United States
Environmental Protection
Agency

Office of Water
Regulations and Standards
Washington, DC 20460

Water June, 1985

EPA

Environmental Profiles and Hazard Indices for Constituents of Municipal Sludge: Iron

PREFACE

This document is one of a series of preliminary assessments dealing with chemicals of potential concern in municipal sewage sludge. The purpose of these documents is to: (a) summarize the available data for the constituents of potential concern, (b) identify the key environmental pathways for each constituent related to a reuse and disposal option (based on hazard indices), and (c) evaluate the conditions under which such a pollutant may pose a hazard. Each document provides a scientific basis for making an initial determination of whether a pollutant, at levels currently observed in sludges, poses a likely hazard to human health or the environment when sludge is disposed of by any of several methods. These methods include landspreading on food chain or nonfood chain crops, distribution and marketing programs, landfilling, incineration and ocean disposal.

These documents are intended to serve as a rapid screening tool to narrow an initial list of pollutants to those of concern. If a significant hazard is indicated by this preliminary analysis, a more detailed assessment will be undertaken to better quantify the risk from this chemical and to derive criteria if warranted. If a hazard is shown to be unlikely, no further assessment will be conducted at this time; however, a reassessment will be conducted after initial regulations are finalized. In no case, however, will criteria be derived solely on the basis of information presented in this document.

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

SECTION 1

INTRODUCTION

This preliminary data profile is one of a series of profiles dealing with chemical pollutants potentially of concern in municipal sewage sludges. Iron (Fe) was initially identified as being of potential concern when sludge is landspread (including distribution and marketing).* This profile is a compilation of information that may be useful in determining whether Fe poses an actual hazard to human health or the environment when sludge is disposed of by this method.

The focus of this document is the calculation of "preliminary hazard indices" for selected potential exposure pathways, as shown in Section 3. Each index illustrates the hazard that could result from movement of a pollutant by a given pathway to cause a given effect (e.g., sludge → soil → plant uptake → animal uptake → human toxicity). The values and assumptions employed in these calculations tend to represent a reasonable "worst case"; analysis of error or uncertainty has been conducted to a limited degree. The resulting value in most cases is indexed to unity; i.e., values >1 may indicate a potential hazard, depending upon the assumptions of the calculation.

The data used for index calculation have been selected or estimated based on information presented in the "preliminary data profile", Section 4. Information in the profile is based on a compilation of the recent literature. An attempt has been made to fill out the profile outline to the greatest extent possible. However, since this is a preliminary analysis, the literature has not been exhaustively perused.

The "preliminary conclusions" drawn from each index in Section 3 are summarized in Section 2. The preliminary hazard indices will be used as a screening tool to determine which pollutants and pathways may pose a hazard. Where a potential hazard is indicated by interpretation of these indices, further analysis will include a more detailed examination of potential risks as well as an examination of site-specific factors. These more rigorous evaluations may change the preliminary conclusions presented in Section 2, which are based on a reasonable "worst case" analysis.

The preliminary hazard indices for selected exposure routes pertinent to landspreading and distribution and marketing are included in this profile. The calculation formulae for these indices are shown in the Appendix. The indices are rounded to two significant figures.

---

* Listings were determined by a series of expert workshops convened during March-May, 1984 by the Office of Water Regulations and Standards (OWRS) to discuss landspreading, landfilling, incineration, and ocean disposal, respectively, of municipal sewage sludge.

SECTION 2

PRELIMINARY CONCLUSIONS FOR IRON IN MUNICIPAL SEWAGE SLUDGE

The following preliminary conclusions have been derived from the calculation of "preliminary hazard indices", which represent conservative or "worst case" analyses of hazard. The indices and their basis and interpretation are explained in Section 3. Their calculation formulae are shown in the Appendix.

I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

A. Effect on Soil Concentration of Iron

Landspreading of municipal sewage sludge at low application rates (5 mt/ha) is not expected to increase soil concentrations of Fe above background levels. At higher application rates (50 mt/ha and 500 mt/ha), a slight increase in Fe soil concentrations may occur (see Index 1).

B. Effect on Soil Biota and Predators of Soil Biota

Conclusions were not drawn because index values could not be calculated due to lack of data (see Indices 2 and 3).

C. Effect on Plants and Plant Tissue Concentration

Phytotoxic effects due to soil concentrations of Fe resulting from landspreading of sludge could not be determined due to lack of data (see Index 4). When municipal sewage sludge is applied to soil at a low rate, no increase in levels of plant tissue concentration of Fe is anticipated. If sludge is applied at 50 mt/ha to 500 mt/ha, the Fe concentration in plants grown in the amended soil may increase moderately (see Index 5). These elevated plant tissue concentrations of Fe are not expected to be precluded by phytotoxicity (see Index 6).

D. Effect on Herbivorous Animals

The consumption of plants grown in sludge-amended soils by herbivorous animals is not expected to pose a toxic hazard due to Fe (see Index 7). The incidental ingestion of sludge-amended soil, however, may pose a toxic hazard to grazing animals when sludge containing a high concentration of Fe is applied (see Index 8).

E. Effect on Humans

Landspreading of sludge is not expected to pose a health hazard due to Fe for humans who consume plants grown in sludge-amended soil, except possibly for adults when sludge containing a high concentration of Fe is applied at a high rate (see

Index 9). The consumption of animal products derived from animals that have either grazed plants grown in sludge-amended soil or have ingested sludge-amended soil is not expected to pose a health threat due to Fe for humans (see Indices 10 and 11). Ingestion of sludge-amended soil or pure sludge by toddlers may increase the health hazard due to Fe above the hazard posed by ingestion of unamended soil. This increase may be substantial when sludge containing a high concentration of Fe is applied at a high rate. For adults, ingestion of sludge-amended soil or sludge is not expected to pose a health hazard due to Fe (see Index 12). The aggregate amount of Fe in the toddler diet resulting from landspreading of sludge may slightly increase the health hazard due to Fe, above the risk posed by the acceptable daily intake of Fe. For adults, a health hazard due to the aggregate amount of Fe in the diet is only expected when sludge containing a high concentration of Fe is landspread at a high rate (see Index 13).

II. LANDFILLING

Based on the recommendations of the experts at the OWRS meetings (April-May, 1984), an assessment of this reuse/disposal option is not being conducted at this time. The U.S. EPA reserves the right to conduct such an assessment for this option in the future.

III. INCINERATION

Based on the recommendations of the experts at the OWRS meetings (April-May, 1984), an assessment of this reuse/disposal option is not being conducted at this time. The U.S. EPA reserves the right to conduct such an assessment for this option in the future.

IV. OCEAN DISPOSAL

Based on the recommendations of the experts at the OWRS meetings (April-May, 1984), an assessment of this reuse/disposal option is not being conducted at this time. The U.S. EPA reserves the right to conduct such an assessment for this option in the future.

SECTION 3

PRELIMINARY HAZARD INDICES FOR IRON IN MUNICIPAL SEWAGE SLUDGE

I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

A. Effect on Soil Concentration of Iron

1. Index of Soil Concentration Increment (Index 1)

a. **Explanation** - Shows degree of elevation of pollutant concentration in soil to which sludge is applied. Calculated for sludges with typical (median if available) and worst (95th percentile if available) pollutant concentrations, respectively, for each of four sludge loadings. Applications (as dry matter) are chosen and explained as follows:

0 mt/ha	No sludge applied. Shown for all indices for purposes of comparison, to distinguish hazard posed by sludge from pre-existing hazard posed by background levels or other sources of the pollutant.
5 mt/ha	Sustainable yearly agronomic application; i.e., loading typical of agricultural practice, supplying $\sim$50 kg available nitrogen per hectare.
50 mt/ha	Higher application as may be used on public lands, reclaimed areas or home gardens.
500 mt/ha	Cumulative loading after years of application.

b. **Assumptions/Limitations** - Assumes pollutant is distributed and retained within the upper 15 cm of soil (i.e., the plow layer), which has an approximate mass (dry matter) of 2×10^3 mt/ha.

c. **Data Used and Rationale**

i. **Sludge concentration of pollutant (SC)**

Typical	28,000 µg/g DW
Worst	78,700 µg/g DW

The typical and worst sludge concentrations are the median and maximum values of sludge concentration data from 14 cities (Cunningham et al., 1975; Dowdy and Larson, 1975; Furr et al., 1976; and Sommers et al., 1976). (See Section 4, p. 4-1.)

ii. **Background concentration of pollutant in soil (BS)** = 20,000 μg/g DW

Shacklette et al. (1971 in TDI, 1981) reported that the geometric mean of Fe concentration in soils from western states was 20,000 μg/g, while the geometric mean for eastern states was 15,000 μg/g. Connor and Shacklette (1975 in TDI, 1981) reported that the geometric means of Fe concentration for different soil types range from 4,700 to 43,000 μg/g. Jackson (1964 in TDI, 1981) reported that Fe concentrations for most soils range from 7,000 to 42,000 μg/g. The value selected as the background concentration in soil was 20,000 μg/g. This value was selected because it falls near the center of the ranges reported for different soil types. (See Section 4, p. 4-2.)

d. **Index 1 Values**

Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Typical	1	1.0	1.0	1.1
Worst	1	1.0	1.1	1.6

e. **Value Interpretation** - Value equals factor by which expected soil concentration exceeds background when sludge is applied. (A value of 2 indicates concentration is doubled; a value of 0.5 indicates reduction by one-half.)

f. **Preliminary Conclusion** - Landspreading of municipal sewage sludge at low application rates (5 mt/ha) is not expected to increase soil concentrations of Fe above background levels. At higher application rates (50 mt/ha and 500 mt/ha), a slight increase in Fe soil concentrations may occur.

B. **Effect on Soil Biota and Predators of Soil Biota**

1. **Index of Soil Biota Toxicity (Index 2)**

a. **Explanation** - Compares pollutant concentrations in sludge-amended soil with soil concentration shown to be toxic for some organism.

b. **Assumptions/Limitations** - Assumes pollutant form in sludge-amended soil is equally bioavailable and toxic as form used in study where toxic effects were demonstrated.

c. **Data Used and Rationale**

i. **Index of soil concentration increment (Index 1)**

See Section 3, p. 3-2.

ii. **Background concentration of pollutant in soil (BS)** = 20,000 μg/g DW

See Section 3, p. 3-2.

iii. **Soil concentration toxic to soil biota (TB)** - Data not immediately available.

d. **Index 2 Values** - Values were not calculated due to lack of data.

e. **Value Interpretation** - Value equals factor by which expected soil concentration exceeds toxic concentration. Value >1 indicates a toxic hazard may exist for soil biota.

f. **Preliminary Conclusion** - Conclusion was not drawn because index values could not be calculated.

