

Potential Environmental Benefits from Blending Biosolids with Other Organic Amendments before Application to Land

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Abstract

Biosolids disposal to landfill or through incineration is wasteful of a resource that is rich in organic matter and plant nutrients. Land application can improve soil fertility and enhance crop production but may result in excessive nitrate N (NO_3^- -N) leaching and residual contamination from pathogens, heavy metals, and xenobiotics. This paper evaluates evidence that these concerns can be reduced significantly by blending biosolids with organic materials to reduce the environmental impact of biosolids application to soils. It appears feasible to combine organic waste streams for use as a resource to build or amend degraded soils. Sawdust and partially pyrolyzed biochars provide an opportunity to reduce the environmental impact of biosolids application, with studies showing reductions of NO_3^- -N leaching of 40 to 80%. However, other organic amendments including lignite coal waste may result in excessive NO_3^- -N leaching. Field trials combining biosolids and biochars for rehabilitation of degraded forest and ecological restoration are recommended.

Core Ideas

- Landfilling or burning biosolids is an expensive waste of a valuable resource.
- High rates of biosolids restore degraded soil but cause excessive nitrate leaching.
- Combining biosolids with other biowastes can mitigate nitrate leaching.
- Dried, but not wet, wood waste effectively mitigates nitrate leaching.
- Partial pyrolysis of wood waste may provide energy-neutral drying.

WE investigate the opportunity and challenges of blending biosolids (sewage sludge) with organic waste materials for land application to improve environmental and economic outcomes. There are numerous publications describing the effects of adding organic amendments such as biochar, wood waste, composts, and lignite to soils (Laghari et al., 2016). Similarly, the beneficial and detrimental effects of biosolids addition to soil are well described. However, there is only disparate information on the effects of mixing these amendments with biosolids, which have physicochemical properties that contrast sharply with most soils. This review seeks to determine whether such mixtures could alleviate some of the negative environmental outcomes associated with the land application biosolids.

Biosolids: Resource and Disposal

Biosolids are the end product of wastewater treatment (Jones-Lepp and Stevens, 2007), rich in organic matter and containing agronomically significant concentrations of plant nutrients (Evanylo, 2009). However, biosolids also contain heavy metals (Haynes et al., 2009), pathogens (Gary et al., 2011), organic and pharmaceutical residues (Shinbrot, 2012), and other xenobiotics including endocrine disruptors (Ramamoorthy et al., 1997; Blair et al., 2000; Liu et al., 2009). Most jurisdictions have regulations proscribing the land application of biosolids with excess contaminant concentrations (NZWWA, 2003).

Stockpiling biosolids can exacerbate the emission of greenhouse gases such as nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4) (Majumder et al., 2014). Chemicals can leach through soils from stockpiled biosolids (Raghab et al., 2013). Treating biosolids as a waste requires disposal and incurs substantial costs for a product that could be a valuable resource if the environmental risks from residual contaminants could be avoided (Magesan and Wang, 2003).

The amount of biosolids produced globally is staggering. In 2008, biosolids production from 18 countries was estimated to be 18 million dry t yr^{-1} (LeBlanc et al., 2008), and China was reported to have doubled its sewage sludge production from 2005 to 2015 (GWI, 2015). Before landfilling and incineration, ocean disposal was the major disposal route; ~50% of the sewage produced worldwide was dumped into the sea (Bothner et al., 1994). Now, biosolids disposal differs between countries;

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for example, in New Zealand, biosolids are disposed of through landfilling (60%), ocean discharge (10%), application to agricultural land (10%) and forests (5%), and for land rehabilitation (10%) and composting or landscaping (5%) (ANZBP, 2014). Landfilling remains the most common form of biosolids disposal (O'Kelly, 2005), with many countries disposing of >50% this way (UNEP, 2016). Modern landfills are complex and costly facilities to build and operate; in New Zealand, disposal cost is approximately US\$140 to 175 t⁻¹, excluding transport costs (WCC, 2008). Furthermore, landfills are major sources of emissions of greenhouse gases, particularly CH₄ and N₂O (Spokas et al., 2006; Bogner et al., 2008), which account for up to 5% of global emissions (Bogner et al., 2008; Miller-Robbie et al., 2015). Incineration of biosolids is similarly widely practiced (Werther and Ogada, 1999), accounting for 70% of biosolids disposal in Japan, 58% in the Netherlands, 34% in Germany, 30% in Canada, 15% in the United States, and 20% in France (LeBlanc et al., 2008). Incineration also releases potentially harmful chemicals such as dioxins, furans, NO_x, N₂O, SO₂, and hydrocarbons (Werther and Ogada, 1999).

