Land Application of Sewage Sludge: Physicochemical and Microbial Response

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1 Introduction

As a result of rapid urbanization, industrialization, and uncontrolled population increase, waste management has become a worldwide problem. In the 2001 census, the urban population of India comprised 285 millions, which accounted for 27% of the total population of the country. The share of urban population has increased from 19.9% in the year 1971 to 27.8% in the year 2001 (Vaidya 2009). The decadal growth from 1991 to 2001 of the urban population was 31.2%. One of the main reasons for increasing urbanization is the migration of rural populations to urban centers for employment. The unprecedented growth of this urban population has put tremendous pressure on the quality of life regarding housing, water, and power supply, and water, air, and soil quality deterioration. A decline in environmental quality from waste generation in these urban centers, especially solid waste, is of major and growing concern.

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Solid waste may comprise municipal solid wastes, such as food waste, rubbish, treated waste (industrial and sewage sludge), construction waste, industrial wastes (e.g., chemicals, scrap products, glass, fly ash, resins, industrial sludge, etc.), and hazardous wastes (e.g., volatile organic chemicals and pathological, biomedical, and pharmaceutical wastes). About 48 million tons of municipal solid waste is generated annually in India (Agarwal et al. 2005). Per capita waste generation in major cities of India ranges from 0.2 to 0.6 kg (Devi and Satyanarayana 2001). Urban local bodies spend approximately Rs. 500–1,500 per ton for solid waste collection, transportation, treatment, and its disposal. With increasing urbanization and consequent boost in the urban population, wastewater generation has increased tremendously. Water is the most essential natural resource of Earth, without which life would be impossible. Water resources are becoming increasingly contaminated from anthropogenic activities that result in its pollution. Although water pollution has both human and natural causes, pollution caused by human activities (e.g., industrial and urban effluents, tube well water withdrawal, agricultural runoff, etc.) is generally more widespread. A particularly egregious example of serious human-related pollution is that most sewage generated in towns and cities that are located on the banks of a river is conveniently allowed to flow into the river (Bhargava 2006; Singh and Agrawal 2008).

Stricter regulations on discharge of effluents and sewage into the rivers have been passed and have increasingly resulted in the construction of new sewage-effluent treatment plants. About 22,900 million liters per day (MLD) of domestic wastewater is generated from urban centers, whereas industrial wastewater generation is 13,500 MLD (CPCB 2005). The total treatment capacity in India for domestic wastewater is 5,900 MLD, whereas this value for industrial wastewater is 8,000 MLD. Total wastewater generation, i.e., industrial as well as domestic, has increased from 7,007 MLD in 1978–1979 to 26,254 MLD in 2003–2004, in class I cities (at least 100,000 population – one lakh – and above). However, wastewater treatment capacity has increased from 2,755.94 MLD in 1978–1979 to 7,044 MLD in 2003–2004 (CPCB 2005). Presently, only 26% of total wastewater released from all activities is treated before discharge.

The insoluble solid residue remaining after sewage is finally processed is referred as biosolids, domestic wastewater residuals, or sewage sludge. The prime objective of treatment of wastewater in a sewage treatment plant is to remove pathogens and disinfect effluent prior to its discharge into water bodies. The treatment efficiency of such plants is dependent on the particular treatment processes used. However, removal of solids in the form of sludge, during wastewater treatment, displaces pathogens from the water stream and concentrates them on the sludge solids (Gerba and Smith 2005). Concentration of pathogens in wastewater and sewage sludge is directly associated with an increased incidence of enteric infections at the treatment plant source area of wastewater. Such infections usually result from certain pathogenic forms of *Escherichia coli*, which are ubiquitous and normally exist in the intestines of humans and other vertebrates.

The term biosolids (referring to that solid fraction that remains after sewage treatment) is regarded to emphasize the beneficial nature of this product. The safe disposal of sewage sludge is one of the major environmental challenges throughout the world. Disposal alternatives frequently undertaken to remove such sludges have included soil application, dumping at sea, land filling, or incineration (Sanchez Monedero et al. 2004). In the United States, dumping of sewage sludge in the ocean was banned as of 31 December 1991 (Hill et al. 1996; USEPA 1999a, b) and in the European Community in 1998 (Zhidong and Wenjing 2009). Land filling and land application of sewage sludge are suggested to be the most economical sludge disposal methods (Mc Grath et al. 1994; Metcalf and Eddy 2003). Land application of sewage sludge is the most economical practice for reducing sewage sludge waste, and this approach also offers the opportunity to recycle beneficial plant nutrients and organic matter to soil for crop production (Laturnus et al. 2007; Singh and Agrawal 2008; Suhadolc et al. 2010; Silva et al. 2010). Assuming that sewage sludge has no significant levels of toxic pollutants, its application on agricultural land has great value, because of the potential it brings for fertilization and soil conditioning. Our purpose in this review is to address the effect that land application of sewage sludge has on soil physicochemical properties and on soil microbial response.