2. Index of Soil Biota Predator Toxicity (Index 3)

a. **Explanation** - Compares pollutant concentrations expected in tissues of organisms inhabiting sludge-amended soil with food concentration shown to be toxic to a predator on soil organisms.

b. **Assumptions/Limitations** - Assumes pollutant form bioconcentrated by soil biota is equivalent in toxicity to form used to demonstrate toxic effects in predator. Effect level in predator may be estimated from that in a different species.

c. **Data Used and Rationale**

i. **Index of soil concentration increment (Index 1)**

See Section 3, p. 3-2.

ii. **Background concentration of pollutant in soil (BS)** = 20,000 μg/g DW

See Section 3, p. 3-2.

iii. **Uptake slope of pollutant in soil biota (UB) -** Data not immediately available.

In the only available study in which Fe content in applied sludge and earthworms was measured (Helmke et al., 1979), there was no clear relationship between applied Fe and tissue Fe. This may have been due in part to the low Fe concentration in sludge of 11,600 μg/g DW, compared to 20,800 μg/g DW in soil. (See Section 4, p. 4-9.)

iv. **Background concentration in soil biota (BB) =** 730 μg/g DW

This background concentration in soil biota represents the control value for earthworms reported by Helmke et al. (1979). (See Section 4, p. 4-9.)

v. **Feed concentration toxic to predator (TR) =** 800 μg/g DW

Birds were selected as a model earthworm predator. The only available information indicating Fe concentrations toxic to birds was for chickens. A diet containing 800 μg/g in the form of $FeSO_4 \cdot 7H_2O$ was associated with reduced growth in chicks (McGhee et al., 1965 in National Academy of Sciences (NAS), 1980). This concentration is considered a conservative choice, since the form of Fe fed to chicks is a soluble form and, thus, may be absorbed more readily then less soluble forms. (See Section 4, p. 4-12.)

d. **Index 3 Values** - Values were not calculated due to lack of data.

e. **Value Interpretation** - Value equals factor by which expected concentration in soil biota exceeds that which is toxic to predator. Value > 1 indicates a toxic hazard may exist for predators of soil biota.

f. **Preliminary Conclusion** - Conclusion was not drawn because index values could not be calculated.

C. **Effect on Plants and Plant Tissue Concentration**

1. **Index of Phytotoxicity (Index 4)**

a. **Explanation** - Compares pollutant concentrations in sludge-amended soil with the lowest soil concentration shown to be toxic for some plant.

b. **Assumptions/Limitations** - Assumes pollutant form in sludge-amended soil is equally bioavailable and toxic as form used in study where toxic effects were demonstrated.

c. **Data Used and Rationale**

i. **Index of soil concentration increment (Index 1)**

See Section 3, p. 3-2.

ii. **Background concentration of pollutant in soil (BS) = 20,000 μg/g DW**

See Section 3, p. 3-2.

iii. **Soil concentration toxic to plants (TP)** - Not determined.

The forms of Fe that predominate in aerated soils, i.e., the hydroxides and oxides of the Fe III or ferric state, are practically insoluble in water and are thus of limited availability to plant roots. Under reducing conditions, characterized by waterlogging and/or low pH, the soluble Fe II or ferrous forms become more prevalent (Fuller, 1977). Fe in sludge may be present in the ferrous state, depending on the oxygen status of the sludge. Under normal soil conditions, soluble Fe added to soil is rapidly precipitated as ferric hydroxide (FeO[OH]), and then gradually converted to even less soluble forms (Council for Agricultural Science and Technology (CAST), 1976). However, at low pH (<5.0) and especially in soils deficient in manganese, Fe solubility is enhanced (CAST, 1976; Asghar and Kanehiro, 1981). Organic matter can also have a reducing effect in soil; the addition of sludge has been shown to cause an increase in soluble soil Fe, even when the sludge itself was low in soluble Fe (John and Van Laerhoven, 1976).

Plants can tolerate high levels of soil Fe under aerobic conditions, as evidenced by the mean soil concentration of 20,000 μg/g DW (see Section 3, p. 3-2.), but soil solution concentrations of soluble Fe as low as 100 mg/L are associated with toxicity in rice (Tanaka et al., 1966 in Foy et al., 1978) (See Section 4, p. 4-10.) Thus, any hazard of Fe toxicity is more a function of soil conditions than of Fe concentration. While sludge addition can promote reducing conditions in soil, this effect is independent of the sludge Fe concentration. Liquid sludge is often phytotoxic when first applied, and this toxicity may be due in part to reduced Fe, but this effect is well known and ordinarily short-lived. Therefore, a soil concentration of total Fe resulting in phytotoxicity will not be stated, and Index 4 will not be calculated. It should be recognized, however, that addition of any sludge that increases soil Fe (see Index 1) may increase the hazard of phytotoxicity in soils prone to such problems.

d. **Index 4 Values** - Values were not calculated due to lack of data.

e. **Value Interpretation** - Value equals factor by which soil concentration exceeds phytotoxic concentration. Value > 1 indicates a phytotoxic hazard may exist.

f. **Preliminary Conclusion** - Index values were not calculated because a soil concentration of total Fe resulting in phytotoxicity could not be identified. The hazard of Fe toxicity is more a function of soil conditions than Fe concentration. However, it should be recognized that any sludge addition that increases soil Fe (see Index 1) may increase the hazard of Fe phytotoxicity in soils prone to such problems.

2. **Index of Plant Concentration Increment Caused by Uptake (Index 5)**

a. **Explanation** - Calculates expected tissue concentration increment in plants grown in sludge-amended soil, using uptake data for the most responsive plant species in the following categories: (1) plants included in the U.S. human diet; and (2) plants serving as animal feed. Plants used vary according to availability of data.

b. **Assumptions/Limitations** - Assumes a linear uptake slope. Neglects the effect of time; i.e., cumulative loading over several years is treated equivalently to single application of the same amount. The uptake factor chosen for the animal diet is assumed to be representative of all crops in the animal diet. See also Index 6 for consideration of phytotoxicity.

c. **Data Used and Rationale**

i. **Index of soil concentration increment (Index 1)**

See Section 3, p. 3-2.

ii. **Background concentration of pollutant in soil (BS) = 20,000 μg/g DW**

See Section 3, p. 3-2.

iii. **Conversion factor between soil concentration and application rate (CO) = 2 kg/ha $(\mu g/g)^{-1}$**

Assumes pollutant is distributed and retained within upper 15 cm of soil (i.e. plow layer) which has an approximate mass (dry matter) of 2×10^3.

iv. **Uptake slope of pollutant in plant tissue (UP)**

Animal diet:
Wheat grain 0.0057 μg/g tissue DW $(kg/ha)^{-1}$

Human diet:
Lettuce leaf 0.0077 μg/g tissue DW $(kg/ha)^{-1}$

Wheat grain was selected to represent a grain crop consumed by livestock. The uptake slope was calculated from data presented by Sabey and Hart (1975) in a field study investigating the chemical composition of plants grown in sludge-amended soil. Although higher uptake slopes were available for sorghum grown in pots with $FeSO_4$-amended soil (Fuller and Lanspa, 1975), the data for wheat were considered more relevant because the wheat was grown on sludge-amended soil. Lettuce leaf was chosen to represent plants consumed by humans, based on a field study by Dowdy and Larson (1975) in which sludge was used. A higher slope for beet tubers (John and Van Laerhoven, 1976) was not used because total Fe was not reported and the slope was based on soluble Fe. In addition, a much higher slope for turnip greens (0.27 μg/g $[kg/ha]^{-1}$) from a field study using sludge (Miller and Boswell, 1979) was not selected because it appeared to be anomalous when compared with the other values available. (See Section 4, p. 4-11.)

v. **Background concentration in plant tissue (BP)**

Animal diet:
Wheat grain 36.3 μg/g DW

Human diet:
Lettuce leaf 94 μg/g DW

Background concentrations of Fe in wheat grain and lettuce leaf were reported by Sabey and Hart (1975) and Dowdy and Larson (1979), respectively. Their studies provided data used to calculate the uptake slopes. (See Section 4, p. 4-11.)

d. **Index 5 Values**

Diet	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Animal	Typical	1.0	1.0	1.1	1.5
	Worst	1.0	1.0	1.4	4.7
Human	Typical	1.0	1.0	1.0	1.3
	Worst	1.0	1.0	1.2	2.9

e. **Value Interpretation** - Value equals factor by which plant tissue concentration is expected to increase above background when grown in sludge-amended soil.

f. **Preliminary Conclusion** - When municipal sewage sludge is applied to soil at a low rate, no increase in levels of plant tissue concentration of Fe is anticipated. If sludge is applied at 50 mt/ha to 500 mt/ha, the Fe concentrations in plants grown in the amended soil may increase moderately.

3. **Index of Plant Concentration Increment Permitted by Phytotoxicity (Index 6)**

a. **Explanation** - Compares maximum plant tissue concentration associated with phytotoxicity with background concentration in same plant tissue. The purpose is to determine whether the plant concentration increments calculated in Index 5 for high applications are truly realistic, or whether such increases would be precluded by phytotoxicity.

b. **Assumptions/Limitations** - Assumes that tissue concentration will be a consistent indicator of phytotoxicity.

c. **Data Used and Rationale**

i. **Maximum plant tissue concentration associated with phytotoxicity (PP)**

Animal diet:
Alfalfa (tops) 1206 μg/g DW

Human diet:
Soybean (tops) 1320 μg/g DW

No information was available on tissue concentration of Fe associated with phytotoxicity for wheat or lettuce. Shetron (1979) reported Fe concentrations as high as 1206 μg/g in alfalfa grown on Fe tailings. No effects were observed on growth and development; however, the study did not report data for yields. Brown and Jones (1977 in Foy et al., 1978) reported growth limitations in soybeans containing tissue concentrations of 1320 μg/g. It is assumed that the tissue concentrations associated with toxicity for alfalfa and soybeans are representative of those for wheat and lettuce. (See Section 4, p. 4-10.)

ii. **Background concentration in plant tissue (BP)**

Animal diet:
Alfalfa 200 μg/g DW

Human diet:
Soybeans 200 μg/g DW

The background concentration of Fe for alfalfa is the concentration given for alfalfa meal in TDI (1981). The concentration of Fe in the upper leaves of soybean plants prior to pod set was reported to be 100 to 200 μg/g (TDI, 1981). The higher concentration was selected to provide a conservative increment value. (See Section 4, p. 4-7.)

d. **Index 6 Values**

Plant	Index Value
Alfalfa	6.0
Soybeans	6.6

e. **Value Interpretation** - Value gives the maximum factor of tissue concentration increment (above background) which is permitted by phytotoxicity. Value is compared with values for the same or similar plant tissues given by Index 5. The lowest of the two indices indicates the maximal increase which can occur at any given application rate.

f. **Preliminary Conclusion** - The index values for alfalfa and soybeans are similar. Increases of Fe concentrations in plant tissues above background concentrations by a factor of 6 are expected to be accompanied by phytotoxicity. Comparison to Index 5 indicates that the highest concentration factors predicted for wheat or lettuce would not be expected to be precluded by phytotoxicity.