Land application of biosolids offers the potential to recycle organic matter and nutrients (O'Connor et al., 2005), but pathogens and trace elements may present a risk to soil quality and human health (Sullivan et al., 2006; Singh and Agrawal, 2008). To meet regulatory conditions required for land application, biosolids often require treatment that includes some combination of aerobic digestion, anaerobic digestion, composting, alkaline stabilization, or thermal drying (Lu et al., 2012). All treatment systems reduce pathogen loads, volatile organic compounds, and other easily oxidized organic fractions, including some organic contaminants. Anaerobic systems reduce the organic matter content of biosolids more than aerobic systems (Marchaim, 2017). Biosolids may be dewatered through thermal drying or by using a press. Fresh biosolids usually have high concentrations of NH₄⁺, which oxidizes to NO₃⁻ in aged biosolids (Ogilvie, 1998). Tables 1 and 2 give the physicochemical properties of biosolids resulting from different wastewater treatment processes.

Land application is also limited by agronomic loading rates of plant available nitrogen (N) in biosolids (Gilmour and Skinner, 1998). Plant available N is related to total inorganic N and a

fraction of mineralization of organic N during biosolids decomposition (Gilmour and Skinner, 1998), although composition ratio changes with age and origin of the biosolids (Bernal et al., 1998; Rouch et al., 2011). Clearly, suitable amendment materials need to be low cost, readily available, and easy to transport and apply.

Potential of Biosolids to Improve Soil Fertility

Biosolids have been widely shown to improve several physicochemical properties of soil, including porosity, cation exchange capacity, conductivity, water- and nutrient-holding capacity, bulk density, aeration, and drainage (Haering et al., 2000; Stoffella et al., 2003; Michalk et al., 2004). It has also been proven that biosolids application improves carbon (C) sequestration in soils (Bolan et al., 2013). The main contributory constituents toward soil improvement are organic matter (>65%) and N (~5%) (Schmidt et al., 2001; Evanylo, 2009; Haynes et al., 2009).

Many countries already use biosolids as a supplement or replacement for inorganic fertilizer (Ozores-Hampton and Peach, 2002; Rajendram et al., 2011). Biosolids can also be used as a stabilized product to reuse as a fertilizer in wetland agriculture, where heavy metals and fecal bacteria indicators can be maintained under regulatory limits (Uggetti et al., 2012). Of course, there is always concern about biosolids application to agricultural land in relation to residual biological and chemical contaminants (Barnett and Russell, 2001; Magesan and Wang, 2003). For this reason, it has been suggested that it may be more efficacious to use biosolids for soil rehabilitation of degraded or disturbed soils, such as recovering plantation-forest soils (Paramashivam et al., 2016a) and for mine waste restorations (Haering et al., 2000).

Problems Associated with Land Application

Any application of biosolids to land carries a risk of negative impacts on soil quality and human health. Most biosolids contain elevated concentrations of heavy metals (McBride et al., 1999) and organic contaminants, including polychlorinated biphenyls (PCBs), dioxins, polyaromatic hydrocarbons

Table 1. General properties of biosolids and sewage sludge at different stages of digestion.

	pH	EC†	Organic matter	CEC‡	Base saturation	Dry solids	NH ₄ ⁺	NO ₃ ⁻	References
		dS m ⁻¹	%	cmol _c kg ⁻¹	%	%	mg kg ⁻¹		
Raw sludge	5.5–6.5	0.4	n/g§	53.5	n/g	6.2 (0.3)	n/g	n/g	(Ogilvie, 1998),(Sanchez-Monedero et al., 2004),(Rouch et al., 2011),
Aerobic sludge	7.6–8.2	2.2 (1.7)	74 (8.5)	101	n/g	2.3	208	526	(Ogilvie, 1998),(Magesan and Wang, 2003),(Rigby and Smith, 2013)
Anaerobic sludge	5.8–8.1	4	14	n/g	n/g	1.7 (0.2)	520	100	(Ogilvie, 1998), (Magesan and Wang, 2003), (Civeira and Lavado, 2008), (Rigby and Smith, 2013)
Digested dry sludge	6.4–7.3	5.5 (0.4)	53 (9.5)	39	n/g	94	4732	431	(Ogilvie, 1998), (Rouch et al., 2011), (Correa et al., 2006)
Aged biosolids (>3 yr)	4.4–4.5	2.4 (0.8)	n/g	n/g	n/g	65	208	1848	(Ogilvie, 1998),(Nash et al., 2011), (Mok et al., 2013),(Laidlaw et al., 2012)
Aged biosolids (>20 yr)	4.5	n/d	51.6	16.7 (0.7)	107 (2.3)	51 (2.2)	130 (7.3)	1352 (2.5)	(Paramashivam et al., 2016b)

† EC, electrical conductivity.

‡ CEC, cation exchange capacity.

§ n/g, not given by the authors; n/d, not determined.

Table 2. Biosolids and sewage sludge elemental composition (references in Table 1). Values in parenthesis represent the standard deviation of the mean.