2 Characteristics of Sewage Sludge

The sewage sludges produced at different treatment plants and during different seasons vary in physicochemical properties. As a result, knowledge of the chemical composition of each kind of sewage sludge is necessary before it is used for land application. The characteristic of sewage sludge depends not only on the nature of the wastewater from which it comes but also on the processes by which the wastewater is processed. Sewage sludge is generally composed of organic compounds, macronutrients, a wide range of micronutrients, nonessential trace metals, organic micropollutants, and microorganisms (Kulling et al. 2001; Singh and Agrawal 2008, 2009) (see Table 1). What humans use in their daily lives (e.g., insecticides, detergents, pharmaceuticals, etc.) finds its way to either water or solid waste, and finally reaches treatment plants. Waste from different household industries also contributes heavy metals to waste water and, therefore, ultimately to sewage sludge (Singh and Agrawal 2008). Some important sources of heavy metals that find their way to the wastewater stream and to sewage sludge are shown in Fig. 1.

The macronutrients present in sewage sludge serve as a good source of plant nutrients, and organic constituents impart beneficial soil conditioning properties (Logan and Harrison 1995; Singh and Agrawal 2008). It is very rare that urban sewerage systems transport only domestic sewage to treatment plants. Usually, industrial effluents and storm-water runoff from roads and other paved areas are also discharged into sewerage treatment systems (Singh and Agrawal 2008). Therefore, sewage sludge may contain many different toxic materials (e.g., heavy metals, pesticides, toxic organics, hormone disruptors, detergents, and various salts), in addition to natural organic material (Mc Grath et al. 2000; Singh and Agrawal 2008). Sewage sludge was collected and characterized from eight Indiana cities in the USA over a 2-year period. Results showed that organic N and inorganic

Table 1 Comparison of physicochemical characteristics of sewage sludge from different countries

Properties	Thailand[a]	Spain[b]	India[c]
pH	6.82	8.6	7.0
Electrical Conductivity (ms cm^{-1})			2.28
Organic Carbon (%)	19.82	43.4	5.52
Total Nitrogen (%)	3.43	2.5	1.73
Total Phosphorus (%)	–	1.06	–
Exchangeable K (mg kg^{-1})	870	–	208.96
Exchangeable Ca (mg kg^{-1})	8,332	–	154.13
Total Fe(mg kg^{-1})			6,059
Total Ni (mg kg^{-1})			47.17
Total Mn (mg kg^{-1})			186.2
Total Zn (mg kg^{-1})	801	174	785.3
Total Pb (mg kg^{-1})	1.22	1.00	60.0
Total Cr (mg kg^{-1})	1,326	445	35.5
Total Cd (mg kg^{-1})	2,621	–	154.5

[a]Parkpain et al. (1998), [b]Martinez et al. (2002), [c]Singh and Agrawal (2009)

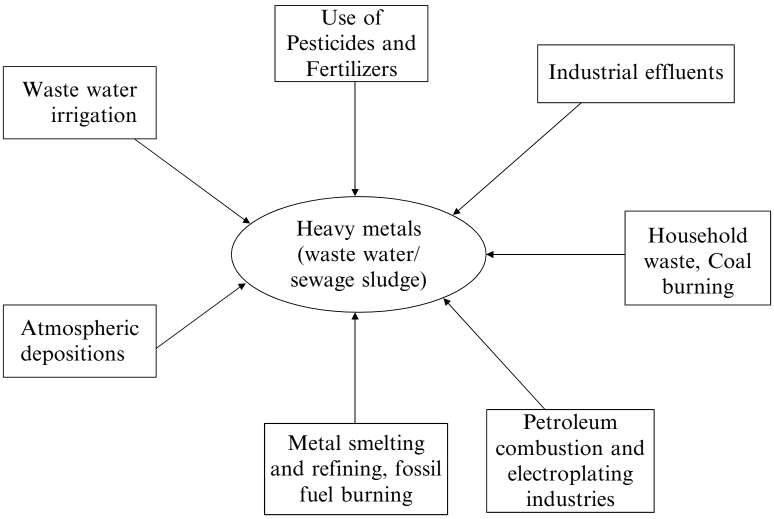

Fig. 1 Sources of heavy metals

P constituted the majority of the total N and P in the characterized sludge, respectively (Sommers et al. 1976). The analyzed sewage sludge contained approximately 50% organic matter and 1–4% inorganic carbon. Relatively constant concentrations of organic and inorganic C, organic N, and inorganic P, Ca, and Mg were present in a given sludge type, throughout the sampling period. The levels of inorganic N, organic P, K, and all other metals were somewhat inconsistent during the entire period of the study (Sommers et al. 1976). The major deviations found were for trace elements and heavy metals, such as Cd, Zn, Cu, Ni, and Pb (Sommers et al. 1976).

Characterization of sewage sludges from Calcutta, India was performed by Maiti et al. (1992) to assess the value of the sludge for plant fertilization. The sewage sludges analyzed were neutral to slightly alkaline and had higher salt content in winter than during the monsoon season (Maiti et al. 1992). Moreover, the cation exchange capacity (CEC) was reported to be higher during the monsoon season. Exchangeable Ca^{+2} was the prevailing cation found in the sludges analyzed, followed by Mg^{+2}, Na^{+}, and K^{+}. The sludges of Calcutta, India were reported to be rich in organic carbon and available N (Maiti et al. 1992).