D. **Effect on Herbivorous Animals**

1. **Index of Animal Toxicity Resulting from Plant Consumption (Index 7)**

a. **Explanation** - Compares pollutant concentrations expected in plant tissues grown in sludge-amended soil with food concentration shown to be toxic to wild or domestic herbivorous animals. Does not consider direct contamination of forage by adhering sludge.

b. **Assumptions/Limitations** - Assumes pollutant form taken up by plants is equivalent in toxicity to form used to demonstrate toxic effects in animal. Uptake or toxicity in specific plants or animals may be estimated from other species.

c. **Data Used and Rationale**

i. **Index of plant concentration increment caused by uptake (Index 5)**

Index 5 values used are those for an animal diet (see Section 3, p. 3-8).

ii. **Background concentration in plant tissue (BP) = 36.3 μg/g DW**

The background concentration value used is for the plant chosen for the animal diet (see Section 3, p. 3-8).

iii. **Feed concentration toxic to herbivorous animal (TA)** = 477 μg/g DW

Cattle fed diets containing iron citrate (a highly available form) at 500 μg/g or more (as Fe) showed a trend toward poorer performance (weight gain and feed consumption); however, the effects were not statistically significant

(Koong et al., 1970 in NAS, 1980). In the same study, a level of 2500 µg/g caused significant reduction of feed intake and daily weight gain. Standish et al. (1969 in NAS, 1980) reported similar findings with slight reduction in weight gain and feed conversion at dietary $FeSO_4$ levels of 477 µg/g (as Fe) and significant reduction in growth and feed intake at 1677 µg/g. Although no significant effects were observed at this dietary level, 477 µg/g was selected to conservatively estimate the feed concentration toxic to herbivorous animals.

Less available forms are tolerated at higher levels. For example, when FeO(OH) was administered in amounts corresponding to a dietary concentration of 1400 µg/g DW (for a total concentration, including food sources of Fe, of 1980 µg/g DW), cattle performance was unaffected, although biochemical indices showed a marked Cu deficiency had developed (Campbell et al., 1974). However, since the availability of Fe forms in common animal feeds is not known (NRC, 1979), toxicity values for the more available forms are used as a conservative approach. (See Section 4, p. 4-12.)

d. **Index 7 Values**

Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Typical	0.076	0.077	0.081	0.11
Worst	0.076	0.080	0.11	0.36

e. **Value Interpretation** - Value equals factor by which expected plant tissue concentration exceeds that which is toxic to animals. Value > 1 indicates a toxic hazard may exist for herbivorous animals.

f. **Preliminary Conclusion** - The consumption of plants grown in sludge-amended soils by herbivorous animals is not expected to pose a toxic hazard due to Fe.

2. **Index of Animal Toxicity Resulting from Sludge Ingestion (Index 8)**

a. **Explanation** - Calculates the amount of pollutant in a grazing animal's diet resulting from sludge adhesion to forage or from incidental ingestion of sludge-amended soil and compares this with the dietary toxic threshold concentration for a grazing animal.

b. **Assumptions/Limitations** - Assumes that sludge is applied over and adheres to growing forage, or that sludge constitutes 5 percent of dry matter in the grazing animal's diet, and that pollutant form in sludge is equally bioavailable and toxic as form used to demonstrate toxic effects. Where no sludge is applied (i.e., 0 mt/ha), assumes diet is 5 percent soil as a basis for comparison.

c. **Data Used and Rationale**

i. **Sludge concentration of pollutant (SC)**

Typical	28,000 μg/g DW
Worst	78,700 μg/g DW

See Section 3, p. 3-1.

ii. **Background concentration of pollutant in soil (BS)** = 20,000 μg/g DW

See Section 3, p. 3-2.

iii. **Fraction of animal diet assumed to be soil (GS)** = 5%

Studies of sludge adhesion to growing forage following applications of liquid or filter-cake sludge show that when 3 to 6 mt/ha of sludge solids is applied, clipped forage initially consists of up to 30 percent sludge on a dry-weight basis (Chaney and Lloyd, 1979; Boswell, 1975). However, this contamination diminishes gradually with time and growth, and generally is not detected in the following year's growth. For example, where pastures amended at 16 and 32 mt/ha were grazed throughout a growing season (168 days), average sludge content of forage was only 2.14 and 4.75 percent, respectively (Bertrand et al., 1981). It seems reasonable to assume that animals may receive long-term dietary exposure to 5 percent sludge if maintained on a forage to which sludge is regularly applied. This estimate of 5 percent sludge is used regardless of application rate, since the above studies did not show a clear relationship between application rate and initial contamination, and since adhesion is not cumulative yearly because of die-back.

Studies of grazing animals indicate that soil ingestion, ordinarily <10 percent of dry weight of diet, may reach as high as 20 percent for cattle and 30 percent for sheep during winter months when forage is reduced (Thornton and Abrams, 1983). If the soil were sludge-amended, it is conceivable that up to 5 percent sludge may be ingested in this manner as well. Therefore, this value accounts for either of these scenarios, whether forage is harvested or grazed in the field.

iv. **Feed concentration toxic to herbivorous animal (TA)** = 1400 μg/g DW

In sludge applied to soil, Fe II is readily oxidized to the less available Fe III (see Section 3, p. 3-5). It is assumed that a similar conversion readily takes place in sludge applied over growing forage, once the sludge is permitted to dry. Therefore, a value for feed concentration toxic to herbivorous animals will be chosen based on data for Fe III (i.e., FeO[OH]), since this index estimates hazard from ingested sludge or soil. A dietary Fe concentration of 1400 μg/g DW administered as FeO(OH), was associated with marked adverse effects on Cu status in cattle (although performance was not affected) (Campbell et al., 1974). However, if forage were grazed immediately after liquid sludge application, the lower value of 477 μg/g DW based on Fe II might be more applicable (see Section 3, p. 3-10 and Section 4, p. 4-12).

d. **Index 8 Values**

Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Typical	0.71	1.0	1.0	1.0
Worst	0.71	2.8	2.8	2.8

e. **Value Interpretation** - Value equals factor by which expected dietary concentration exceeds toxic concentration. Value > 1 indicates a toxic hazard may exist for grazing animals.

f. **Preliminary Conclusion** - The incidental ingestion of sludge-amended soil may pose a toxic hazard to grazing animals when sludge containing a high concentration of Fe is applied.

E. Effect on Humans

1. Index of Human Toxicity Resulting from Plant Consumption (Index 9)

a. **Explanation** - Calculates dietary intake expected to result from consumption of crops grown on sludge-amended soil. Compares dietary intake with acceptable daily intake (ADI) of the pollutant.

b. **Assumptions/Limitations** - Assumes that all crops are grown on sludge-amended soil and that all those considered to be affected take up the pollutant at the same rate as the most responsive plant(s) (as chosen in Index 5). Divides possible variations in dietary intake into two categories: toddlers (18 months to 3 years) and individuals over 3 years old.

c. **Data Used and Rationale**

i. **Index of plant concentration increment caused by uptake (Index 5)**

Index 5 values used are those for a human diet (see Section 3, p. 3-8).

ii. **Background concentration in plant tissue (BP) =** 94 μg/g DW

The background concentration value used is for the plant chosen for the human diet (see Section 3, p. 3-8).

iii. **Daily human dietary intake of affected plant tissue (DT)**

Toddler	74.5	g/day
Adult	205	g/day

The intake value for adults is based on daily intake of crop foods (excluding fruit) by vegetarians (Ryan et al., 1982); vegetarians were chosen to represent the worst case. The value for toddlers is based on the FDA Revised Total Diet (Pennington, 1983) and food groupings listed by the U.S. EPA (1984). Dry weights for individual food groups were estimated from composition data given by the U.S. Department of Agriculture (USDA) (1975). These values were composited to estimated dry-weight consumption of all non-fruit crops.

iv. Average daily human dietary intake of pollutant (DI)

Toddler	15,000 μg/day
Adult	17,400 μg/day

Sollman (1957 as cited in U.S. EPA, 1976) reported a range of 7,000 to 35,000 μg/day in diets with an average of 16,000 μg/day. Bjorn-Rasmussen et al. (1974 in TDI, 1981) reported an average daily intake of 17,400 μg/g in males. The daily nutritional requirement for Fe is 1,000 to 2,000 μg, but larger quantities are required in the diet due to poor absorption. NRC Recommended Daily Allowances (RDAs) for Fe ranged from 10,000 to 18,000 μg/day depending on age and sex (NRC, 1980 in TDI, 1981). The RDA for children 1 to 3 years old (15,000 μg/day) was chosen to represent average daily intake in toddlers. The average daily intake for males, 17,400 μg/day, was chosen as the average daily intake for adults. This value is within the range of RDA values and reflects a reported average intake.

v. Acceptable daily intake of pollutant (ADI) = 35,000 μg/day

No information was available on acceptable daily intake of Fe. Recommended daily intakes (RDAs) ranged from 10,000 to 18,000 μg, depending on age and sex (NRC, 1980 in TDI, 1981). The RDA for pregnant and lactating women includes Fe supplements to the diet of 30 to 60 mg daily. RDAs are considered the minimal requirement for normal healthy persons and necessary for the avoidance of Fe deficiency, anemia, or other manifestations of severe lack of Fe (TDI, 1981). Diets are reported to range from 7,000 to 35,000 μg/day by Sollman (1957 in U.S. EPA, 1976). High incidence of hemochromatosis and siderosis were observed among Bantu populations where males consumed 50 to 100 mg/day of Fe from beer alone (Bothwell et al., 1964 in TDI, 1981).