	Raw sludge	Aerobic sludge	Anaerobic sludge	Digested dry sludge	Aged biosolids (>3 yr)	Kaikōura biosolids (>20 yr)
Total C, %	44 (0.05)	41 (1.8)	41 (4.5)	38 (1)	23	30 (0.5)
Total N, %	2.2 (0.1)	4.8 (2)	9.3 (4.2)	4.7 (0.9)	1.9	3.1 (0.06)
Organic N, %	2	3.6	n/g†	4.1	n/g	n/d
C/N	20 (1.1)	8.5 (2.7)	4.4	8.1 (1.3)	12.1	9.7 (0.02)
Al, mg kg ⁻¹	3242 (962)	6522	11412	8618	21709 (333)	17351 (500)
As, mg kg ⁻¹	2.2 (1.8)	6.8 (3.2)	16	0.5	22 (3.5)	n/d
Cd, mg kg ⁻¹	0.9 (0.3)	2 (0.8)	3.7 (1.8)	3 (2.3)	20 (4)	2.3 (0.1)
Ca, mg kg ⁻¹	15450 (8450)	21348	48294	4268	11953 (441)	9455 (534)
Cu, mg kg ⁻¹	138 (9.5)	161 (113)	437 (106)	300 (105)	689 (105)	637 (39)
Cr, mg kg ⁻¹	239 (206)	408 (396)	1022 (208)	114	776 (208)	34.2 (0.3)
Fe, mg kg ⁻¹	2794 (274)	4253 (2573)	9882	28450 (1455)	16925 (2962)	8352 (221)
Pb, mg kg ⁻¹	60 (0.0)	73 (42)	240 (15)	140 (60)	497 (112)	114 (5.5)
Mg, mg kg ⁻¹	1995 (46)	n/g	15833 (1177)	3495 (455)	1746 (46)	2994 (55)
Mn, mg kg ⁻¹	75 (29)	159 (66)	369	196 (1)	103 (17)	189 (2.2)
Hg, mg kg ⁻¹	0.6 (0.3)	0.8	2.8	0.4	6.8 (0.8)	n/d
Ni, mg kg ⁻¹	19.5 (11)	61	91	17.3 (1.8)	155 (29)	26.4 (1)
P, mg kg ⁻¹	3100	1400	3710 (3290)	15444 (5729)	5737 (120)	3463 (248)
K, mg kg ⁻¹	2814 (696)	4565	18206 (1180)	2887 (1152)	3171 (78)	3014 (173)
Se, mg kg ⁻¹	1 (0.2)	3	5.3	2	n/g	n/d
Na, mg kg ⁻¹	4959 (719)	3957	6647 (353)	2170 (1919)	1744 (59)	299 (12)
S, mg kg ⁻¹	n/g	n/g	40000	n/g	12771 (4079)	6736(250)
Zn, mg kg ⁻¹	325 (86)	617 (280)	1647 (47)	859 (323)	1611 (373)	1047 (69)

† n/g, not given by the authors; n/d, not determined.

(PAHs), pesticides, herbicides, polybrominated diphenyl ethers (PBDEs), nonylphenol, linear alkyl sulfonate, and pharmaceuticals (LeBlanc et al., 2008). Particular concern has been raised about the presence of endocrine-disrupting compounds (Liu et al., 2009). Biosolids application can result in excessive N and P leaching, causing eutrophication of waters (Elliott et al., 2002; Paramashivam et al., 2016b), unpleasant odors (Rynk and Goldstein, 2003; Lu et al., 2012), and pathogens (Sullivan et al., 2006; Singh and Agrawal, 2008). Controlled application to appropriate soil depths in the correct season with consideration of crop harvest and animal grazing undoubtedly minimizes the impact of biosolids application (Smith, 1995); however, these forms of management are unlikely to provide a complete solution to concerns about real or perceived contamination issues.

Global standards exist for acceptable biosolids application rates to agricultural land (EPA-VA, 2004; NZWWA, 2003), but much higher amounts may be required to rebuild and rehabilitate forest or mine reclamation land (Sopper and Seaker, 1990). In one study, 20 yr of biosolids application to a plantation forest soil in Washington was shown to have enhanced tree growth without any apparent negative impact on either human health or the environment (Henry et al., 1994). Nevertheless, similar to concerns on agricultural land, excessive loading of biosolids to forest rehabilitation or mining land may lead to major concerns of nutrient leaching (Wang et al., 2003; Paramashivam et al., 2016b).

Organic Amendments

There is gathering evidence that a combination of biosolids with low-N organic materials offers an opportunity to reduce N leaching from soils amended with biosolids (Table 3). Coapplication of materials that sorb contaminants and mitigate negative impact on the environment obviously needs to provide

convincing evidence that this can be realistically achieved (Miller-Robbie et al., 2015). Pyrolysis of organic waste such forestry, garden, and agricultural wastes produces biochar. Biochar shows promise to sorb xenobiotic organic contaminants (Spokas et al., 2009; Wang et al., 2010; Zhang et al., 2010); inorganic components including NH_3 , N_2O , NO_3^- , and NH_4^+ (Taghizadeh-Toosi et al., 2011; Taghizadeh-Toosi et al., 2012; Paramashivam et al., 2016b); and metals (Uchimiya et al., 2010; Park et al., 2011). Knowles et al. (2011) and Gartler et al. (2013) demonstrated that biosolids–biochar mixtures resulted in the same or greater biomass production in a range of species compared with adding biosolids alone. This indicates that, although some biochars reduce N leaching from biosolids, they do not reduce N bioavailability to the point where it affects plant growth.