A comparison of the physicochemical characteristics of sewage sludge collected from different countries is presented in Table 1. Results clearly show that sludge pH varies, and may be either acidic or alkaline (Parkpain et al. 1998; Martinez et al. 2002; Singh and Agrawal 2009). The organic matter content also varied considerably. By contrast, the content of total N and P did not vary that much (Table 1). Among heavy metals present, levels of Cu, Zn, and Mn were variable, whereas the Cd content was more consistent among samples analyzed. The sewage sludge collected from Dindigul (Tamil Nadu), India was recommended for land application, since this sewage sludge had nearly neutral pH, high organic matter, good N, P, and Ca content, and was free of toxic heavy metals such as Cr, Pb, and Hg (Nandakumar et al. 1998).

Singh and Agrawal (2010a, b, c) characterized the sewage sludge from Dinapur Sewage Treatment Plant (DSTP), Varanasi, India. This sewage sludge was neutral in pH and had high electrical conductance and high concentrations of organic C, total N, available P, Fe, Na^{+}, K^{+}, Ca^{2+}, and Mg^{2+} (Singh and Agrawal 2010a, b, c) (Table 1). Zn was present at the highest concentration in this sewage sludge, followed by levels of Cu, Mn, Cd, Pb, Ni, and Cr (Singh and Agrawal 2010a, b, c) (Table 1).

3 Effects of Sewage Sludge Application on Soil Properties

The disposal of sewage sludge by applying it to land is increasing in popularity because of the potential it offers to recycle valuable components (e.g., organic matter, N, P, and other plant nutrients) (Martinez et al. 2002; Singh and Agrawal 2008, 2010b, c). The aapplication of sewage sludge to agricultural soil not only enables nutrients to be recycled, but may eliminate the need for commercial fertilization of cropland (Sommers 1977; Singh and Agrawal 2007, 2009). Because sludges are organic fertilizers, application of them to soils increases soil fertility over time (Archie and Smith 1981). Unwise sewage sludge amendment practices, however, may disturb soil properties, especially when high concentrations of metals and toxic constituents are present in the sludge.

3.1 Physical Properties

The physical condition of soils has been improved by application of sewage sludges (Epstein 1975; Table 2). An increase in soil pH has been reported to occur in soils to which municipal sewage sludge was applied (Tsadilas et al. 1995). Cases of soil

Table 2 Effect of sewage sludge amendments on selected soil physical, chemical, and biological properties

Properties	Effect	References
Physical		
pH	Decrease	Epstein et al. (1976), Nielson et al. (1998), Moreno et al. (1997)
	Increase	Tsadilas et al. (1995), Nielson et al. (1975)
Soil aggregate stability	Increase	Ojeda et al. (2003)
Bulk density	Decrease	Ramulu (2002), Ojeda et al. (2003)
Water-holding capacity	Increase	Epstein (1975), Ramulu (2002)
Porosity	Increase	Ramulu (2002)
Humus content	Increase	Kulling et al. (2001)
Chemical		
Toxic elements	Increase	Adams and Sanders (1984), Kulling et al. (2001), Lopez- Mosaurea et al. (1975)
Soil organic carbon	Increase	Kladivko and Nelson (1975), Singh and Agrawal (2007, 2009, 2010)
Electrical conductance	Increase	Martinez et al. (2002), Ramulu (2002), Singh and Agrawal (2007, 2009, 2010b, c)
N and P	Increase	Martinez et al. (2002), Sommers (1977), Hậni et al. (1996), Walter et al. (2000), Singh and Agrawal (2007, 2009, 2010b, c)
Cation exchange capacity	Increase	Ramulu (2002), Soon (1981)
Biological		
Yeast population	Increase	Kulling et al. (2001)
Pathogenic organisms	Increase	Kulling et al. (2001), Ramulu (2002)
Aerobic bacteria	Increase	Kulling et al. (2001), Ramulu (2002)
Soil microbial activity, soil respiration	Increase	Garcia et al. (1993), Hậni et al. (1996), Banerjee et al. (1997)
	Decrease	Fließbach et al. (1994), Viera and de Souza Silva (2003)

pH being lowered have also been reported after land application of sewage sludges (Epstein et al. 1976; Singh and Agrawal 2010b, c) (Table 2). The changes that occur in soil pH after application of sewage sludges have been correlated with the level of calcium carbonate existing in the sludge, and with production of acids during sludge decomposition (Sommers 1977). Humic acid may be released as a result of biodegradation of sewage sludges rich in organic carbon; such humic acids may contribute to lower soil pH (Moreno et al. 1997). Sorption of metals onto soils is strongly related to soil properties. Generally, heavy metals are more bioavailable for plant uptake at lower pH levels; therefore, the pH of sewage sludge is an important consideration for metal-toxicity potential to plants (Lepp 1981). Several researchers have shown that metal sorption by soils increased with increasing pH (Naidu et al. 1994), organic matter (Gerritse and Van Driel 1984; Udom et al. 2004), cation exchange capacity (Buchter et al. 1989), and the contents of iron and manganese oxides. However, there is a lack of information concerning the adsorption of sludge-borne heavy metals on different soils (Sigua 2005).