The value of 35,000 μg/day was selected to represent the high end of the range of normal daily intake, with the exception of pregnant and lactating women. This value was conservatively chosen to avoid problems associated with chronic excessive intake of Fe.

d. **Index 9 Values**

Group	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Toddler	Typical	0.43	0.43	0.43	0.48
	Worst	0.43	0.43	0.48	0.81
Adult	Typical	0.50	0.50	0.51	0.64
	Worst	0.50	0.51	0.63	1.6

e. **Value Interpretation** - Value equals factor by which expected intake exceeds ADI. Value > 1 indicates a possible human health threat. Comparison with the null index value at 0 mt/ha indicates the degree to which any hazard is due to sludge application, as opposed to pre-existing dietary sources.

f. **Preliminary Conclusion** - Landspreading of sludge is not expected to pose a health hazard due to Fe for humans who consume plants grown in sludge-amended soil, except possibly for adults when sludge containing a high concentration of Fe is applied at a high rate.

2. **Index of Human Toxicity Resulting from Consumption of Animal Products Derived from Animals Feeding on Plants (Index 10)**

a. **Explanation** - Calculates human dietary intake expected to result from consumption of animal products derived from domestic animals given feed grown on sludge-amended soil (crop or pasture land) but not directly contaminated by adhering sludge. Compares expected intake with ADI.

b. **Assumptions/Limitations** - Assumes that all animal products are from animals receiving all their feed from sludge-amended soil. The uptake slope of pollutant in animal tissue (UA) used is assumed to be representative of all animal tissue comprised by the daily human dietary intake (DA) used. Divides possible variations in dietary intake into two categories: toddlers (18 months to 3 years) and individuals over 3 years old.

c. **Data Used and Rationale**

i. **Index of plant concentration increment caused by uptake (Index 5)**

Index 5 values used are those for an animal diet (see Section 3, p. 3-8).

ii. **Background concentration in plant tissue (BP) = 36.3 μg/g DW**

The background concentration value used is for the plant chosen for the animal diet (see Section 3, p. 3-8).

iii. **Uptake slope of pollutant in animal tissue (UA) = 0.26 μg/g tissue DW (μg/g feed DW)$^{-1}$**

Standish et al. (1969 in NAS, 1980) reported uptake of Fe in steers fed diets containing $FeSO_4$. Uptake slopes were calculated for liver, spleen, kidney, heart and muscle. Spleen tissue had the highest uptake slope but was not selected for use in the index because it does not represent tissue normally consumed by humans. Liver had the second highest uptake slope and was selected for calculation of the index since it is a common component of the human diet. The uptake slope for muscle was very low. This slope was not chosen because Standish et al. (1969 in NAS, 1980) noted that the increase in muscle tissue concentration of Fe was not significant. (See Section 4, p. 4-13.)

iv. **Daily human dietary intake of affected animal tissue (DA)**

Toddler	0.97 g/day
Adult	5.76 g/day

The FDA Revised Total diet (Pennington, 1983) lists average daily intake of beef liver fresh weight for various age-sex classes. The 95th percentile of liver consumption (chosen in order to be conservative) is assumed to be approximately 3 times the mean values. conversion to dry weight is based on data from USDA (1975).

v. **Average daily human dietary intake of pollutant (DI)**

Toddler 15,000 μg/day
Adult 17,400 μg/day

See Section 3, p. 3-15.

vi. **Acceptable daily intake of pollutant (ADI)** = 35,000 μg/day

See Section 3, p. 3-15.

d. **Index 10 Values**

Group	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Toddler	Typical	0.43	0.43	0.43	0.43
	Worst	0.43	0.43	0.43	0.43
Adult	Typical	0.50	0.50	0.50	0.50
	Worst	0.50	0.50	0.50	0.50

e. **Value Interpretation** - Same as for Index 9.

f. **Preliminary Conclusion** - The consumption of animal products from animals that have grazed plants grown in sludge-amended soil is not expected to pose a health threat due to Fe for humans.

3. **Index of Human Toxicity Resulting from Consumption of Animal Products Derived from Animals Ingesting Soil (Index 11)**

a. **Explanation** - Calculates human dietary intake expected to result from consumption of animal products derived from grazing animals incidentally ingesting sludge-amended soil. Compares expected intake with ADI.

b. **Assumptions/Limitations** - Assumes that all animal products are from animals grazing sludge-amended soil, and that all animal products consumed take up the pollutant at the highest rate observed for muscle of any commonly consumed species or at the rate observed for beef liver or dairy products (whichever is higher). Divides possible variations in dietary intake into two categories: toddlers (18 months to 3 years) and individuals over three years old.

c. **Data Used and Rationale**

i. **Animal tissue** = Beef liver

Section 3, p. 3-17.

ii. **Background concentration of pollutant in soil (BS)** = 20,000 μg/g DW

See Section 3, p. 3-2.

iii. **Sludge concentration of pollutant (SC)**

Typical	28,000 μg/g DW
Worst	78,700 μg/g DW

See Section 3, p. 3-1.

iv. **Fraction of animal diet assumed to be soil (GS)** = 5%

See Section 3, p. 3-12.

v. **Uptake slope of pollutant in animal tissue (UA)** = 0.26 μg/g tissue DW (μg/g feed DW)$^{-1}$

See Section 3, p. 3-17.

vi. **Daily human dietary intake of affected animal tissue (DA)**

Toddler	0.97 g/day
Adult	5.76 g/day

See Section 3, p. 3-17.

vii. **Average daily human dietary intake of pollutant (DI)**

Toddler	15,000 μg/day
Adult	17,400 μg/day

See Section 3, p. 3-15.

viii. **Acceptable daily intake of pollutant (ADI)** = 35,000 μg/day

See Section 3, p. 3-15.

d. **Index 11 Values**

Group	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Toddler	Typical	0.44	0.44	0.44	0.44
	Worst	0.44	0.46	0.46	0.46
Adult	Typical	0.54	0.56	0.56	0.56
	Worst	0.54	0.67	0.67	0.67

e. **Value Interpretation** - Same as for Index 9.

f. **Preliminary Conclusion** - The consumption of animal products from animals that have ingested sludge-amended soils is not expected to pose a health threat due to Fe for humans.

4. **Index of Human Toxicity from Soil Ingestion (Index 12)**

a. **Explanation** - Calculates the amount of pollutant in the diet of a child who ingests soil (pica child) amended with sludge. Compares this amount with ADI.

b. **Assumptions/Limitations** - Assumes that the pica child consumes an average of 5 g/day of sludge-amended soil. If an ADI specific for a child is not available, this index assumes that the ADI for a 10 kg child is the same as that for a 70 kg adult. It is thus assumed that uncertainty factors used in deriving the ADI provide protection for the child, taking into account the smaller body size and any other differences in sensitivity.

c. **Data Used and Rationale**

i. **Index of soil concentration increment (Index 1)**

See Section 3, p. 3-2.

ii. **Sludge concentration of pollutant (SC)**

Typical 28,000 μg/g DW
Worst 78,700 μg/g DW

See Section 3, p. 3-1.

iii. **Background concentration of pollutant in soil (BS)** = 20,000 μg/g DW

See Section 3, p. 3-2.

iv. **Assumed amount of soil in human diet (DS)**

Pica child	5 g/day
Adult	0.02 g/day

The value of 5 g/day for a pica child is a worst-case estimate employed by U.S. EPA's Exposure Assessment Group (U.S. EPA, 1983). The value of 0.02 g/day for an adult is an estimate from U.S. EPA (1984).

v. **Average daily human dietary intake of pollutant (DI)**

Toddler	15,000 μg/day
Adult	17,400 μg/day

See Section 3, p. 3-15.

vi. **Acceptable daily intake of pollutant (ADI)** = 35,000 μg/day

See Section 3, p. 3-15.

d. **Index 12 Values**

		Sludge Application Rate (mt/ha)				
Group	Sludge Concentration	0	5	50	500	Pure Sludge
Toddler	Typical	3.3	3.3	3.3	3.5	4.4
	Worst	3.3	3.3	3.5	5.0	12
Adult	Typical	0.51	0.51	0.51	0.51	0.51
	Worst	0.51	0.51	0.51	0.52	0.54

e. **Value Interpretation** - Same as for Index 9.

f. **Preliminary Conclusion** - Ingestion of sludge-amended soil or pure sludge by toddlers may increase the health hazard due to Fe, above the hazard posed by ingestion of unamended soil. This increase may be substantial when sludge containing a high concentration of Fe is applied at a high rate. For adults, ingestion of sludge-amended soil or sludge is not expected to pose a health hazard due to Fe.

5. **Index of Aggregate Human Toxicity (Index 13)**

a. **Explanation** - Calculates the aggregate amount of pollutant in the human diet resulting from pathways described in Indices 9 to 12. Compares this amount with ADI.

b. **Assumptions/Limitations** - As described for Indices 9 to 12.

c. **Data Used and Rationale** - As described for Indices 9 to 12.

d. **Index 13 Values**

Group	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Toddler	Typical	3.3	3.3	3.3	3.6
	Worst	3.3	3.3	3.6	5.4
Adult	Typical	0.55	0.57	0.59	0.71
	Worst	0.55	0.69	0.81	1.7

e. **Value Interpretation** - Same as for Index 9.

f. **Preliminary Conclusion** - The aggregate amount of Fe in the toddler diet resulting from landspreading of sludge may slightly increase the health hazard due to Fe above the risk posed by the acceptable daily intake of Fe. For adults, a health hazard due to the aggregate amount of Fe in the diet is only expected when sludge containing a high concentration of Fe is landspread at a high rate.

II. LANDFILLING

Based on the recommendations of the experts at the OWRS meetings (April-May, 1984), an assessment of this reuse/disposal option is not being conducted at this time. The U.S. EPA reserves the right to conduct such an assessment for this option in the future.

III. INCINERATION

Based on the recommendations of the experts at the OWRS meetings (April-May, 1984), an assessment of this reuse/disposal option is not being conducted at this time. The U.S. EPA reserves the right to conduct such an assessment for this option in the future.

