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ENVIRONMENTAL FACTORS AFFECTING SUSTAINABLE USES OF SEWAGE SLUDGE AS AGRICULTURAL FERTILIZER*

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ABSTRACT

Sustainable development means striking a balance between economic growth and environmental protection. Industrial development is a necessary element in any nation's economic growth, but it is vital that potential environmental problems are considered at the same time. Increased energy cost and renewed interests in sustaining a safe environment have resulted in renewed attempts to use sewage sludge as a fertilizer. This article shows that the application of sewage sludge on agricultural or forest lands appears promising.

INTRODUCTION

Our planet sustains life through a delicate, intricate web of ecological systems. Ecology is concerned with the relationship between organisms and their environment, and encourages us to think in terms of whole systems [1, 2] including the "biosphere" itself, the entire spectrum of physical and biological components that make up the skin of life on earth.

People are products of the environment, agents in its evolution, and significant influences on its present character. An understanding of ecosystems, watersheds, or forests can only come from knowing the full range of plants, animals, micro-organisms, weather, soil, and water that comprise them. Scientists have only a glimmer of understanding of this biological complexity and cannot comprehend all the intricate interspecies connections that perpetuate the cleansing fertility and

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productivity of the land and oceans. We share this planet with a community of countless other living beings on whom our long-term survival and wealth depend.

Environmental problems are the joint concern of all nations. In spite of widespread public awareness in many nations, the rate of planetary ecological destruction is accelerating. U.S. Vice President Gore has portrayed a planet at risk from industrial technology, loss of biodiversity, desertification, urbanization, climate change, global pollution, and overpopulation [3]. Some 1.7 billion people lack access to clean water, 25,000 people die from water-borne diseases daily, world chemical production doubles in volume every seven to eight years, pesticides are made today at a rate 13,000 times faster than in 1962, every person in the United States produces more than his or her weight in waste every day [3].

The idea of sustainable development has been articulated by the World Commission on Environment and Development [4], a body sponsored by the United Nations. Sustainable development holds that the world must pursue *development which meets the needs of the present generation without compromising the ability of future generations to meet their own needs.* Sustainable development reinforces and extends long-standing principles of water resources management [5-7]. Yet, it has been exceedingly difficult to put these principles into practice in the past, and it is likely to become even more challenging in years to come. For example, economic necessity leads to overgrazing and deforestation, so reducing the productivity of land and soil, increasing the frequency of floods and droughts, and ravaging our environmental capital and ecological genetic heritage.

This kind of development is a threat to the survival of our species. As many have observed, sustainable development will require new ways of thinking and new institutions that recognize the global nature of environmental problems. It may well require a conscious change in philosophy and action unprecedented in human history [1, 2, 8]. Unlike the spontaneous and largely unconscious agricultural and industrial revolutions of more environmentally naive times, the sustainable development revolution will be a matter of forethought and planning at every level.

World peoples are making greater efforts to adopt production and waste management practices that will prevent contamination of surface water and groundwater. Some farm operations are also encouraging soil conservation. Yet the symptoms of environmental degradation continue and multiply. The agricultural applications of sewage sludge hold great promise as a sustainable approach to reducing water and groundwater pollution and conserving soil and other resources.

QUALITY OF SEWAGE SLUDGE

In the last two decades, industry and government have become increasingly aware of the need to clean up municipal and industrial effluents and reduce pollution of rivers, lakes, and groundwater. Wastewater effluent quality standards have become ever stricter, new treatment methods are being developed in many quarters, and ambitious government wastewater treatment programs have attempted to address water pollution [7, 9]. These are commendable efforts, but the inevitable result is the production of sewage sludge, which can be considered as a type of waste. If it is buried, incinerated, or discharged in the sea, the problem is not solved and we are back to square one. Moreover, we have wasted a potentially useful substance. A promising solution is the use of sewage sludge fertilizers. This article explores factors that affect the suitability of sewage sludge in agricultural applications.

