vol. 1, H. L. McKim, ed. U.S. Army Corps of Engineers, CRREL, Hanover, New Hampshire, USA.

Brande, G.L., et al. 1978. Use of wastewater on land--Food chain concerns. Pp. 59-65 in State of Knowledge in Land Treatment, Vol. 1, H.L. McKim, ed. U.S. Army Corps of Engineers, CRREL, Hanover, New Hampshire, USA.

Brenniman, G.R., W.H. Kojola, P.S. Levy, B.W. Carnow, T. Namakata, and E.C. Breck. 1979. Health Effects of Human Exposure to Barium in Drinking Water. EPA-600/1-79-003. U.S. Environmental Protection Agency, Cincinnati, Ohio, USA.

Bryan, F.L. 1977. Diseases transmitted by foods contaminated by wastewater. J. Food Protection 40:45-56.

Carnow, B., et al. 1979. Health Effects of Aerosols Emitted from an Activated Sludge Plant. EPA-600/1-79-019. U.S. Environmental Protection Agency, Cincinnati, Ohio, USA.

Chang, A.C., and A.L. Page. 1978. Toxic chemicals associated with land treatment of wastewater. Pp. 47-57 in State of Knowledge in Land Treatment of Wastewater, Vol. 1, H.L. McKim, ed. U.S. Army Corps of Engineers, CRREL, Hanover, New Hampshire, USA.

Council for Agricultural Science and Technology. 1976. Application of Sewage Sludge to Cropland: Appraisal of Potential Hazards of the Heavy Metals to Plants and Animals. EPA-430/9-76-013. U.S. Environmental Protection Agency, Washington, D.C., USA.

Croxford, A.H. 1978. Melbourne, Australia, Wastewater System--Case Study. Paper No. 78-2576, American Soc. Agric. Eng. Winter Meeting, Chicago, Illinois, USA.

Demirjian, A., et al. 1981. The Fate of Organic Pollutants in a Wastewater Land Treatment System Using Lagoon Impoundment and Spray Irrigation. Progress Report for Grant No. CR-806873. Muskegon County Wastewater Management System and Department of Public Works, Muskegon, Michigan, USA.

Fishbein, L. 1977. Toxicology of selenium and tellurium. Pp. 191-240 Toxicology of Trace Metals, R.A. Goyer and M.A. Mahlman, eds. John Wiley & Sons, New York, New York, USA.

Fries, G.J. 1980. An assessment of potential residues in animal products from application of sewage sludge containing polychlorinated biphenyls to agricultural land. Pp. 348-349 in Sludge--Health Risks of Land Application, G. Bitton et al., eds. Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan, USA.

Hathaway, S.W. 1980. Sources of Toxic Compounds in Household Wastewater. U.S. Environmental Protection Agency, Cincinnati, Ohio, USA.

Hinesly, T.D., et al. 1979. Residual effects of irrigating corn with digested sewage sludge. J. Environ. Qual. 8:35-38.

Hossner, L.R., et al. 1978. Sewage Disposal on Agricultural Soils: Chemical and Microbiological Implications. Vol. I, Chemical Implications. EPA-600/2-78-131a. U.S. Environmental Protection Agency, Ada, Oklahoma, USA.

Hurst, C.J., et al. 1980. Survival of enteroviruses in rapid-infiltration basins during the land application of wastewater. Appl. Environ. Microbiol. 40:192-200.

Jenkins, T.J., and A.J. Palazzo. 1981. Wastewater Treatment by a Prototype Slow Rate Land Treatment System. Report 81-14. U.S. Army Corps of Engineers, CRREL, Hanover, New Hampshire, USA.

Johnston, J.B., R.A. Larson, J.A. Grunan, D. Ellis, and C. Jone. 1962. Identification of Organic Pollutants and Mutagens in Industrial and Municipal Effluents. Final report submitted to the Illinois Environmental Protection Agency. Project FW-38. Institute for Environmental Studies, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA.

Jones, P.W., et al. 1980. The occurrence and significance to animal health of salmonellas in sewage and sewage sludges. J. Hygiene 84:47-62.

Katzenelson, E., et al. 1976. Risk of communicable disease infection associated with wastewater irrigation in agricultural settlements. Science 195:944-946.

Kenaga, E.E. 1981. Comparative toxicity of 131.596 chemicals to plant seeds. Ecotoxicol. Environ. Safety 5:469-475.

Keswick, B.H., and C.P. Gerba. 1980. Viruses in groundwater. Environ. Sci. Tech. 14:1290-1297.

Kienholz, E.W. 1980. Effects of toxic chemicals present in sewage sludge on animal health. Pp. 153-171 in Sludge--Health Risks of Land Application, G. Bitton et al., eds. Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan, USA.

Lance, J.C., and C.P. Gerba. 1978. Pretreatment requirements before land application of municipal wastewater. Pp. 293-304 in State of Knowledge in Land Treatment of Wastewater, Vol. 1, H.I. McKim, ed. U.S. Army Corps of Engineers, CRREL, Hanover, New Hampshire, USA.