IV. OCEAN DISPOSAL

Based on the recommendations of the experts at the OWRS meetings (April-May, 1984), an assessment of this reuse/disposal option is not being conducted at this time. The U.S. EPA reserves the right to conduct such an assessment for this option in the future.

SECTION 4

PRELIMINARY DATA PROFILE FOR IRON IN MUNICIPAL SEWAGE SLUDGE

I. OCCURRENCE

A. Sludge

1. Frequency of Detection

100% - based on ubiquitous nature and use in wastewater treatment

2. Concentration

Range 1,000 to 37,000 ppm (DW) — TDI, 1981 (p. 185)

Source of Sludge	Fe Concentration (μg/g DW)	Reference
Janesville, WI	11,900	Cunningham et al., 1975 (p. 448)
Fond du Lac, WI	13,900	Cunningham et al., 1975 (p. 448)
Wisconsin Rapids, WI	78,700	Cunningham et al., 1975 (p. 448)
Waukesha, WI	27,400	Cunningham et al., 1975 (p. 448)
Stillwater, MN	9,870	Dowdy and Larson, 1975 (p. 279)
Washington, D.C.	44,960	Furr et al., 1976 (p. 87)
Anderson, IN	17,200	Sommers et al., 1976 (p. 305)
Crawfordsville, IN	39,500	Sommers et al., 1976 (p. 305)
Kokomo, IN	28,500	Sommers et al., 1976 (p. 305)
Lebanon, IN	23,700	Sommers et al., 1976 (p. 305)
Logansport, IN	30,800	Sommers et al., 1976 (p. 305)
Noblesville, IN	13,100	Sommers et al., 1976 (p. 305)
Peru, IN	18,300	Sommers et al., 1976 (p. 305)
Tipton, IN	35,000	Sommers et al., 1976 (p. 305)
Median value for 14 cities	28,000	
Worst value for 14 cities	78,700	

B. Soil - Unpolluted

1. Frequency of Detection

Fe is the fourth most abundant element in the earth's crust; ubiquitous	TDI, 1981 (p. 184)

2. Concentration

Range 7000 to 42,000 ppm	Jackson, 1964 in TDI, 1981 (p. 187)
4700 to 43,000 ppm - range of geometric means for different soil types	Connor and Shacklette, 1975 in TDI, 1981 (p. 187)
20,000 geometric mean - western States 15,000 geometric mean - eastern States	Shacklette et al., 1971 in TDI, 1981 (p. 187)

C. Water - Unpolluted

1. Frequency of Detection

Assumed 100% due to ubiquitous nature

2. Concentration

a. Freshwater

≤ 1 μg/L in true solution in surface water 2 to 200 μg/L reported ranges	TDI, 1981 (p. 184)
0.04 to 0.67 mg/L	Hem, 1970 (p. 12)

b. Seawater

0.1 to 3.0 μg/L	Berner, 1970 in TDI, 1981 (p. 193)
0.01 mg/L	Hem, 1970 (p. 11)

c. Drinking Water

0.3 mg/L criterion for domestic water supplies	U.S. EPA, 1976 (p. 78)

1.8 mg/L in spring water and 3.4 mg/L in distilled water, taste of Fe detected	Cohen et al., 1960 in U.S. EPA, 1976 (p. 79)

D. Air

1. **Frequency of Detection**

Assumed 100% due to ubiquitous nature

2. **Concentration**

a. **Urban**

14 μg/m^3 (industrial sector of Chicago)	TDI, 1981 (p. 185)
1580 ng/m^3 mean for urban location in U.S.	TDI, 1981 (p. 194)

b. **Rural**

50 ng/m^3 (Colstrip, MN)	TDI, 1981 (p. 185)

E. **Food**

1. **Total Average Intake**

6 mg/1000 kcal (4.9 to 6.3 mg range) in typical western diet	TDI, 1981 (p. 416)
NRC Recommended Daily Allowances	NRC, 1980 in TDI, 1981 (p. 412)

Children, 1 to 3 yrs	15,000 μg/day
Males, 11 to 18 yrs	18,000 μg/day
Males, 19 to 51+ yrs	10,000 μg/day
Females, 11 to 50 yrs	18,000 μg/day
Females, 51+ yrs	10,000 μg/day

30 to 60 mg supplemental Fe required daily for pregnant and lactating women	NRC, 1980 in TDI, 1981 (p. 412)
12 mg Fe per day in typical vegetarian diet	TDI, 1981 (p. 418)
17.4 mg Fe per day in diet of typical men	Bjorn-Rasmussen et al., 1974 in TDI, 1981 (p. 566)

1 to 2 mg daily nutritional requirement but larger quantities required due to poor absorption. Diets contain 7 to 35 mg per day and average 16 mg.	Sollman, 1957 in EPA, 1976 (p. 79)

2. **Concentration**

Food	Fe concentration ppm (DW)	Source
Barley	50	TDI, 1981 (p. 326)
Citrus, pulp	200	TDI, 1981 (p. 326)
Corn grain	200	TDI, 1981 (p. 326)
Oats	70	TDI, 1981 (p. 326)
Rice bran	190	TDI, 1981 (p. 326)
Wheat bran	150	TDI, 1981 (p. 326)
Wheat grain	50	TDI, 1981 (p. 326)

Fe Content of Some Representative Foods	TDI, 1981 (p. 417)

	mg Fe/100 Kcal	mg Fe/100g Edible Portion
Liver, calf	5.4	14.2
Lettuce	7.8	1.4
Green beans	2.4	0.6
Eggs	1.4	2.3
Ground beef	1.4	3.2
Chicken, dark meat	1.0	1.7
Chicken, white meat	0.8	1.3
Wheat flour, refined	0.2	0.8
Milk	Trace	Trace
Sugar	<0.1	0.1

II. HUMAN EFFECTS

A. Ingestion

1. Carcinogenicity

a. Qualitative Assessment

Cancer of the esophagus has been found to be associated with both Fe deficiency and Fe overload,	MacPhail et al., 1979 in TDI, 1981 (p. 550)

but no causal relationship has been established.

b. **Potency**

None demonstrated for ingestion route.

c. **Effects**

Liver carcinoma occurs in about 15% of subjects with idiopathic hemochromatosis. Hemochromatosis may increase the risk of primary tumor development elsewhere in the body.	Finch and Finch, 1955

2. **Chronic Toxicity**

a. **ADI**

No ADI has been established for Fe.

b. **Effects**

≥100 mg Fe/day in male Bantu population over many years results in siderosis. Fe derives from beer brewed in iron containers.	Bothwell et al., 1965 in TDI, 1981 (p. 511)
≥275 mg Fe/day for ≥10 years has resulted in cases of hemochromatosis.	TDI, 1981 (p. 516)

3. **Absorption Factor**

Nonheme - Fe	1-10%	TDI, 1981
Heme - Fe	10-25%	(p. 397)

Ferric iron absorption is greatly increased when given with brandy or whiskey to normal fasting subjects.	Charlton et al., 1964 in TDI, 1981

4. **Existing Regulations**

Water Quality Criteria (July 1976) = 0.3 mg/L	U.S. EPA, 1976

B. Inhalation

1. Carcinogenicity

a. Qualitative Assessment

No carcinogenicity has been demonstrated for ferric oxides.	TDI, 1981 (p. 556)

b. Potency

None demonstrated for inhalation route.

c. Effects

No cancers were found to be induced in inhalation exposure of animals by iron oxide, although the latter does act as a carcinogen in the presence of known carcinogens.	U.S. EPA, 1982 (p. 19)

2. Chronic Toxicity

a. Inhalation Threshold or MPIH

See below, "Existing Regulations"

b. Effects

Exposure to levels of ferric oxide above the threshold values has been known to cause lung irritation.	TDI, 1981 (p. 541)

3. Absorption Factor

Data not immediately available.

4. Existing Regulations

5 mg/m^3 TWA iron oxide fume (Fe_2O_3) 10 mg/m^3 STEL as Fe	ACGIH, 1982

III. PLANT EFFECTS

A. Phytotoxicity

1. Soil Concentration

>400 ppm soluble Fe associated with toxicity to rice; >500 ppm highly toxic	Nhung and Ponnamperuma, 1966 in Foy

	et al., 1978 (p. 532)
100 to 500 ppm soluble Fe produced Fe toxicity in rice	Tanaka et al., 1966 in Foy et al., 1978 (p. 533)
Fe poses little hazard to crop production and plant accumulation when sludge is applied to soils because of its low solubility. As a result, it has low availability to plants.	CAST, 1976 (pp. 2 and 24)
50 and 100 t/ha of sludge with 122,000 mg/kg Fe increased yield of fodder rape over controls.	Narwal et al., 1983 (p. 361)

2. **Tissue Concentration**

See Table 4-1.

B. **Uptake**

Plant	Part	Concentration ppm (DW)	Source
Corn	grain	30-50	TDI, 1981 (p. 323)
Peanut	leaf	50-300	TDI, 1981 (p. 323)
Rice	leaf	89-193	TDI, 1981 (p. 323)
Sorghum	plant	160-250	TDI, 1981 (p. 323)
Cabbage	leaf	40-100	TDI, 1981 (p. 323)
Cereal grains	grain	30-60	NAS, 1980 (p. 243)

100 to 700 ppm in cultivated grasses	NAS, 1980 (p. 243)
200 ppm alfalfa meal	TDI, 1981 (p. 326)
100 to 200 µg/g in upper leaves of soybeans prior to pod set	TDI, 1981 (p. 323)

See Table 4-2.

IV. DOMESTIC ANIMAL AND WILDLIFE EFFECTS

A. Toxicity

"Evidence for Fe toxicity in domestic or farm animals, or animals living in their natural habitat, is practically nonexistent". TDI, 1981

See Table 4-3.

B. Uptake

See Table 4-4.

V. AQUATIC LIFE EFFECTS

A. Toxicity

1. Freshwater

a. Acute

Mayfly larvae	Fe^{2+}	320 μg/L	U.S. EPA, 1982
Mosquitofish	Fe^{2+}	102,900 μg/L	(p. 23-26)
Dapthnia magna	Fe^{3+}	9,600 μg/L	
Amphipods	Fe^{3+}	100,000 μg/L (suspension)	

b. Chronic

Coho salmon	Fe^{3+}	1110 μg/L
Brook trout	Fe^{3+}	9690 μg/L
Fathead minnows	Fe^{3+}	<1870 μg/L
Amphipods	Fe^{3+}	<4120 μg/L

There is no final freshwater acute or chronic value for Fe because the minimum data based requirements were not met.