The quality of raw sludge is only partly under the control of sewage works management and its characteristics vary considerably [10]. The wastewater treatment plant receives heavy metals from industrial and domestic discharges [11]. The heavy metals (Cd, Cu, Zn, Pb, Hg, Cr, Ni) are concentrated in the primary sludge and in the biomass of the activated sludge [10, 12-18]. With industrial source control, households are becoming a major source of heavy metals delivered to wastewater treatment plants. In fact, in major countries, pressure on industry to reduce the amount of heavy metals it discharges to sewers (following implementation of directive limiting the amount of metals in sludges being spread on soils) has already had an effect. Domestic pipework is contributing copper, lead and zinc, particularly in soft water areas. Cleaning products, especially phosphate-based detergents account for cadmium and mercury loads.

In the primary settling tank, insoluble metals are partly precipitated [19]. In the activated sludge, the interaction of soluble or insoluble metals with the biological flocs mainly contributes to passive adsorption on the cells [13, 14], partly due to complex formations with extracellular polymers [20]. Some physical entrapment of the metals in the bioflocs also occurs [14]. According to Stephenson and Lester [13], the most insoluble metals are removed readily and preferentially. Thus, cadmium, chromium, copper, lead and zinc removal are over 75 percent, whereas that of cobalt, molybdenum and nickel hardly reaches 40 percent or less.

SLUDGE TREATMENT

For most situations, sludge needs to be treated by biological (aerobic or anaerobic digestion), chemical, thermal, or other appropriate processes (this can include long-term storage) so as to significantly reduce its fermentability and the health hazards resulting from its use. According to Bruce and Davis [21], the general intention is clear, that is to process sludge so as to reduce its nuisance value from odor and to reduce significantly the number of pathogens present.

The metals are subjected to variations during their speciation as they undergo aerobic or anaerobic digestion (stabilization). Sewage sludge can be stabilized in various ways, all with the major object of rendering the sludge less offensive particularly with regard to odor. Most stabilization processes are also effective in reducing pathogen numbers [22-24]. Anaerobic mesophilic digestion is still by far the most common method of stabilization. Apart from its effectiveness in odor control, it is also efficient for pathogen destruction so long as a suitable storage period is provided after the primary digestion stage. Energy recovery from digester gas is also advantageous in some cases. Aerobic digestion continues the growth of aerobic microorganisms beyond the period of cell synthesis to the stage of auto-oxidation. Aerobic digestion is strongly influenced by temperature; a change from 20°C to 10°C can extend stabilization time by 50 percent for an equal percentage reduction in volatile matter. The rate of reduction of volatile matter obtained by stabilization is, in normal weather conditions, considerably lower than that obtained with heated anaerobic digestion. The United States Environmental Protection Agency's criterion for complete digestion is around 38 percent reduction of volatile solids. The elimination of pathogenic germs is also less effective (about 85%) and the destruction of worms' eggs more doubtful. Aerobic stabilization is a more flexible process than anaerobic digestion in which the methane bacteria are affected by the ecological conditions (including the presence of heavy cations, especially Cr^{6+}).

FINAL SLUDGE DISPOSAL

The treatment and final sludge disposal costs represent 50 percent of the overall cost of the municipal wastewater treatment [25-28]. The volume of sludge generated amounts approximately to 1 percent of the volume of wastewater treated [27, 29], with a solids content of 1 to 7 percent [26, 28]. Research or development relating to the treatment and disposal of sewage sludge has increased markedly in the last ten to twenty years. In most cases, the disposal on agricultural lands or forest of digested sludges proves to be the most economical means of final disposal [27, 29-32]. Incineration is costly [30, 32-34] due to high fuel consumption and contribution to pollution caused by metals attachment to ashes that have to be disposed of. Landfill and sea disposal (where sludges are carried away by ocean currents) are more restricted than before because of environmental problems [26, 28]. The metals may leach out from the landfill. In a 1989 publication, the U.S. Natural Resources Defense Council [35] estimated that 5 trillion gallons of industrial wastewater and 2.3 trillion gallons of sewage—in various degrees of treatment—are released into America's coastal waters each year, along with 3.6 trillion gallons of sewage sludges with large amounts of nutrient loading (N and P). A large quantity of nutrients in an ecosystem will bring about profound changes. The open ocean systems, although much larger than the coastal systems, are also more vulnerable because the organisms in them are adapted to cope with low levels of nutrients and have no experience with toxic materials in sewage sludges. Some scientists argue that the ban on the deep sea disposal of sewage sludge ignores new knowledge about the ability of the ocean to absorb such waste and closes off possibilities for getting rid of sewage in a way that could be safer and less expensive than dumping it in harbors and landfills, or burning it in incinerators.