Organic matter that is added to soil in the form of sewage sludge composts improves several soil properties, including bulk density, porosity, and water-holding capacity (Ramulu 2002; Table 2). The chemical properties of sludge–soil mixtures not only depend on the properties of soil or sludge or sludge application rates but also on soil pH and on how these components interact (Parkpain et al. 1998). Epstein (1975) conducted a study to evaluate the effect of 0.5% sewage sludge application to soil on water retention, hydraulic conductivity and aggregate stability; results showed that raw and digested sludge improved total soil-water retention capacity, with the greatest enhancement occurring in raw-sludge-amended soil. Moreover, the sludge added to soil resulted in a significant increase in soil hydraulic conductivity after 27 days of incubation. The highest percentage of stable aggregates was reported in a raw sludge treatment that occurred during the first 118 days of incubation. After 175 days, the percentage of stable aggregates for sludge treatments remained the same, averaging 34 vs. 17% for untreated soil (Epstein 1975).

In a field experiment designed to study the effect of long-term sewage sludge application on the chemistry and biology of soils, Hậni et al. (1996) reported increased nutrients (mainly P) and heavy metals from the agricultural use of high levels of sewage sludge. According to Hậni et al. (1996), the soluble fraction of heavy metals, as well organic pollutants in soil, is a determining factor in deciding the stage at which heavy metal toxicity to soil microorganisms or microbial processes in soil is likely to be evident.

3.2 Chemical Properties

According to Hue and Ranjith (1994), the concentrations of metal in sewage sludge depends on factors that include both the (1) origin of the sewage and the (2) sewage treatment processes used. The bioavailability of sludge-borne metals in soil is influenced by several soil properties, including pH, redox potential (Eh), sesquioxide content, and organic matter content, as well as the rate of sludge application (Hue and Ranjith 1994). Adams and Sanders (1984) evaluated the effect pH has on the release rates of Zn, Cu, and Ni from sewage sludges. These authors reported that the concentration of metal released from sewage sludge to the supernatant liquid increased as pH decreased below a threshold value; this threshold value was 5.8 for Zn-loaded sludge, 6.3 for Ni-loaded sludge, and 4.5 for Cu-loaded sludges. The metal content of the supernatant was small and relatively constant at pHs above the aforesaid values. In speciation experiments, the proportion of soluble Cu present as Cu^{+2} in $CuCl_2$ was related to pH, whereas the proportion of soluble Zn present as Zn^{+2} was scarcely correlated with pH (Adams and Sanders 1984).

Hernandez et al. (1991) conducted a study to analyze what influence sewage sludge application had to a Calciorthid soil on the soil availability of macronutrients (N, P, and K) and heavy metals (Fe, Cu, Zn, Mn, Ni, Cr, Cd, and Pb). The total N and extractable N and P content increased in the sludge-amended soil, whereas the extractable K remained unaltered. The Cu, Zn, and Pb levels increased, while Fe content decreased. Extractability of Fe, Cu, Mn, Zn, and Pb increased, when sludge was applied, as compared to the unamended control.

Relatively high rates of sludge application increased the soil cation exchange capacity, which helped to retain essential plant nutrients within the rooting zone. Such nutrients are retained as a result of additional cation binding sites being created (Soon 1981). Such responses, however, depend upon the sewage soil ratio. The higher the proportion of organic matter in sludges, the more bulk density was decreased and aggregate stability increased (Ojeda et al. 2003; Table 2). Sludge-related improvements in soil physical properties also increased water-holding capacity by promoting higher water retention in sludge-amended soils (Ojeda et al. 2003; Table 2).

Analysis of sewage-sludge-fed agricultural soil layers (0–15 and 15–30 cm) around Calcutta, collected from different upland and lowland sites, showed slightly alkaline pHs (Maiti et al. 1992). Subsurface soil had a higher pH (7.5) than did the surface ones (7.3). The soil of upland sites had slightly higher CEC [18.4–22.8 (cmol (p^+ kg^{-1}))] than did lowland ones [15.1–19.1 (cmol (p^+ kg^{-1}))]. Surface soil contained higher amounts of organic carbon (1.31%) than did subsurface ones (1.16%). Ca^{+2} was the dominant cation [11.5–19.3 cmol (p^+ kg^{-1})] in the sewage-fed soil, followed by Mg^{+2} [2.1–2.7 cmol (p^+ kg^{-1})], Na^+ [0.4–0.9 cmol (p^+ kg^{-1})], and K^+ [0.1–0.3 cmol (p^+ kg^{-1})]. Available N and P were at moderate to high levels.

Sewage sludge amendment always poses an environment risk, resulting from nutrient imbalances and toxic element accumulation, and leaching. Transfer of metal from sewage sludge to soil and later to groundwater via leaching poses potential health and environmental risks from plant uptake (McBride et al. 1997; Bhogal et al. 2003; Mahdavi and Jafari 2010). Korboulewsky et al. (2002) studied the effects of sewage sludge composts applied at the rates of 10, 30, and 90 tons ha^{-1} fresh wt, on a vineyard in southeastern France. These authors quantified the rate of in situ N mineralization, soil organic matter levels, and evaluated selected environmental risks, including N and P leaching rates, and levels of heavy-metal accumulation in soil. It was found that soil organic matter levels increased at all the treatment doses, but neither total nor available heavy metal concentrations increased. Because the sewage sludge studied contained very low levels of heavy metals, and existed mainly in nonextractable and nonexchangeable forms (Breslin 1999), composting it reduced the heavy metal availability by adsorption or complexing processes with humic substances. The levels of mineral nitrogen present increased in the plots in which the topsoil was amended during the first and the second summers. The risk of N leaching was very low in contrast to P at the recommended sludge amendment rate. The increase of P content in amended soil was significant in both top and subsoil layers in all treated plots. The maximum increase in P content occurred at the highest rate of sludge applied. However, at lower sludge amendment rates no significant differences were observed. It has been shown, in column leaching (Ashworth and Alloway 2004) studies, and in batch (Burton et al. 2003) experiments, that heavy metal ions may leach more easily in the presence of sewage sludge than in its absence. Moreover, as dissolved organic matter (DOM) concentration increases, the movement and translocation of heavy metals in soil increases; by contrast, an increase in soil organic matter (bounded with soil particles) and pH decreases heavy metal mobility (Liu et al. 2007; McCarthy and Zachara 1989; McBride et al. 1999). As a result of the net negative charge of DOM at typical soil pHs, it generally moves easily through the soil system (Dunnivant et al. 1992).