2. Saltwater

a. Acute

Worm species	Fe^{2+}	100,000 μg/L
Mummichog	Fe^{2+} (ferric chloride)	26,900 μg/L
Mummichog	Fe^{3+} (ferric ammonium chloride)	31,500 μg/L
Mummichog	Fe^{2+} (ferrous ammonium sulfate)	110,800 μg/L

No final saltwater acute value could be calculated.

b. **Chronic**

Acceptable chronic toxicity values were not found for any saltwater animal.

B. **Uptake**

Data not immediately available.

VI. SOIL BIOTA EFFECTS

A. **Toxicity**

Data not immediately available.

B. **Uptake**

Fe concentration (µg/g) in tissues and casts of earthworms grown on sludge-amended soil (20,800 µg/g Fe in soil, 11,600 µg/g Fe in sludge). Wet or dry weight not specified. Since there was no clear relationship between applied Fe and Fe in earthworms, an uptake slope could not be calculated.

Helmke et al., 1979 (pp. 324 to 325)

Fe Application Rate	1971[a]		1972[a]		1973[a]	
	worms	casts	worms	casts	worms	casts
Control	730	23,000	1860	21,900	500	20,800
174 kg/ha	1190	23,500	5300	21,000	750	19,200
348 kg/ha	-	-	390	19,500	410	19,300
696 kg/ha	2010	23,300	560	20,000	380	18,500

[a] Date of sludge application. Sampling conducted in 1975 or 1976.

VII. PHYSICOCHEMICAL DATA FOR ESTIMATING FATE AND TRANSPORT

Atomic weight: 55.847
Melting point: 1535°C
Boiling point: 2750°C
Specific gravity: 7.86 at 20°C
Solubility in water: insoluble

CRC Handbook of Chemistry and Physics, 1976 (p. B-119)

TABLE 4-1. PHYTOTOXICITY OF IRON

Plant/tissue	Chemical Form Applied	Soil pH	Control Tissue Concentration (µg/g DW)	Experimental Soil Concentration (µg/g DW)	Experimental Tissue Concentration (µg/g DW)	Effect	References
Rice seedlings	Fe^{++}	5.6	NR[a]	490 mg/L[b,e]	NR	Death of rice seedlings	Nhung and Ponnamperuma, 1966 in Foy et al., 1978
	Fe^{++}	5.6	NR	>500 mg/L[c,e]	NR	Highly toxic to rice	
	Fe^{++}	5.6	NR	>400 mg/L[c,e]	NR	Toxicity in rice	
	Fe^{++}	acid	NR	730 mg/L[e]	NR	Killed rice plants 1 day after transplanting	
	Fe^{++}	acid	NR	365 mg/L[d,e]	NR	Toxicity symptoms	
	Fe^{++}	acid	NR	655 mg/L[e]	NR	Toxicity symptoms	
Tobacco/leaf	Fe^{++}	NR	NR	NR	450 - 1126[b]	Plant injury Decreased leaf strength	Rhoads, 1971 in Foy et al., 1978
Rice/root	Fe^{++}	3.7	NR	100 mg/L[e]	NR	Plant toxicity	Tanaka et al., 1966 in Foy et al., 1978
		NR	NR	500 mg/L[e]	NR	Plant toxicity	
Soybean/top	Fe^{++}	NR	NR	NR	1320	Growth limitations	Brown and Jones, 1977 in Foy et al., 1978
Alfalfa/top	Iron tailings (field)	6.6	NR	2134	1206	No observed effects on growth and development[f]	Shetron, 1979

[a] NR = Not reported.
[b] Associated aluminum concentration 68 µg/g.
[c] Associated aluminum concentrations 25 µg/g.
[d] At planting.
[e] Refers to concentration of soluble Fe in soil solution or culture medium.
[f] Study did not report analysis of yield.

TABLE 4-2. UPTAKE OF IRON BY PLANTS

Plant/tissue	Chemical Form Applied (study type)	Soil pH	Range (N) of Application Rates (kg/ha)[a]	Control Tissue Concentration (μg/g DW)	Uptake[b] Slope	References
Plainsman sorghum/tops	Fe as $FeSO_4$ (pot)	7.6	0 - 736 (2)	112	0.065	Fuller and Lanspa, 1975
Kafir sorghum/tops	Fe as $FeSO_4$ (pot)	7.6	0 - 736 (2)	107	0.018	Fuller and Lanspa, 1975
Lettuce/leaf	Primary digested sludge and milorganite (pot)	6.4	3075 - 4360 (3)[c]	113	0.0075[d]	John and Van Laerhoven, 1976
Beet/tubers	Primary digested sludge and milorganite (pot)	6.4	3075 - 4360 (3)[c]	128	0.0112[d]	John and Van Laerhoven, 1976
Wheat/grain	Combined liquid digested sludge (field)[e]	NR (loamy sand)	0 - 1400 (3)	36.3	0.0057	Sabey and Hart, 1975
Tomato/fruit	Anaerobically digested dried sludge (field)	5.3	0 - 9870 (5)	17	0.0025	Dowdy and Larson, 1975
Lettuce/leaf	Anaerobically digested dried sludge (field)	5.3	0 - 4442 (4)	94	0.0077	Dowdy and Larson, 1975
Turnip/greens	Secondary digested sludge (field)	5.6	0 - 1116 (3)	377	0.27	Miller and Boswell, 1979 (p. 1362)

[a] N = Number of application rates, including control.
[b] Slope = y/x: x = kg Fe applied/ha; y = μg Fe/g plant tissue (dry weight).
[c] Unit is μg Fe/g soil, where Fe is 1N HNO_3 - extractable, not total. Total Fe not reported.
[d] Slope is computed assuming 1 μg/g = 2 kg/ha to convert soil concentration to application rate.
[e] Sludge consisted of 50% anaerobically digested primary sludge and 50% aerobically digested primary sludge.

TABLE 4-3. TOXICITY OF IRON TO DOMESTIC ANIMALS AND WILDLIFE

Species (N)[a]	Chemical Form Fed	Feed Concentration (μg/g DW)	Water Concentration (mg/L)	Daily Intake (mg/kg DW)	Duration of Study (days)	Effect	References[b]
Swine (6)	$FeSO_4$	3000	NR[c]	NR	56	No Effect	O'Donovan et al., 1963
	$FeSO_4$	4000	NR	NR	56	Reduced growth	O'Donovan et al., 1963
Chicken (20)	$FeSO_4$	400	NR	NR	28	No effect	McGhee et al., 1965
	$FeSO_4$	800	NR	NR	28	Reduced growth	McGhee et al., 1965
Cattle (6)	$FeSO_4$	477	NR	NR	84	Slight decrease in gains and food conversion	Standish et al., 1969
	$FeSO_4$	1677	NR	NR	84	Significant reductions in growth and feed intake	Standish et al., 1969
Cattle (8)	Iron citrate	100	NR	NR	98	No adverse effect	Standish et al., 1971
	Iron citrate	500 - 1000	NR	NR	NR	Trend toward poorer performance (weight gain, feed consumption)	Koong et al., 1970
	Iron citrate	2500	NR	NR	NR	Significant reduction in feed intake and daily weight gain	Koong et al., 1970
Cattle (8)	FeO(OH)	1400	NR	30	210	Marked depression of liver and blood Cu, caeruloplasmin and amine oxidase. No effect on performance	Campbell et al., 1974

[a] N = Number of animals/treatment group.
[b] Source of all information in table is from NAS, 1980 (p. 244 and pp. 249 to 252).
[c] NR = Not reported.

TABLE 4-4. UPTAKE OF IRON BY DOMESTIC ANIMALS AND WILDLIFE

Species(N)[a]	Chemical Form Fed	Range (N)[b] of Feed Tissue Concentration (µg/g DW)	Tissue Analyzed	Control Tissue Concentration (µg/g DW)[c]	Uptake[c,d] Slope	References
Steers	$FeSO_4$	0 - 1600 (2)	Liver	185	0.26	Standish et al., 1969 in NAS, 1980
	$FeSO_4$	0 - 1600 (2)	Spleen	1219	4.8	
	$FeSO_4$	0 - 1600 (2)	Kidney	315	0.059	
	$FeSO_4$	0 - 1600 (2)	Heart	291	0.024	
	$FeSO_4$	0 - 1600 (2)	Muscle	91	0.004	

[a] N = Number of animals/treatment group.
[b] N = Number of feed concentrations, including control.
[c] When tissue values were reported as wet weight, unless otherwise indicated a moisture content of 77% was assumed for kidney, 70% for liver and 72% for muscle.
[d] Slope = y/x: x = µg/g feed (DW); y = µg/g tissue (DW).

SECTION 5

REFERENCES

American Conference of Governmental and Industrial Hygienists. 1982. Threshold Limit Values for Chemical Substances in Work Air Adopted by ACGIH for 1982. Cincinnati, OH.

Asghar, M., and Y. Kanehiro. 1981. The Fate of Applied Iron and Manganese in an Oxigol and an Ultisol from Hawaii. Soil Sci. 131:53-55.

Berner, R. 1970. Iron-Abundance in Natural Waters. In: Wedepohl, K. H. (ed.), Handbook of Geochemistry. Springer-Verlag. New York, NY. (As cited in TDI, 1981.)

Bertrand, J. E., M. C. Lutrick, G. T. Edds, and R. L. West. 1981. Metal Residues in Tissues, Animal Performance and Carcass Quality with Beef Steers Grazing Pensacola Bahiagrass Pastures Treated with Liquid Digested Sludge. J. Ani. Sci. 53:1.

Bjorn-Rasmussen, E., et al. 1974. Food Iron Absorption in Man: Applications of the Two-Pool Extrinsic Tag Method to Measure Heme and Nonheme Iron Absorption from the Whole Diet. J. Clin. Invest. 53:247. (As cited in TDI, 1981.)

Boswell, F. C. 1975. Municipal Sewage Sludge and Selected Element Applications to Soil: Effect on Soil and Fescue. J. Environ. Qual. 4(2):267-273.

Bothwell, T. H., et al. 1964. Iron Overload in Bantu Subjects: Studies on the Availability of Iron in Bantu Beer. Am. J. Clin. Nutr. 14:47. (As cited in TDI, 1981.)