In the United Kingdom, impressive progress in sewage sludge management was prompted by the government announcement of the decision to cease the dumping of sewage sludge to sea by 1998 [36]. This decision obviously puts much greater pressure on land-based disposal outlets. A considerable proportion of the sludge in this country is disposed of through dumping at sea. Consequently, the water companies were focusing a lot of attention on alternative disposal outlets [37]. Compared with other European countries, the beneficial use of sludge is rather important in Holland. Table 1 presents figures from 1984 for sludge disposal practice in ten European countries [38]. From 1992 on, the new Netherlands Soil Protection Act places more stringent limits on heavy metal concentrations (Table 2). The philosophy behind the very stringent Dutch guidelines is based on an ideal of long-term soil quality protection, creating a situation in the year 2,000 in which no more pollutants are applied to the soil than are removed by the crops [38].

QUALITY FERTILIZER OF SEWAGE SLUDGE

Sewage sludge [32] or sewage decontaminated by bacterial leaching of heavy metals [39] has been proven to be a good quality fertilizer because of the following properties:

- the typical sewage contains up to 4.1 percent nitrogen, 1.4 percent phosphorous and 0.3 percent potassium on a dry solids basis;
- the sludge helps store plant nutrients in the soil;
- organic matter is brought along with nutrients to soils;
- soil structure is reinforced;
- water retention capacity of the soil is improved.

Sikora et al. studied N movement from 1m trenches filled with sewage sludge and covered with a layer of soil [40]. They found that much of the N in the sludge leached into the soil over a period of about four years. The original concentration of N in the sludge was more than 30 mg N g^{-1} dry sludge. After 1508 days it had decreased from 6 mg g^{-1} to 12 mg g^{-1}. During the same period, concentrations of organic N, NH_4^+ and NO_3^- increased substantially in the soil beneath the trenches. Concentrations of NO_3^--N in the soil beside this pit indicated that there was lateral movement from it. It appears that much of the N in the waste matter in the pits will eventually leach into the surrounding soil. Some will be lost through denitrification, some will be taken up by vegetation, and probably a significant fraction will eventually enter ground and surface waters.

Table 1. Sludge Disposal Practice in Europe (1984)

	Belgium	Denmark	France	Germany	Greece	Italy	Luxambourg	Netherlands	Spain	United Kingdom	European Community
Landfill	51*	45	53	59	97	55	18	27	10	19	44
Agricultural land	27	45	27	32	3	34	81	64	62	48	40
Incineration	22	10	20	9	—	11	—	3	—	3	9
Sea disposal	—	—	—	—	—	—	—	6	28	30	7

*Percentage by each method.
Source: Meijer [38].