Magdoff and Amadon (1980) performed both laboratory and field experiments to evaluate the contribution that the nitrogen in sewage sludge makes to crops. Aerobically treated secondary liquid sewage sludge was applied to supply 50, 100, 150, and 200 kg N ha^{-1} $year^{-1}$ (as ammonium nitrate) to corn (*Zea mays L.*) and hay (timothy, Kentucky bluegrass, quack grass, and red and white clover). These forages were grown on Hadley sandy loam and Nellis loam soils. Under laboratory conditions, more than 54% of the organic N added to the sludge-amended corn soil was mineralized. Under field condition, mineralization of organic N from sludge that had been applied to corn and hay averaged 55% during the first year of application. The amount of sludge organic N mineralized appeared to vary according to the percent organic N present in the sludge (Sommers 1977).

In soil, trace elements may exist as solid phases, free ions in soil solution, soluble organic mineral complexes, or adsorbed onto colloidal particles. Addition of sewage sludge to soils may affect the potential availability of heavy metals to plants (Wang et al. 1997). The solubility, and consequently the mobility of metals added in sewage sludge are controlled, in part, by organic matter decomposition and resultant creation of soluble organic carriers of metals (Chaney and Ryan 1993). Trace metal bioavailability is also dependent upon the form of organic matter present, i.e., soluble (fulvic acid) or insoluble (humic acid) forms (McBride 1995). Insoluble organic matter inhibits the uptake of metals, which are tightly bound to organic matter, thus reducing bioavailability. Soluble organic matter, however, increases bioavailability by forming soluble metal organic complexes (Mc Bride 1995). When organic matter decomposition rates are stable, the level of soluble organic matter present is reduced, which leads to a reduction in metal bioavailability.

Morera et al. (2002) studied the bioavailability of Cu, Ni, Pb, and Zn from municipal sewage sludge to sunflower plants (*Helianthus annus L.*) in four different types of soils (i.e., Ithnic Haplumbrept (LH), Calcixerollic Xerochrept (Cx1 and Cx2), and Paralithic Xerorth (Px)). Each of these soils retained different physicochemical properties. The purpose of the experiment was to evaluate the influence of several sewage sludge application rates (0, 80, 160, and 320 tons/ha dry wt.), and soil type on the bioavailability of heavy metals, and interaction among these variables. The acid pH of the LH soil favored the bioavailability of Zn from sewage sludge, whereas Cu bioavailability was greater in alkaline soils. The high organic matter content of the acid soil (LH) produced complexes with Cu and thus impaired its uptake by plants. A contrasting trend occurred with respect to metal concentrations in acid and alkaline soils. The plant concentrations of Zn, Cu, Pb, and Ni decreased with increases in sludge application rates for the acid soil (LH), whereas in alkaline soils (Cx1), Zn and Cu levels increased. There were minor changes in metal concentrations of plants grown in Cx2 and Px soils that resulted from increased sludge doses. The results of this study further suggested that soil type has a larger effect on metal bioavailability than did sludge application rates.

3.3 Biological Properties

Species used to monitor the health of an environment or ecosystem are referred to as "biological indicators." Biological indicators may constitute any biological species or group thereof, that have a function or population marker that can be used to determine ecosystem or environmental integrity. Biological indicators are often employed to represent some aspect of living soil components, and such indicators usually respond more rapidly than do physical and chemical indicators to changing soil conditions (Anderson and Gray 1990; Powlson 1994; Pascual et al. 2000). Moreover, biological indicators are useful as sensitive tools for detecting changes in soil conditions that may occur.

3.3.1 Soil Microbial Biomass and Enzymes

Of total soil microbial biomass, soil fungi often comprise at least 75–95% and together with bacteria are responsible for about 90% of the total energy flux of organic matter decomposition in soil (Paul and Clark 1996). Among the key fertility parameters and biological properties of soils, special emphases are given to soil enzyme activity.

Soil enzymatic measurements are used to provide a biological index of soil fertility, and soil enzyme activity is used as an indicator for many soil biological processes. Soil enzymatic activities have often been used to establish indices of soil fertility, since they reflect the effects of cultivation, soil properties, and pedological amendments (Skujins 1978; Ceccanti et al. 1993). Soil enzymes are constantly being synthesized, accumulated, inactivated, and/or degraded and, therefore, play vital agricultural and nutrient cycling roles (Tabatabai 1994; Dick 1997). The heavy metals present in sewage sludge may indirectly affect soil enzymatic activities (Kandeler et al. 2000). According to Fließbach et al. (1994), the effect of sewage sludge on biological activity can be used as a soil pollution indicator. Amending soils with sewage sludge increased soil microbial activity, soil respiration, and soil enzymatic activities (Banerjee et al. 1997). However, when incubations were longer and heavy metal availability was higher, reduced soil enzyme activities were reported (Fließbach et al. 1994).