Sawdust has been used effectively to adsorb contaminated dyes (Shukla et al., 2002), heavy metals (Handreck, 1990; Trolve and Reid, 2003; Esperschütz et al., 2016) and inorganic and organic contaminants from water (Robertson and Cherry, 1995; Bugbee, 1999; Schipper and Vojvodic-Vukovic, 2000; Kim et al., 2003; Harmayani and Anwar, 2012; Israel et al., 2014). Used as a bulking agent with biosolids, sawdust can remove pathogens, which can be explained, for example, by the toxicity of tannin compounds to pathogens (Banegas et al., 2007). Pine sawdust has been used to treat groundwater; one study showed that removal of NO_3^- -N from groundwater via denitrification was at a rate of 0.8 to 12.8 ng N cm⁻³ h⁻¹ (Schipper and Vojvodic-Vukovic, 2000), where the sawdust provided a C source for denitrifying bacteria in a low-oxygen environment.

Lignite is a waste from the coal industry that is ineffective for energy production due to its high moisture content (Simmler et al., 2013). Budaeva et al. (2006) reported that NH_4^+ sorption from wastewater by a type of lignite was up to 23.2 g NH_4^+ kg⁻¹.

Table 3. Outcomes of experiments combining biosolids with organic materials. Ratios are given by mass unless otherwise stated.

Name and details of the material	Mixing ratio	Experiment	Finding of the study (mixture of biosolids + material compared with control)	References
Pine biochar 350°C (<i>Pinus radiata</i>)	Biochar 102 t ha ⁻¹ eq. Biosolids 600 and 1200 kg N ha ⁻¹ eq.	Lysimeter in the field	50% reduction in NO ₃ ⁻ leaching	(Knowles et al., 2011)
(i) Pine biochar 350°C (<i>Pinus radiata</i>)	(i) 1:1 biochar:biosolids	(i) Laboratory column	80% reduction in NH ₄ ⁺ -N	(Paramashivam et al., 2016b)
(ii) Dry pine sawdust (wood waste)	(ii) 2:5 sawdust:biosolids	(ii) Laboratory column	Eliminated NH ₄ ⁺ -N and NO ₃ ⁻ -N was reduced >40%	(Paramashivam et al., 2016b)
Pine biochar 350°C (<i>Pinus radiata</i>)	Soil containing 20% biochar and 10% biosolids by volume	Greenhouse pot experiment	Beetroot (<i>Beta vulgaris</i>) Zn (dry weight) uptake increased 178 mg kg ⁻¹ and Cd, Cu, Pb were below the WHO's guideline values.	(Gartler et al., 2013)
Sawdust	2:1 sawdust:sawdust. 1250 kg N ha ⁻¹ eq.	Greenhouse pot experiment	(i) N, P, Cu, Mn and Zn uptake increased in Italian ryegrass compared with control (ii) Cd uptake was reduced by 50% compared with biosolids alone treatment.	(Esperschütz et al., 2016)
Sawdust	Various combinations of sawdust with aerobic and anaerobic sludge	Incubation experiment	Suitable composting ratio was identified as 1:1 by volume with aerobic sludge and 1:3 for anaerobic sludge.	(Banegas et al., 2007)
Sawdust	Sawdust: biosolids mixtures with the C/N adjusted to 20:1. Mixture added at 1, 3, 7, and 14 t ha ⁻¹	Mine tailings reclamation and leaching experiments with lysimeters	Sawdust mixed with highest sewage sludge rate reduced NO ₃ ⁻ -N by 100 mg kg ⁻¹ compared with no sawdust addition.	(Daniels et al., 2001)
Lignite (mine waste)	2:5 lignite:biosolids	Laboratory column	66% reduction in NH ₄ ⁺ -N, but no effect on NO ₃ ⁻ -N leaching	(Paramashivam et al., 2016a)
Lignite	1, 3, 4, and 7.1 parts of lignite to 3.4 parts of biosolids	Greenhouse pot experiment: <i>Lolium perenne</i> ryegrass were grown in each treatment	Cd uptake was reduced by 30% in ryegrass at 1% lignite application rate	(Simmler et al., 2013)

After several years of amendment with lignite, soil had a higher C content (35%), slightly higher N content (33%), and a higher C/N ratio than control soil. Lignite mixed with biosolids has also been shown to reduce heavy metal uptake by plants (Simmler et al., 2013) and inorganic N leaching from soil (Paramashivam et al., 2016a).