Table 2. Comparison of Netherlands Heavy Metal Limits for Sewage Sludge for Agricultural Use (mg/kg dry wt.) with European Community Guidelines

	Netherlands Limit Values until Jan. 1, 1992	Netherlands Limit Values 1992-1995	Netherlands Limit Values 1995-2000	European Community 1986
Arsenic	25	25	15	—
Cadmium	5	3.5	1.25	20-40
Chromium	500	350	100	—
Copper	900	425	75	1000-1750
Lead	500	300	100	750-1200
Mercury	5	3.5	0.75	16-25
Nickel	100	70	30	300-400
Zinc	2000	1400	300	2500-4000

HEAVY METALS PROBLEM IN SLUDGES

Heavy metals are pollutants of primary concern not only because of their toxicity but also due to their accumulation in plants [33, 41, 42], causing subsequent decrease in yield, and accumulation in human food chain [21], as well as contamination of surface and underground waters [28, 41, 43, 44]. Animals like plant grazers tend to accumulate copper and selenium in their bodies. Accumulation of Mn, Fe, Zn and Cd [33] in plants has already been detected. The limits for molybdenum are also set to protect the health of ruminant animals, since an excess of this element in the diet may interfere with trace element metabolism and cause induced copper deficiency [21].

In general, the metals in insoluble form (lead, mercury and chromium) are less available to plant uptake, whereas the metals in the dissolved form (cadmium, nickel, zinc, and copper) have been demonstrated to exhibit greater mobility and are thus more available for plant uptake [43]. Webber et al. showed that copper and nickel are two and eight times more toxic than zinc respectively [45]. Unequivocally, cadmium is the most problematic. Its toxicity to kidneys in mammals is well known [28, 46-50]. Webber et al. [45] concluded that cadmium should be taken as the basis for establishing regulations concerning the tolerance concentrations of heavy metals in sludges [51].

HEAVY METALS NORMS IN SLUDGES FOR DIFFERENT COUNTRIES IN THE WORLD

In the United Kingdom, the average concentration of cadmium in the sludge is 29.9 mg/kg dry wt. of sludge [32] compared to 16 mg/kg dry wt. [27] in the United States. The United States average value is below the norm set at 25 mg/kg dry wt.,

[41] but is much higher than the Dutch standard of 5 mg/kg on dry weight basis. Table 3 gives the value of accepted norms for different countries in the world [45]. Those norms are very variable, and reflect the degree of risk accepted by the different governments.

Table 4 summarizes the norms which will provide guidelines to the European Economic Communities (EEC) countries [32]. The limit can be applicable to soils or to heavy metals content of the sludges. A norm for chromium is to follow soon. According to Davis, it is broadly compatible with existing norms in United Kingdom guidelines [32]. The general aim of the guidelines is to regulate the use of sewage sludge in agriculture in such a way as to prevent harmful effects on soil vegetation, animal and man, while encouraging its correct use. Table 3 shows that Netherlands norms are more strict than those of EEC. The legislation in EEC countries is changing very quickly. Bruce and Davis describes the metal limits prior to the new limits imposed by the current Code of Practice sewage sludge in use in the United Kingdom [21]. The article by Ramsay briefly describes the EEC Directives and its influence on this Code of Practice [52].

Lester et al. estimated that 82 to 85 percent of the sludges in the United Kingdom do not conform to the norm for zinc equivalent concept [28]. Tjell, in a survey, found that 63 percent of the sludges in the United Kingdom and 60 percent of those from Federal Republic of Germany do not comply to their respective norms [41]. Wong and Henry estimated that up to 50 percent of the sludges in Ontario (Canada) do not conform to the Ontario guidelines [53]. In the United States, Wozniak and Huang found that 50 to 60 percent of the sludges do not satisfy the norm imposed by the United States Environmental Protection Agency (USEPA) [54]. Finally, Tjell concluded that it was well acknowledged that problems of potential phytotoxicity are real and that the regulations for Cd control should be tightened [41].