Bothwell, T. H., et al. 1965. Oral Iron Overload. S. Afr. Med. J. 39:892. (As cited in TDI, 1981.)

Brown, J. C., and W. E. Jones. 1977. Manganese and Iron Toxicities Dependent on Soybean Variety. Commun. Soil Sci. Plant. Anal. 8:1-15. (As cited in Foy et al., 1978.)

Campbell, A. G., M. R. Coup, W. H. Bishop, and D. E. Wright. 1974. Effect of Elevated Iron Uptake on the Copper Status of Grazing Cattle. N. Z. J. Agric. Res. 17:393-399.

Chaney, R. L., and C. A. Lloyd. 1979. Adherence of Spray-Applied Liquid Digested Sewage Sludge to Tall Fescue. J. Environ. Qual. 8(3):407-411.

Charlton, et al. 1964. Effect of Alcohol on Iron Absorption. Br. Med. Jour. 2:1427. (As cited in TDI, 1981.)

Cohen, J. M., et al. 1960. Taste Threshold Concentrations of Metals in Drinking Water. Jour. Amer. Water Works Assn. 52:660. (As cited in U.S. EPA, 1976.)

Connor, J. J. and H. T. Shacklette. 1975. Background Geochemistry of Some Rocks, Soils, Plants, and Vegetables in the Coterminous United States. Geological Survey Professional Paper. 574-F. U.S. Government Printing Office. Washington, D.C. (As cited in TDI, 1981.)

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.

CRC Handbook of Chemistry and Physics. 1976. 57th Edition. CRC Press, Cleveland, OH.

Cunningham, J. D., D. R. Keeney, and J. A. Ryan. 1975. Yield and Metal Composition of Corn and Rye Grown on Sewage-Sludge Amended Soil. J. Environ. Qual. 4(4):448-454.

Dowdy, R. H., and W. E. Larson. 1975. The Availability of Sludge-Borne Metals to Various Vegetable Crops. J. Environ. Qual. 4(2):278-282.

Finch, S. C., and C. A. Finch. 1955. Idiopathic Hemochromatosis, An Iron Storage Disease. A. Iron Metabolism in Hemochromatosis. Medicine. 34:381. (As cited in TDI, 1981.)

Foy, C. D., R. L. Chaney, and M. C. White. 1978. The Physiology of Metal Toxicity in Plants. Ann. Rev. Plant. Physiol. 29:511-66.

Fuller, W. H., and K. Lanspa. 1975. Uptake of Iron and Copper by Sorghum from Mine Trailings. J. Environ. Qual. 4(3):417-422.

Fuller, W. 1977. Movement of Selected Metals, Asbestos, and Cyanide in Soil: Applications to Waste Disposal Problems. Prepared for U.S. EPA under Contract No. 68-03-0208. EPA 600/2-77-020. Cincinnati, OH. April.

Furr, A. K., G. S. Stoewsand, C. A. Bache, and D. J. Lisk. 1976. Study of Guinea Pigs Fed Swiss Chard Grown on Municipal Sludge-Amended Soil. Arch. Environ. Health. March/April: 87-91.

Helmke, P. A., W. P. Robarge, R. L. Korotev, and P. J. Schomberg. 1979. Effect of Soil-Applied Sewage Sludge on Concentrations of Elements in Earthworms. J. Environ. Qual. 8(3):322-327.

Hem, J. D. 1970. Study and Interpretation of the Chemical Characteristics of Natural Water. Geological Survey Water-Supply Paper. 1473. U.S. Government Printing Office, Washington, D.C.

Jackson, M. L. 1964. Chemical Composition of Soils. In: Bear, E. E. (ed.), Chemistry of the Soil. American Chem. Soc. Monograph Series No. 160. Rheinhold Publ. Corp. New York, NY. (As cited in TDI, 1981.)

John, M. K., and C. J. Van Laerhoven. 1976. Effect of Sewage Sludge Composition, Application Rate, and Lime Regime on Plant Availability of Heavy Metals. J. Environ. Qual. 5(3):246-251.

Koong, L. J., M. B. Wise, and E. R. Barrick. 1970. Effect of Elevated Dietary Levels of Iron on the Performance and Blood Constituents of Calves. J. Ani. Sci. 31:422.

MacPhail, A. P., et al. 1979. Changing Patterns of Dietary Iron Overload in Black South Africans. Am. Jour. Clin. Nutr. 32:1272. (As cited in TDI, 1981.)

McGhee, F., C. R. Greger, and J. R. Couch. 1965. Copper and Iron Toxicity. Poult. Sci. 44:310.

Miller, J., and F. C. Boswell. 1979. Mineral Content of Selected Tissues and Feces of Rats Fed Turnip Greens Grown on Soil Treated with Sewage Sludge. J. Agric. Food Chem. 27(6):1361-65.

Narwal, R. P., B. R. Singh, and A. R. Panhwar. 1983. Plant Availability of Heavy Metals in a Sludge-Treated Soil: I. Effect of Sewage Sludge and Soil pH on the Yield and Chemical Composition of Rape. J. Env. Qual. 12(3):358-365.

National Academy of Sciences. 1980. Mineral Tolerances of Domestic Animals. National Research Council Subcommittee on Mineral Toxicity in Animals. Washington, D.C.

National Research Council. 1979. Iron. University Park Press, Baltimore, MD.

National Research Council. 1980. Food and Nutrition Board. Revised Edition of Recommended Daily Allowances of Foods - Iron. National Academy of Sciences, Washington, D.C. (As cited in TDI, 1981.)

Nhung, M. T. M., and F. N. Ponnamperuma. 1966. Effects of Calcium Carbonate, Manganese Dioxide, Ferric Hydroxide, and Prolonged Flooding, Chemical and Electrochemical Changes and Growth of Rice in a Flooded Acid Sulfate Soil. Soil. Sci. 102:29-41. (As cited in Foy et al., 1978.)

O'Donovan, P. B., R. A. Pickett, M. P. Plumlee, and W. M. Beeson. 1963. Iron Toxicity in the Young Pig. J. Ani. Sci. 22:1075.

Pennington, J. A. T. 1983. Revision of the Total Diet Study Food Lists and Diets. J. Am. Diet. Assoc. 82:166-173.

Rhoads, F. M. 1971. Relations Between Fe in Irrigation Water and Leaf Quality of Cigar Wrapper Tobacco. Agron. J. 63:938-40.

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.

Sabey, B. R., and W. E. Hart. 1975. Land Application of Sewage Sludge: I. Effect on Growth and Chemical Corporation of Plants. J. Environ. Qual. 4(2):252-256.

Shacklette, H. T., et al. 1971. Elemental Composition of Superficial Materials in the Coterminous United States. U.S. Geological Society Professional Paper 574-D. U.S. Government Printing Office, Washington, D.C. 71 pp.

Shetron, S. G. 1979. Chemical Composition of Alfalfa (Medicago sativa L.) Grown on Iron and Copper Mine Mill Wastes. U.S. Fish and Wildlife Service, Wildlife Needs in Eastern U.S. Symposium, WV. NTIS PB 79-05830. pp. 311-319.

Sollman, T. M. 1957. A Manual of Pharmacology. 8th Ed. W. B. Saunders Co. Philadelphia, PA.

Sommers, L. E., D. W. Nelson, and K. J. Yost. 1976. Variable Nature of Chemical Compositon of Sewage Sludges. J. Environ. Qual. 5(3):303-306.

Standish, J. F., C. B. Ammerman, C. F. Simpson, F. C. Neal, and A. Z. Palmer. 1969. Influence of Graded Levels of Dietary Iron, as Ferrous Sulfate, on Performance and Tissue Mineral Composition of Steers. J. Ani. Sci. 29:496.

Standish, J. F., C. B. Ammerman, A. Z. Palmer, and C. F. Simpson. 1971. Influence of Dietary Iron and Phosphorus on the Performance, Tissue Mineral Composition and Mineral Absorption in Steers. J. Ani. Sci. 33:171.

TDI, Inc. 1981. Multimedia Criteria for Iron and Compounds. Draft Prepared for EPA. Cincinnati, OH.

Tanaka, A., R. Loe, and S. A. Navasero. 1966. Some Mechanisms Involved in the Development of Iron Symptoms in the Rick Plant. Soil Sci. Plant Natr. 19:173-82. (As cited in Foy et al., 1978.)

Thornton, I., and P. Abrams. 1983. Soil Ingestion - A Major Pathway of Heavy Metals into Livestock Grazing Contaminated Land. Sci. Total Environ. 28:287-294.

U.S. Department of Agriculture. 1975. Composition of Foods. Agricultural Handbook No. 8.

U.S. Environmental Protection Agency. 1976. Quality Criteria for Water. Washington, D.C.

U.S. Environmental Protection Agency. 1982. Draft Interim Criterion Statement: Iron. Ambient Water Quality Criterion for the Protection of Human Health. Internal Review CIN-82-D008. Environmental Criteria and Assessment Office, Cincinnati, OH.

U.S. Environmental Protection Agency. 1983. Assessment of Human Exposure to Arsenic: Tacoma, Washington. Internal Document. OHEA-E-075-U. Office of Health and Environmental Assessment, Washington, D.C. July 19.

U.S. Environmental Protection Agency. 1984. Air Quality Criteria for Lead. External Review Draft. EPA 600/8-83-028B. Environmental Criteria and Assessment Office, Research Triangle Park, NC. September.

APPENDIX

PRELIMINARY HAZARD INDEX CALCULATIONS FOR IRON IN MUNICIPAL SEWAGE SLUDGE

I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

A. Effect on Soil Concentration of Iron

1. Index of Soil Concentration Increment (Index 1)

a. Formula

$$\text{Index 1} = \frac{(SC \times AR) + (BS \times MS)}{BS\ (AR + MS)}$$

where:

SC = Sludge concentration of pollutant (μg/g DW)
AR = Sludge application rate (mt DW/ha)
BS = Background concentration of pollutant in soil (μg/g DW)
MS = 2000 mt DW/ha = Assumed mass of soil in upper 15 cm

b. Sample calculation

$$1.000997 = \frac{(28000\ \mu g/g\ DW \times 5\ mt/ha) + (20000\ \mu g/g\ DW \times 2000\ mt/ha)}{20000\ \mu g/g\ DW\ (5\ mt/ha + 2000\ mt/ha)}$$

B. Effect on Soil Biota and Predators of Soil Biota

1. Index of Soil Biota Toxicity (Index 2)

a. Formula

$$\text{Index 2} = \frac{I_1 \times BS}{TB}$$

where:

I_1 = Index 1 = Index of soil concentration increment (unitless)
BS = Background concentration of pollutant in soil (μg/g DW)
TB = Soil concentration toxic to soil biota (μg/g DW)

b. Sample calculation - Values were not calculated due to lack of data.