Addressing Nitrogen Mobility

A strategically managed nutrient plan is required to reduce N loss from biosolids amendments while promoting plant production. The main forms of N in biosolids are organic N (~95%), NO₃⁻ (~4%), and NH₄⁺ (~1%) (Henry et al., 2000; Daniels et al., 2001). After land application of biosolids, some fraction of the organic N is mineralized by microorganisms in the soil and transformed to mobile inorganic forms (Prasad and Power, 1997). Nitrate is highly mobile in soil and can be readily leached through the soil profile. Otherwise, inorganic species (NH₃, NO₃⁻, and NH₄⁺) are potentially available for plant uptake, apart from any losses to volatilization, immobilization, or leaching (Prasad and Power, 1997). The main areas for considerations are (i) mineralization rates of the biosolids, (ii) volatilization rate of NH₄⁺-N, (iii) NO₃⁻-N concentrations in the biosolids at application time, (iv) rate of N uptake by vegetation, and (v) existing soil conditions and fertility (Haynes et al., 2009).

Biosolids application rates are a critical step in land application. For example, 18 mo after the application of biosolids to a vineyard soil at rates of 10, 30, and 90 Mg ha⁻¹ (fresh weight), soil organic matter increased by up to 3000 mg kg⁻¹ and inorganic N concentrations by 5 to 26 kg N ha⁻¹ (Korboulewsky et al., 2002). Despite the benefits of higher application rates, only the lowest rate of 10 Mg ha⁻¹ was regarded as a safe application

rate with no N leaching from the soil. Similar recommended application rates on cotton (*Gossypium hirsutum* L.) crops were reported by Samaras et al. (2008) and on sunflower (*Helianthus annuus* L.) by Lavado (2006). Many other studies report that application rates ranging from 10 to 30 Mg ha⁻¹ avoid excessive N leaching from soils and do not pose an undue risk to the environment or human health (Binder et al., 2002; Brenton et al., 2007; Rajendram et al., 2011). Even biosolids that have been through advanced treatment systems can result in high levels of NO₃⁻-N leaching if they introduce a high N load combined with a low C/N ratio. Therefore, higher rates of application will require some additional amendment to restrict nutrient leaching.

Organic Amendments to Blend with Biosolids

Few practicable amendments are low cost, easily transportable, and readily available. One example is sawdust and wood waste from commercial timber logging and sawmilling (Schipper and Vojvodic-Vukovic, 2000). Gerwing et al. (1996) reported that logging in eastern Amazonia produced some 24.7 m³ ha⁻¹ of wood waste. Decomposition of untreated wood waste added to a soil increases greenhouse gas emissions; although conversion to biochar partly addresses this concern (Gholz et al., 2000), pyrolyzation is a costly and time-consuming process. Greenhouse gas emissions resulting from the addition of wood waste to soil should be balanced against the alternatives, namely incineration or landfilling, which will ultimately result in the conversion of the wood to CO₂ or CH₄, respectively. An alternative to wood waste is lignite, which is abundant worldwide; recoverable world lignite resources are approximately 195 × 10⁹ t, with 333 × 10⁶ t being located in New Zealand (WEC, 2010).

Physicochemical characteristics of potential organic amendments (Table 4) determine the sorption of contaminants when this material is blended with biosolids. A porous structure is a prominent feature that is key to nutrient absorption or water and nutrient retention by biochar (McLaughlin et al., 2012). With lignite, there is a positive correlation between the porous texture and the molecular size of the sorbed species (Pope, 1984). Both materials have high C/N ratios (43–1300), which also has a critical influence on N mobility within soil (McLaren and Cameron, 1996; Kwiatkowska et al., 2008).

We found recently that lignite and most biochars are not effective in reducing NO_3^- leaching from soils amended with biosolids in a low-fertility soil (Paramashivam et al., 2016a). Lignite lessened the beneficial growth effects of adding biosolids to soil and exacerbated N_2O production. However, sawdust and partially pyrolyzed biochars (resulting from heterogeneous temperatures in the pyrolysis kiln) have provided convincing results from laboratory and glasshouse trials when applied with biosolids to the same soils (Paramashivam et al., 2016b). In batch sorption and column leaching experiments, biochars and fresh sawdust failed to sorb NO_3^- , but NO_3^- leaching was reduced by *Pinus radiata* D. Don sawdust with a low moisture content. One type of low-temperature (350°C) biochar also effectively sorbed NH_4^+ , reducing leaching from columns by 40 to 80%. Blending biosolids with some organic materials can reduce the environmental impact of biosolids application. These findings require further testing in the field.