Even when metals in sludges are within the regulations they tend to reach toxic levels in the soil very quickly. Chang et al. measured soil metal levels resulting from the disposal of Los Angeles sludge [55]. This particular sludge met the guidelines regarding cumulative load for metals, set by the United States Environmental Protection Agency (USEPA) for land disposal of sludges. However, it was found that Cu, Zn, Cd, Pb, Ni, and Cr concentrations increased by five to nine fold compared to the original untreated soil levels. Most of the metals remained in the first layer of soil (0-15 cm depth) and only 1 percent was taken up by plants [55]. In a study with milorganite, Levine et al. reported two fold increases in soil concentrations of Cu, Zn, Pb, and Cd from sludges that met USEPA guidelines [56]. Adamu et al. reported a rapid accumulation of metals in soil over a ten-year period, from sludge containing 50 percent of the total cumulative metal loading permitted by the USEPA [57]. Similar problems of soil contamination have been reported in England [58]. Soil contamination is a cause for concern, considering that the threshold values for phytotoxicity are 105 mg/kg soil for Cu and 319 mg/kg soil for Zn [59]. USEPA has proposed a threefold reduction in the

Table 3. Maximum Permissible Heavy Metal Concentrations (mg/kg dry wt.) in Sludges Considered to be Acceptable for Use on Agricultural Lands

									State of			All Countries		EEC Directive	
Element	Belgium	Canada	Denmark	Finland	France	Germany	Netherlands	Norway	Massachusetts	Sweden	Switzerland	Range	Median	R*	M**
As	10	75					10					10-75	10		
Cd	10	20	8	30	20	20	10	10	2	15	30	8-30	7	20	40
Co	20	150		100				20		50	100	20-150	75		
Cr	500			1000	1000	1200	500	200	1000	1000	1000	200-1200	1000	750	
Cu	500			3000	1000	1200	600	1500	1000	3000	1000	500-3000	1100	1000	1500
Hg	10	5	6	25	10	25	10	7	10	8	10	5-25	10	16	
Mn	500			3000				500				500-3000	500		
Mo		20									20		20		
Ni	100	180	30	500	200	200	100	100	200	500	200	30-500	200	300	400
Pb	300	500	400	1200	800	1200	300	300	300	300	1000	300-1200	500	750	1000
Se	25	14			100							14-100	25		
Zn	2000	1850		3000	3000	3000	3000	3000	2500	10000	1000	1000-10000	3000	2500	3000

*R = Recommended.
**M = Mandatory.

Table 4. Limit Values for Metals in EEC Countries

Metal	Soil (mg/kg dry wt.)	Sludge (mg/kg dry wt.)	Annual Amounts (kg/ha/yr)
Cadmium	1-3	20-40	0.15
Copper	50-140	1000-1750	12
Nickel	30-75	300-400	3
Zinc	150-300	2500-4000	30
Lead	50-300	750-1200	15
Mercury	1-1.5	16-25	0.1

Source: Davis [32].

cumulative loading of Cu and Zn permitted in farmlands, from the practice of sewage sludge disposal [60]. These controversies led to a new proposal for regulating disposal of sewage sludge [61]. Source control requires the identification of all contributing sources of pollution [62, 63], making it costly and difficult to apply. An alternative solution consists in considering the decontamination of the sludges at the wastewater treatment plant.

CONCLUSION

As part of the effort for a more rational and durable use of natural resources, the fertilization potential of wastewater treatment sludges for agriculture and forestry should not be underestimated. In fact, municipal sludges contain most of the essential elements for plant growth, in particular nitrogen, phosphorus and other macro nutrients; the sludges can increase the nutritional status of agricultural and forest soils in a manner similar to the use of chemical fertilizers.

The recycling of municipal sludge as fertilizer has raised questions among researchers and managers regarding the environmental effects of this practice. The presence of heavy metals, organic contaminants and pathogenic organisms in sewage sludge had been of particular concern.

The debate regarding heavy metals led to the creation of regulations which dissallowed the application of sludges on soils containing high concentrations of a single metal, and which prohibited the use of sludges containing concentrations of metals above the permissible levels. As reported by Webber and Shamess, it appears that this approach has been successful, for the area surrounding Halton, Ontario, Canada [64]. After thirty-seven years of spreading sludge, the treated soils have not attained the critical levels for metals. For sludges which cannot be used for spreading due to their elevated metal concentrations, we must consider the decontamination of the sludges at the wastewater treatment plant which allow the reduction of metal concentrations to acceptable limits.

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