National Research Council. 1980. Recommended Dietary Allowances, 9th rev. ed. National Academy Press, Washington, D.C., USA.

Page, A.L., and A.C. Chang. 1981. Trace metal in soils and plants receiving municipal wastewater irrigation. Pp. 351-372 in Municipal Wastewater in Agriculture, F.M. D'Itri et al., eds., Academic Press, New York, New York, USA.

Pound, C.E., et al. 1978. Long Term Effects of Land Application of Domestic Wastewater: Hollister, California, Rapid Infiltration Site. EPA-600/2-78-084. U.S. Environmental Protection Agency, Ada, Oklahoma, USA.

Reed, S.C. 1979. Health Aspects of Land Treatment. U.S. Army Corps of Engineers, CRREL, Hanover, New Hampshire, USA.

Rudolfs, W., et al. 1951. Contamination of vegetables grown in polluted soil, III. Field studies on Ascaris eggs. Sewage Ind. Wastes 23:656-660.

Ryan, J.A., H.R. Pahren, and J.B. Lucas. 1982. Controlling cadmium in the human food chain: A review and rationale based on health effects. Environ. Res. 28:251-302.

Sagik, B.P., et al. 1978. Infectious disease potential of the land application of wastewater. Pp. 35-46 in State of Knowledge in Land Treatment of Wastewater, Vol. 1, H.L. McKim, ed. U.S. Army Corps of Engineers, CRREL, Hanover, New Hampshire, USA.

Sandstead, H.H. 1977. Nutrient interactions with toxic elements. Pp. 241-256 in Toxicology of Trace Elements, R.A. Goyer and M.A. Mahlman, ed. John Wiley & Sons, New York, New York, USA.

Schalscha, E.B., et al. 1978. Irrigation with untreated sewage water and its effect on the content of heavy metals in soils and crops. Pp. 275-281 in State of Knowledge in Land Treatment of Wastewater, Vol. 1, H.L. McKim, ed. U.S. Army Corps of Engineers, CRREL, Hanover, New Hampshire, USA.

Schaub, S.A., et al. 1978. Monitoring of microbiological aerosols at wastewater sprinkler irrigation sites. Pp. 377-388 in State of Knowledge in Land Treatment of Wastewater, Vol. 1, H.L. McKim, ed. U.S. Army Corps of Engineers, CRREL, Hanover, New Hampshire, USA.

Sepp, E. 1971. The Use of Sewage for Irrigation: A Literature Review, rev. ed. Bureau of Sanitary Engineering, Department of Public Health, State of California, Sacramento, California, USA.

Shuval, H.I., and B. Fattal. 1980. Epidemiological study of wastewater irrigation in kibbutzim in Israel. In Wastewater Aerosols and Disease, H.R. Pahren and W. Jakubowski, eds., EPA-600/9-80-028. U.S. Environmental Protection Agency, Cincinnati, Ohio, USA.

Sorber, C.A. 1976. Viruses in aerosolized wastewater. Pp. 83-86 in Virus Aspects of Applying Municipal Waste to Land, L.B. Baldwin et al., eds. University of Florida, Gainesville, Florida, USA.

Stewart, J.W.B. 1979. Soil chemistry: Heavy metal accumulation and transfer in effluent irrigated soils. In Seminar Papers on Effluent Irrigation under Prairie Conditions. Environment Canada, Environmental Protection Service, Regina, Saskatchewan, Canada.

Sunderman, F.W., Jr. 1977. Metal carcinogenesis. Pp. 257-295 in Toxicology of Trace Elements, R.A. Goyer and M.A. Mahlman, eds. John Wiley & Sons, New York, New York, USA.

Tate, R.L. 1978. Cultural and environmental factors affecting the longevity of Escherichia coli in histosols. Appl. Environ. Microbiol. 35:925-929.

Teltsch, B., et al. 1980. Isolation and identification of pathogenic microorganisms at wastewater-irrigated fields: Ratios in air and wastewater. Appl. Environ. Microbiol. 39:1183-1190.

Thornton, J.R. 1981. High colonic pH promotes colorectal cancer. Lancet 1:1081-1083.

Underwood, E.S. 1977. Trace Elements in Human and Animal Nutrition. 4th ed. Academic Press, New York, New York, USA.

U.S. Environmental Protection Agency. 1977. Process Design Manual for Land Treatment of Municipal Wastewater. U.S. Environmental Protection Agency. Cincinnati, Ohio, USA.

Vaughn, J.M., et al. 1981. Virus removal during groundwater recharge: Effects of infiltration rate on adsorption of poliovirus to soil. Appl. Environ. Microbiol. 41:139-147.

Windholz, Martha, et al. 1976. The Merck Index, 9th ed. Merck & Co., Inc., Rathway, New Jersey, USA.