Sorption of Xenobiotics and Heavy Metals

Biodegradation is the major pathway to breakdown xenobiotic compounds (Piveteau et al., 2001; Ye et al., 2004), ranging from days and weeks to years [some compounds, e.g., 1,1,1-trichloro-2,2-bis(4-chlorophenyl)ethane (DDT), take up to decades] (Fetzner, 2000). Organic amendments can promote biodegradation via several mechanisms. Organic amendments that contain an easily oxidized C source, such as low-molecular-weight organic acids, will promote the growth of microorganisms, which may in turn degrade some organic contaminants (Martin et al., 2014). Microorganisms such as white rot fungi [an assemblage of species, including *Pleurotus ostreatus* (Jacq. ex Fr.) P. Kumm and *Trametes versicolor* (L.) Lloyd.] that degrade lignin in wood waste can enhance the degradation of persistent organic pollutants such as pentachlorophenol (Mileski et al., 1988). Microbial inhibition in biosolids caused by poor aeration, low pH, or high concentrations of metals may be reduced by mixing the biosolids

Table 4. Key parameters potential organic amendments that could be mixed with biosolids. Values in brackets represent the standard deviation of the mean.

Material	HTT† °C	pH (H ₂ O)	C	N	H	O	CEC‡ cmol kg ⁻¹	BSS	Ash	Volatiles		Fixed C	References
										%	%		
Pine sawdust	-	5.7–7.6	51 (0.04)	0.06 (0.001)	n/d¶	n/d	10.6	448 (6.8)	1.4 (0.5)	72.4 (4)	n/g	(Paramashivam et al., 2016b), (Wilén et al., 2004)	
Pine (commercially pyrolyzed char)	350	6.9	78 (0.08)	0.06 (0.02)	n/d	n/d	9.1	88 (2.2)	3.3	53	36.2	(Paramashivam et al., 2016b)	
Feedstock for pyrolyzation													
Pine	350	5.1	71	0.1	5	25	29	22	1.2 (0.6)	45 (12)	55 (12)	(Enders et al., 2012), (Pereira Calvelo et al., 2011), (Hina et al., 2010)	
	400	6.9	77	0.6	4.6	14.5	30	0.1>	2.3 (0.8)	38.2 (4.5)	59.6 (4.1)		
	550	6.1–10	83 (2.8)	0.4 (0.2)	3.3 (0.1)	12 (2.8)	25	12	3.4 (0.9)	27 (6.5)	69 (5.2)		
Corn stover	500	6.5–9.9	54 (10)	1.1 (0.2)	3 (0.3)	10 (2.5)	40 (12)	142	33 (8)	29 (2.4)	38 (13)	(Enders et al., 2012), (Brewer et al., 2011)	
	550	6.6–10	55 (18)	0.9 (0.3)	2.8 (0.5)	13 (1)	28	n/a	29 (15)	34 (3.7)	37 (12)		
	600	6.7–10	51 (20)	0.9 (0.3)	2.2 (0.2)	9.3 (0.05)	33 (6.5)	172	36 (20)	21 (3.5)	43 (17)		
Switchgrass	450	6.2	38	0.5	2.2	9	28	n/a	50	17	32	(Enders et al., 2012), (Brewer et al., 2011)	
	500	6.6	52 (12)	1.2 (0.7)	2	2.4	26	n/a	55	32.3 (21)	36 (4.3)		
	550	6.7	42	0.5	2	5	26	n/a	50	14	35		
Poplar	400	7.2–9	55 (17)	0.6 (0.2)	3.4 (1.1)	38 (19)	n/a	n/a	2.9 (0.9)	35	61	(Pereira Calvelo et al., 2011),	
	550	8.8	76	1	3.6	13	n/a	n/a	6.5	28	66		
Oak	400	4.6–6.9	64 (11)	0.4 (0.2)	3.2	17.1	51.3 (9.9)	15	0.8	37 (4.5)	58	(Enders et al., 2012), (Zhang et al., 2015)	
	600	6.4–9.5	72 (13)	0.4 (0.09)	2.5	8.5	54.8 (42)	7.5	1.3	20.2 (7.9)	71		
Oak (with steam activation)	400	9.6	30.3	0.5	n/a	n/a	36.2	n/a	n/a	n/a	n/a	(Zhang et al., 2015)	
	600	9.6	37.1	0.4	n/a	n/a	42.6	n/a	n/a	n/a	n/a		
Lignite													
New Vale, New Zealand	-	4.5	86 (0.4)	1.3 (0.01)	n/a	n/a	43.6 (0.8)	115.3 (0.5)	n/a	n/a	n/a	(Paramashivam et al., 2016a).	
5 coal mine sites from Central Europe	-	5.1–6.2	63.4 (0.2)	0.9 (0.04)	5.5 (0.2)	27.4 (0.4)	20–70	n/g	19 (1.2)	n/g	n/g	(Janos et al., 2011)	
International humic substance society (IHSS)	-	4.2	65	1.2	5	28	72	n/g	13	n/g	n/g	(Janos et al., 2011)	

† HTT, highest treatment temperature for that particular pyrolysis.

‡ CEC, cation exchange capacity.

§ BS, base saturation.

¶ n/d, not determined; n/g, not given by the authors; n/a, not analyzed.

with organic amendments (Song and Schobert, 1996; Pehlivan and Arslan, 2007; Chassapis et al., 2009; Knowles et al., 2011; Simmler et al., 2013; Doskocil et al., 2015).