Urease (urea amidohydrolase) is the enzyme that catalyzes the hydrolysis of urea to CO_2 and NH_4 ions, by acting on C-N nonpeptide bonds in linear amides (Antonious 2009). Urease is an important soil enzyme that also mediates the conversion of organic N to inorganic N by hydrolysis of urea to ammonia (Byrnes and Freney 1995). Invertase (β-D-fructofuranosidase) is a ubiquitous enzyme in soils (Gianfreda et al. 1995). The activities of urease and invertase are important in soil for releasing simple carbon and nitrogen sources that contribute to the growth and multiplication of soil microorganisms. According to Garcia et al. (1993), sewage sludge contains high amounts of enzymatic substrates. These easily available substrates stimulate microbial growth and enzyme production. Suhadolc et al. (2004), pointed out that increased Pb, Zn, and Cd bioavailability in heavy-metal-contaminated soils affects the structure of soil microbial communities and significantly reduces the rate of mineralization of the pesticide isoproturon (from 20 to 5%).

The effects of adding different levels (0, 100, 200, and 300 ton ha^{-1} dry wt.) and C/N ratios (3:1, 6:1, and 9:1) of sewage sludge on activities of β-glucosidase, alkaline phosphatase, arylsulphatase, and urease in a clay loam soil (at 25°C and 60% water-holding capacity) were studied by Kizilkaya and Bayrakli (2005). Nitrogen was added to the sludge as a $(NH_4)_2SO_4$ solution to obtain the desired C/N ratios. Compared to unamended control samples, a more rapid and significant increase in soil enzymatic activity occurred at different doses and at different C/N ratios of the sewage sludge amendments. Enzyme activities varied with differences in incubation period. Soils with the highest C/N ratio and sludge dose had the highest ß-glucosidase activity. Alkaline phosphatase and aryl sulphatase showed an incremental increase in their activity during the first 30 days of incubation, followed by a pronounced decrease as compared to unamended soil. Urease activity, however, showed an increase within 15 days, and thereafter its activity declined. The highest activities of urease, alkaline phosphatase, and arylsulphatase were observed in soil amended with a low C/N ratio and the highest dose of sludge.

Parat et al. (2005) studied the long-term (20 year) effect of farm yard manure (FYM) (10 ton ha^{-1} $year^{-1}$) and sewage sludge (10 and 100 ton ha^{-1} $year^{-1}$, added every 2 years) amendments on soil organic matter in a fluvisol soil. At the highest dose of sludge amendment, the organic carbon content was 2.5 times higher than that of the unamended soil. Microbial biomass also remained higher in the sludge-amended soils. In another study, three different soil types were treated with two sources of sewage sludge at four different rates (1, 3, 10, and 20% sludge/soil ratio dry wt.), and the β-glucosidase activity at different incubation periods was assayed (Eivazi and Zakaria 1993). Enzyme activity was inhibited at the lower loadings, but was enhanced at the higher application rates. Inhibition of enzyme activity was more pronounced for the soil having higher trace-metal concentrations in the sludge (Eivazi and Zakaria 1993). The increase in enzyme activity was attributed to enhanced microbial activity, which was stimulated by the higher nutrient and organic matter content levels of the sludge-amended soil.

Hậni et al. (1996) reported that the microbial activity in soil will normally be boosted when sewage sludge amendments are added. But, immediate enrichment with organic matter or inorganic and organic pollutants has also produced negative effects on soil microflora. The most significant harmful effects produced on soil microorganisms from sludge applications are the reduced size of total biomass, reduced nitrogen fixing activity, and changes in soil microbial population composition. However, it is still uncertain at which step heavy-metal toxicity becomes evident to soil microorganisms or to microbial processes (Hậni et al. (1996).

Viera and de Souza Silva (2003) studied the effect of frequent sludge amendments on soil dehydrogenase activity and microbial biomass C. The experiment was carried out at Jaguariuna, Brazil on loamy/clayey-textured dark red dystroferric oxisol, in which maize was cultivated. The treatments included: a control without fertilization or sludge, a chemical fertilized treatment, a sludge dose 1 (1N), sludge dose 2 (2N), sludge dose 3 (4N), and sludge dose 4 (8N). The dose of sludge was based on an N concentration equivalent to that recommended for maize. Other doses were two, four and eight times the base dose. The sludge was applied in April 1999, December 1999, and October 2000. After 132 days of incubation, the sludge dose 8N was detrimental to the soil microflora, as a result of the soil microbial biomass and dehydrogenase activity being reduced at this amendment dose.