2. **Index of Soil Biota Predator Toxicity (Index 3)**

a. **Formula**

$$\text{Index 3} = \frac{(I_1 - 1)(BS \times UB) + BB}{TR}$$

where:

I_1 = Index 1 = Index of soil concentration increment (unitless)
BS = Background concentration of pollutant in soil (μg/g DW)
UB = Uptake slope of pollutant in soil biota (μg/g tissue DW [μg/g soil DW]$^{-1}$)
BB = Background concentration in soil biota (μg/g DW)
TR = Feed concentration toxic to predator (μg/g DW)

b. **Sample calculation** - Values were not calculated due to lack of data.

C. **Effect on Plants and Plant Tissue Concentration**

1. **Index of Phytotoxicity (Index 4)**

a. **Formula**

$$\text{Index 4} = \frac{I_1 \times BS}{TP}$$

where:

I_1 = Index 1 = Index of soil concentration increment (unitless)
BS = Background concentration of pollutant in soil (μg/g DW)
TP = Soil concentration toxic to plants (μg/g DW)

b. **Sample calculation** - Values were not calculated due to lack of data.

2. **Index of Plant Concentration Increment Caused by Uptake (Index 5)**

a. **Formula**

$$\text{Index 5} = \frac{(I_1 - 1) \times BS}{BP} \times CO \times UP + 1$$

where:

I_1 = Index 1 = Index of soil concentration increment (unitless)
BS = Background concentration of pollutant in soil (μg/g DW)
CO = 2 kg/ha $(\mu g/g)^{-1}$ = Conversion factor between soil concentration and application rate
UP = Uptake slope of pollutant in plant tissue (μg/g tissue DW $[kg/ha]^{-1}$)
BP = Background concentration in plant tissue (μg/g DW)

b. **Sample calculation**

$$1.003268 = \frac{(1.000997-1) \times 20000\ \mu g/g\ DW}{36.3\ \mu g/g\ DW} \times \frac{2\ kg/ha}{\mu g/g\ soil} \times \frac{0.0057\ \mu g/g\ tissue}{kg/ha} + 1$$

3. **Index of Plant Concentration Increment Permitted by Phytotoxicity (Index 6)**

a. **Formula**

$$\text{Index 6} = \frac{PP}{BP}$$

where:

PP = Maximum plant tissue concentration associated with phytotoxicity (μg/g DW)
BP = Background concentration in plant tissue (μg/g DW)

b. **Sample calculation**

$$6.0 = \frac{1206\ \mu g/g\ DW}{200\ \mu g/g\ DW}$$

C. **Effect on Herbivorous Animals**

1. **Index of Animal Toxicity Resulting from Plant Consumption (Index 7)**

a. **Formula**

$$\text{Index 7} = \frac{I_5 \times BP}{TA}$$

where:

I_5 = Index 5 = Index of plant concentration increment caused by uptake (unitless)
BP = Background concentration in plant tissue (μg/g DW)
TA = Feed concentration toxic to herbivorous animal (μg/g DW)

b. **Sample calculation**

$$0.076577 = \frac{1.003268 \times 36.3\ \mu g/g\ DW}{477\ \mu g/g\ DW}$$

2. **Index of Animal Toxicity Resulting from Sludge Ingestion (Index 8)**

a. **Formula**

If AR = 0, $I_8 = \frac{BS \times GS}{TA}$

If AR ≠ 0, $I_8 = \frac{SC \times GS}{TA}$

where:

AR = Sludge application rate (mt DW/ha)
SC = Sludge concentration of pollutant (μg/g DW)
BS = Background concentration of pollutant in soil (μg/g DW)
GS = Fraction of animal diet assumed to be soil (unitless)
TA = Feed concentration toxic to herbivorous animal (μg/g DW)

b. **Sample calculation**

If AR = 0, $0.714285 = \frac{20000\ \mu g/g\ DW \times 0.05}{1400\ \mu g/g\ DW}$

If AR ≠ 0, $1.0 = \frac{28000\ \mu g/g\ DW \times 0.05}{1400\ \mu g/g\ DW}$

E. **Effect on Humans**

1. **Index of Human Toxicity Resulting from Plant Consumption (Index 9)**

a. **Formula**

$$\text{Index 9} = \frac{[(I_5 - 1)\ BP \times DT] + DI}{ADI}$$

where:

I_5 = Index 5 = Index of plant concentration increment caused by uptake (unitless)
BP = Background concentration in plant tissue (μg/g DW)
DT = Daily human dietary intake of affected plant tissue (g/day DW)
DI = Average daily human dietary intake of pollutant (μg/day)
ADI = Acceptable daily intake of pollutant (μg/day)

b. Sample calculation (toddler)

$$0.429225 = \frac{[(1.003268 - 1) \times 94\ \mu g/g\ DW \times 74.5\ g/day] + 15000\ \mu g/day}{35000\ \mu g/day}$$

2. Index of Human Toxicity Resulting from Consumption of Animal Products Derived from Animals Feeding on Plants (Index 10)

a. Formula

$$\text{Index } 10 = \frac{[(I_5 - 1)\ BP \times UA \times DA] + DI}{ADI}$$

where:

I_5 = Index 5 = Index of plant concentration increment caused by uptake (unitless)
BP = Background concentration in plant tissue (μg/g DW)
UA = Uptake slope of pollutant in animal tissue (μg/g tissue DW [μg/g feed DW]$^{-1}$)
DA = Daily human dietary intake of affected animal tissue (g/day DW)
DI = Average daily human dietary intake of pollutant (μg/day)
ADI = Acceptable daily intake of pollutant (μg/day)

b. Sample calculation (toddler)

0.428573 =

$$\frac{1.003268-1) \times 36.3\ \mu g/g\ DW \times 0.26\ \mu g/g\ tissue[\mu g/g\ feed]^{-1} \times 0.97\ g/day] + 15000\ \mu g/day}{35000\ \mu g/day}$$

3. **Index of Human Toxicity Resulting from Consumption of Animal Products Derived from Animals Ingesting Soil (Index 11)**

a. **Formula**

If AR = 0, $\text{Index 11} = \frac{(BS \times GS \times UA \times DA) + DI}{ADI}$

If AR ≠ 0, $\text{Index 11} = \frac{(SC \times GS \times UA \times DA) + DI}{ADI}$

where:

AR = Sludge application rate (mt DW/ha)
BS = Background concentration of pollutant in soil (μg/g DW)
SC = Sludge concentration of pollutant (μg/g DW)
GS = Fraction of animal diet assumed to be soil (unitless)
UA = Uptake slope of pollutant in animal tissue (μg/g tissue DW [μg/g feed DW^{-1}]
DA = Average daily human dietary intake of affected animal tissue (g/day DW)
DI = Average daily human dietary intake of pollutant (μg/day)
ADI = Acceptable daily intake of pollutant (μg/day)

b. **Sample calculation (toddler)**

0.438659 =

$$\frac{(28000\ \mu g/g\ DW \times 0.05 \times 0.26\ \mu g/g\ tissue\ [\mu g/g\ feed]^{-1} \times 0.97\ g/day\ DW) + 15000\ \mu g/day}{35000\ \mu g/day}$$

4. **Index of Human Toxicity Resulting from Soil Ingestion (Index 12)**

a. **Formula**

$$\text{Index 12} = \frac{(I_1 \times BS \times DS) + DI}{ADI}$$

Pure sludge ingestion: $\text{Index 12} = \frac{(SC \times DS) + DI}{ADI}$

where:

I_1 = Index 1 = Index of soil concentration increment (unitless)
SC = Sludge concentration of pollutant (μg/g DW)

BS = Background concentration of pollutant in soil (μg/g DW)
DS = Assumed amount of soil in human diet (g/day)
DI = Average daily dietary intake of pollutant (μg/day)
ADI = Acceptable daily intake of pollutant (μg/day)

b. **Sample calculation (toddler)**

$$3.288564 = \frac{(1.000997 \times 20000\ \mu g/g\ DW \times 5\ g\ soil/day) + 15000\ \mu g/day}{35000\ \mu g/day}$$

Pure sludge:

$$4.428571 = \frac{(28000\ \mu g/g\ DW \times 5\ g\ soil/day) + 15000\ \mu g/day}{35000\ \mu g/day}$$

5. **Index of Aggregate Human Toxicity (Index 13)**

a. **Formula**

$$\text{Index 13} = I_9 + I_{10} + I_{11} + I_{12} - \frac{3DI}{ADI}$$

where:

I_9 = Index 9 = Index of human toxicity resulting from plant consumption (unitless)
I_{10} = Index 10 = Index of human toxicity resulting from consumption of animal products derived from animals feeding on plants (unitless)
I_{11} = Index 11 = Index of human toxicity resulting from consumption of animal products derived from animals ingesting soil (unitless)
I_{12} = Index 12 = Index of human toxicity resulting from soil ingestion (unitless)
DI = Average daily dietary intake of pollutant (μg/day)
ADI = Acceptable daily intake of pollutant (μg/day)

b. **Sample calculation (toddler)**

$$3.299307 = (0.429225 + 0.428573 + 0.438659 + 3.288564) - \left(\frac{3 \times 15000\ \mu g/day}{35000\ \mu g/day}\right)$$

II. LANDFILLING

Based on the recommendations of the experts at the OWRS meetings (April-May, 1984), an assessment of this reuse/disposal option is not being conducted at this time. The U.S. EPA reserves the right to conduct such an assessment for this option in the future.

III. INCINERATION

Based on the recommendations of the experts at the OWRS meetings (April-May, 1984), an assessment of this reuse/disposal option is not being conducted at this time. The U.S. EPA reserves the right to conduct such an assessment for this option in the future.

IV. OCEAN DISPOSAL

Based on the recommendations of the experts at the OWRS meetings (April-May, 1984), an assessment of this reuse/disposal option is not being conducted at this time. The U.S. EPA reserves the right to conduct such an assessment for this option in the future.