Xenobiotics can be immobilized or entrapped within the micropores of organic soil amendment (Fetzner, 2000). Biochar has been widely used for the sorption of xenobiotic contaminants from the soil (Wang et al., 2010). Zhang et al. (2010) have reported that the phenanthrene sorption linear distribution coefficient of soil amended with biochar was $3.4 \times 10^4 \text{ L kg}^{-1}$, and soil without amendment was only 47 L kg^{-1} .

Heavy metal concentrations in biosolids will be reduced by dilution when the biosolids are mixed with an organic amendment that has low metal concentrations. Amendments such as biochar can increase the pH of biosolids-amended soil, resulting in increased sorption and precipitation of heavy metal cations (Beesley et al., 2011). Heavy metals may be immobilized by sorption onto exchange sites on an organic amendment. Lignite increases the cation exchange capacity of the material due its high humic acid content (Kucerik et al., 2003; Janos et al., 2011). Lignite effectively immobilizes metallic ions and heavy metals such as Cu, Pb, Cd, Ni, and Zn in contaminated soils (Karczewska et al., 1996; Pehlivan et al., 2004; Budaeva et al., 2006; Domańska and Smolinska, 2012; Doskocil and Pekar, 2012) and removes radionuclides and potential toxic metals from wastewater (Mohan and Chander, 2006; Mizera et al., 2007). Unlike the degradation of xenobiotics, the immobilization of heavy metals may not be permanent; the degradation of organic amendments, as well as the biosolids themselves, may result in desorption of heavy metals and their subsequent leaching or plant uptake (Tella et al., 2016). In some cases, organic materials may increase the solubility of heavy metals such as Cu, which can form mobile complexes with dissolved organic C associated with the amendment (Bolan et al., 2003). However, the solubilized Cu complex may not be bioavailable (Kunhikrishnan et al., 2013).

Conclusions

Biosolids can provide organic matter and a rich source of nutrients to improve soil quality, but food chain risks and wider environmental concerns reduce or even prevent its wide-scale application to agricultural land in many countries. Wastewater treatment options are unable to address all of these concerns, but landfilling and incineration do not provide a sustainable alternative. Coapplication with other organic waste streams to land certainly does not always provide a viable solution; however, there is evidence that mixtures containing sawdust and partially pyrolyzed biochars are effective in mitigating excessive nitrate leaching from biosolids-amended soils. Lignite coal waste, while ineffective at mitigating nitrate leaching, may reduce plant uptake of biosolids-borne contaminants such as Cd. Economically and environmentally acceptable solutions that will allow biosolids application to agricultural land remain highly challenging, but the requirement to improve soil quality for forest and mine rehabilitation probably justifies more field investigations. Combining biosolids with other organic wastes to rehabilitate degraded land remains a potentially practicable and sustainable management of these resources.