Microbial populations and enzymatic activities in sewage-sludge-amended soils were studied at two application rates (5 and 1% dry wt.) by Hattori (1988) to elucidate the role of soil microorganisms in decomposing sewage sludge. The authors found that organic C and N mineralization rates rapidly increased bacterial number and proteinase activity in the soil and reached a maximum within the first 3 days, declining rapidly thereafter. The actinomycetes and fungi counts reached their maximum after 2 or 3 weeks of incubation and thereafter remained at the same level. The amino-acid N content found in 6N HCl extracts of sludge-amended soil decreased markedly. The proteinase-producing bacteria contributed significantly to the rapid degradation observed during the early days of the sludge amendment experiment, whereas actinomycetes and fungi contributed to a gradual degradation during the end phase. The sludge amendment enhanced soil microbial biomass by 8–28% (at the sludge amendment rate of 0.75% dry wt.), and the enhancement was greatest in the clay-loam, and the least in the sandy-loam soil (Dar 1996). The activities of three soil enzymes (i.e., dehydrogenase, alkaline phosphatase, and arginine ammonification) were enhanced by 18–25%, 9–23% and 8–12%, respectively, as compared to activities in unamended soils. The increase was greater in sandy loam than in loam, or clay loam soils.

Soil fertility may increase from additions of sewage sludge, although sludges may also be important causes of soil pollution. Some metals present in sludge, e.g., Cu, Ni, and Zn, are essential micronutrients for plants and microorganisms (Alloway 1995). However, at higher concentrations, even these micronutrients may be toxic. Adverse effects of sludge metals on soil microorganisms pose a potential threat to soil quality, particularly through the disruption of nutrient cycling. In most studies in which soils have been amended with sewage sludge, reductions in microbial biomass (Leita et al. 1995; Fließbach et al. 1994) and enzymatic activity (Kuperman and Carriero 1997) were found, when soils were contaminated with heavy metals. However, the influence of heavy metals on soil respiration is less well known. Some researchers have reported significantly lower CO_2 evolution in metal-contaminated soils (Doelman and Haanstra 1984; Freedman and Hutchinson 1980; Hattori 1992, Kuperman and Carreiro 1997). Others have reported the opposite (e.g., Leita et al. 1995; Fließbach et al. 1994; Bardgett and Saggar 1994). Additionally, a range of studies have indicated that respiration responses to metal inputs may vary with the time that has elapsed since application (e.g., Doelman and Haanstra 1984). Sludge applied to soils often contains a variety of metals. Responses of microbes to such metal combinations may be synergistic, antagonistic, or additive (Chander and Brookes 1991a). Because of the complexity of such interactions, it is very difficult to establish a minimum soil concentration for individual metals at which adverse effects on microorganisms may occur (Brookes 1995). Chander and

Table 3 Principal pathogens of concern in municipal wastewater and sewage sludge

Pathogen of concern	Disease or symptoms caused by the organism
Bacteria	
Salmonella spp.	Salmonellosis (food poisoning), typhoid
Shigella spp.	Bacillary dysentery
Yersinia spp.	Acute gastroenteritis (diarrhea, abdominal pain)
Vibrio cholerae	Cholera
Campylobacter jejuni	Gastroenteritis
Escherichia coli	Gastroenteritis
Viruses	
Poliovirus	Poliomyelitis
Coxsackievirus	Meningitis, pneumonia, hepatitis, fever
Echovirus	Meningitis, paralysis, encephalitis fever
Hepatitis A virus	Infectious hepatitis
Reovirus	Respiratory infections, gastroenteritis
Astroviruses	Gastroenteritis
Protozoa	
Cryptosporidium	Gastroenteritis, cryptosporidiosis
Entamoeba histolytica	Acute enteritis
Giardia lamblia	Giardiasis (diarrhea and abdominal cramps)
Toxoplasma gondii	Toxoplasmosis
Balantidium coli	Diarrhea, dysentery
Helminth worms	
Ascaris lumbricoides	Digestive disturbances, abdominal pain
Trichuris trichiura	Diarrhea, anemia, weight loss
Taenia sasginata	Nervousness, insomnia, anorexia
Taenia solium	Nervousness, insomnia, anorexia
Hymenolepis nana	Taeniasis
Necator americanus	Hookworm disease

Source: Rose et al. (1996); Epstein (1998); USEPA (1999a, b)

Brookes (1991b) reported that, in metal contaminated soils, microorganisms are under stress and soil biomass reduction occurs mainly as a result of inefficient biomass synthesis.

3.3.2 Pathogens

According to Sidhu et al. (2001), biosolids originating from wastewater treatment plants contain a wide range of pathogens naturally, some of which may be present in large numbers and may represent a public health hazard (e.g., *Salmonella* spp.). In dehydrated anaerobically digested sludge wastewater, the concentration of *Salmonella* spp. may exceed 10^5 g^{-1} of dry wt. (Russ and Yanko 1981). According to Epstein (1998), some pathogens are found in sewage sludge and these long survive their land application (Table 3). Viruses of small size and other pathogens present in sewage sludge, if not killed, may leach into ground water (Powelson et al. 1991). There are four major types of human pathogenic (disease-causing) organisms (bacteria, viruses, protozoa, and helminthes), and all may be present in domestic sewage. The actual species and quantity of pathogens present in domestic sewage from a particular municipality depends on the health status of the local community, and may vary significantly at different times. The concentration of pathogens in treated sewage sludge (biosolids) also depends on the reductions achieved by wastewater and sewage-sludge treatment processes. During the typical wastewater treatment process, the microorganisms present in sewage are reduced in number and become concentrated in the sewage sludge. However, some pathogens are still present in the effluent, which can contaminate recreational waters and drinking water supplies (Rose et al. 1996) (Table 3).

Lewis and Gattie (2002) reported that, of all the pathogenic organisms present in sewage sludge, enteric viruses are of the utmost risk to humans, owing to their resistance to high pH and heat treatment, high infectivity, and survivability (Gibbs et al. 1994; Lewis and Gattie 2002). The bacteria (e.g., fecal coliform, *Listeria monocytogenes*, and enterococci) found in sludge are capable of surviving anaerobic digestion (Sidhu 2000; Gerba et al. 2002; Estrada et al. 2004). After waste treatment processes and land application of sewage sludge, regrowth may also occur (and does occur with *Salmonella* sp). Several plant disease-causing pathogens have also been reported to exist in sewage sludge (Santos and Bettiol 2003; Al-Zubeiry 2005). Contamination of ground and surface water by chemicals and pathogens, and odor from volatile organics are some of the potential problems associated with the use of sludges on cropland (USEPA 1994).

Bioaerosols are particulate matter of microbial, plant or animal origin that measure less than 20 µm in diameter (Goyer et al. 2001). They consist of pathogenic or nonpathogenic live or dead bacteria, viruses, molds, pollens, etc. Bioaerosols are of considerable concern because they are associated with a wide range of health problems such as contagious infections, allergies, and cancer (Bray and Ryan 1991; Douwes et al. 2003). These are also of concern from the use of sewage sludge amendment, since bioaerosols can transmit many enteric microorganisms (Pahren and Jakubowski 1980). Land application of sewage sludge can result in the transport of pathogens through aerosols downwind of sludge storage sites, contamination of ground water, drinking-water wells, stock ponds, or food chain contamination from eating food grown in sludge-treated land.

4 Conclusions

The land application of sewage sludges to agricultural soils, and associated practices, is the most cost-effective management technique for disposing of sewage sludges and offers potential improvements over conventional disposal methods, such as landfilling or incineration. One advantage of such land application of sludges is that it recycles plants nutrients that are present in the sludge. Nutrients present in sewage sludge are also useful to the soil microbial biomass. Using sewage sludge as a soil amendment promotes microbiological activity, but may have the opposite outcome if toxic heavy metals are present in the applied sludges. Researchers have studied both the positive and negative effects of land application of sewage sludges and have reported dissimilar effects from sewage sludge on soil microbial biomass and activity. In some studies, appreciable concentrations of heavy metals in sewage sludge did not appear to have any negative influence on soil microbial biomass and enzyme activities. However, other reports have clearly illustrated that the heavy metals present in sewage sludge do decrease the proportion of microbial biomass C in total soil organic matter.

Increases in soil microbial biomass from sewage sludge amendments mainly result from stimulation of the indigenous soil microbes by microbes present in the sludge organic residues. Microbial biomass also increases from the addition of substrate-C. The effect of heavy metals on soil microbes depends on the characteristics of the soil as well as on the character and rates of sewage sludge applied. It is known that that biosolids originating from wastewater treatment plants contain a wide variety of pathogens. Several plant-disease causing pathogens have also been reported to occur in the biosolids.

Our main conclusions from reviewing the cogent literature and from preparing this review are as follows:

1. Although the application of sewage sludge in agricultural practice may be beneficial, it also may contaminate ground water, drinking water from wells, and the food chain
2. Land applications of sewage sludge may result in transport of pathogens through aerosols to areas of human habitation
3. Considering the foregoing, the physicochemical analysis of sewage sludge is necessary before a decision is made to use it for land application
4. To reach a clearer conclusion on the value of sewage sludge disposal by land application under diverse conditions, more research is required. In particular, research is needed on application to different soil types and at sewage sludge amendment rates to evaluate effects on soil microbial biomass

5 Summary

In the present review, we address the effects of sewage sludge amendment on soil physicochemical properties and on soil microbial biomass. Sewage sludge is a by-product of sewage treatment processes and is increasingly applied to agricultural lands as a source of fertilizer, and as an alternative to conventional means of disposal. The particular characteristics of sewage sludge depend upon the quality of sewage from which it is made, and the type of treatment processes through which it passes. Sewage sludge may substitute for inorganic fertilizers because it is rich in organic and inorganic plant nutrients.

However, the presence of potentially toxic metals and pathogens in sewage sludge often restricts its uses. Ground water and food chain contamination resulting

from sewage sludge amendment is one major concern worldwide. The health of soils is represented by a composite of their physical, chemical and biological properties. Amending soil with sewage sludge modifies the physicochemical and biological properties of soils. Perhaps the central constituent of soil that is important in the context of sewage sludge amendment is microbial biomass. Soil microbial biomass, the key living part of the soil, is very closely associated with the content of organic matter that exists in arable agricultural soils. When sewage sludge is land-applied, soil enzyme activities may be directly or indirectly affected by the presence of heavy metals. In several studies, results have shown that sewage sludge amendment increased soil microbial and soil enzyme activities; however, reduction in soil enzyme activity has also been reported. When incubation periods of sewage sludge were longer, heavy metal bioavailability increased. Soil pathogenic activity has also been reported to increase as a result of land application of sewage sludges. The level of pathogens in treated sewage sludge (biosolids) depends on the processes used to treat wastewater and sewage sludge. Agricultural application of sewage sludge may result in the transport of pathogens through aerosols downwind of sludge storage or dispersal sites, may contaminate ground water, stock ponds, or may produce food chain contamination from eating food grown in sludge-treated land.

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