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References

- ANZBP. 2014. New Zealand biosolids statistics. Aust. N. Z. Biosolids Partnership, Aust. Water Assoc. <https://www.biosolids.com.au/guidelines/new-zealand-biosolids-statistics/> (accessed 15 Aug. 2016).
- Banegas, V., J.L. Moreno, J.L. Moreno, C. Garcia, G. Leon, and T. Hernandez. 2007. Composting anaerobic and aerobic sewage sludges using two proportions of sawdust. *Waste Manag.* 27:1317–1327. doi:10.1016/j.wasman.2006.09.008
- Barnett, J., and J. Russell. 2001. Application of waste to land: The dairy industry's perspective. In: *Proceedings of the New Zealand Land Collective Annual Conference*, Rotorua, Invercargill, New Zealand. New Zealand Land Treatment Collective, Porirua, New Zealand. p. 139–141.
- Beesley, L., E. Moreno-Jimenez, J.L. Gomez-Eyles, E. Harris, B. Robinson, and T. Sizmur. 2011. A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. *Environ. Pollut.* 159:3269–3282. doi:10.1016/j.envpol.2011.07.023
- Bernal, M.P., A.F. Navarro, M.A. Sanchez-Monedero, A. Roig, and J. Cegarra. 1998. Influence of sewage sludge compost stability and maturity on carbon and nitrogen mineralization in soil. *Soil Biol. Biochem.* 30:305–313. doi:10.1016/S0038-0717(97)00129-6
- Binder, D.L., A. Dobermann, D.H. Sander, and K.G. Cassman. 2002. Biosolids as nitrogen source for irrigated maize and rainfed sorghum. *Soil Sci. Soc. Am. J.* 66:531–543. doi:10.2136/sssaj2002.5310
- Blair, R.M., H. Fang, W.S. Branham, B.S. Hass, S.L. Dial, C.L. Moland et al. 2000. The estrogen receptor relative binding affinities of 188 natural and xenochemicals: Structural diversity of ligands. *Toxicol. Sci.* 54:138–153. doi:10.1093/toxsci/54.1.138
- Bogner, J., A.M. Abdelrafie, C.A. Diaz, A. Faaij, Q. Gao, S. Hashimoto et al. 2008. Waste management. In: B. Metz, O. Davidson, P. Bosch, R. Dave, and L. Meyer, editors, *Climate change 2007: Mitigation of climate change. Working Group III contribution to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge Univ. Press., New York. p. 585–618.
- Bolan N., D. Adriano, S. Mani, A. Khan. 2003. Adsorption, complexation, and phytoavailability of copper as influenced by organic manure. *Environ. Toxicol. Chem.* 22:450–456.
- Bolan, N.S., A. Kunhikrishnan, and R. Naidu. 2013. Carbon storage in a heavy clay soil landfill site after biosolid application. *Sci. Total Environ.* 465:216–225. doi:10.1016/j.scitotenv.2012.12.093
- Bothner, M.H., H. Takada, I.T. Knight, R.T. Hill, B. Butman, J.W. Farrington et al. 1994. Sewage contamination in sediments beneath a deep-ocean dump site off New York. *Mar. Environ. Res.* 38:43–59. doi:10.1016/0141-1136(94)90045-0
- Brenton, C.M., E.B. Fish, and R. Mata-Gonzalez. 2007. Macronutrient and trace element leaching following biosolids application on semi-arid rangeland soils. *Arid Land Res. Manage.* 21:143–156. doi:10.1080/15324980701267783
- Brewer, C.E., R. Unger, K. Schmidt-Rohr, and R.C. Brown. 2011. Criteria to select biochars for field studies based on biochar chemical properties. *Bio-Energy Res.* 4:312–323. doi:10.1007/s12155-011-9133-7
- Budaeva, A.D., E.V. Zoltoev, V.D. Tikhova, and N.V. Bodoev. 2006. Interaction of heavy metal ions with ammonium humates. *Russ. J. Appl. Chem.* 79:920–923. doi:10.1134/S1070427206060103
- Bugbee, G.J. 1999. Effects of hardwood sawdust in potting media containing biosolids compost on plant growth, fertilizer needs, and nitrogen leaching. *Commun. Soil Sci. Plant Anal.* 30:689–698. doi:10.1080/00103629909370238
- Chassapis, K., M. Roulia, and D. Tsigirigi. 2009. Chemistry of metal-humic complexes contained in Megalopolis lignite and potential application in modern organomineral fertilization. *Int. J. Coal Geol.* 78:288–295. doi:10.1016/j.coal.2009.03.004
- Civeira, G., and R.S. Lavado. 2008. Nitrate losses, nutrients and heavy metal accumulation from substrates assembled for urban soils reconstruction. *J. Environ. Manage.* 88:1619–1623. doi:10.1016/j.jenvman.2007.08.005
- Correa, R.S., R.E. White, and A.J. Weatherley. 2006. Effect of compost treatment of sewage sludge on nitrogen behavior in two soils. *Waste Manag.* 26:614–619. doi:10.1016/j.wasman.2005.09.008
- Daniels, W.L., G.K. Evanylo, S.M. Nagle, and J.M. Schmidt. 2001. Effects of biosolids loading rate and sawdust additions on row crop yield and nitrate leaching potentials in Virginia sand and gravel mine reclamation. In: *Proceedings of the 2001 Meeting of the American Association for Surface Mining and Reclamation*, Albuquerque, NM. 3–7 June 2001. Am. Soc. for Surface Mining and Reclamation, Lexington KY. p. 399–405. doi:10.21000/JASMR01010399

- Domańska, K.K., and B. Smolinska. 2012. Advantages of lignite addition in purification process of soil polluted by heavy metals. *Biotechnol. Food Sci.* 76:51–58.
- Doskocil, L., L. Grasset, V. Enev, L. Kalina, and M. Pekar. 2015. Study of water-extractable fractions from South Moravian lignite. *Environ. Earth Sci.* 73:3873–3885. doi:10.1007/s12665-014-3671-1
- Doskocil, L., and M. Pekar. 2012. Removal of metal ions from multi-component mixture using natural lignite. *Fuel Process. Technol.* 101:29–34. doi:10.1016/j.fuproc.2012.02.010
- Elliott, H.A., G.A. O'Connor, and S. Brinton. 2002. Phosphorus leaching from biosolids-amended sandy soils. *J. Environ. Qual.* 31:681–689. doi:10.2134/jeq2002.0681
- Enders, A., K. Hanley, T. Whitman, S. Joseph, and J. Lehmann. 2012. Characterization of biochars to evaluate recalcitrance and agronomic performance. *Bioresour. Technol.* 114:644–653. doi:10.1016/j.biortech.2012.03.022
- EPA-VA. 2004. Guidelines for Environmental management: Biosolids land application. *Environ. Prot. Agency Victoria, Southbank, VIC.*
- Esperschütz, J., O. Lense, C. Anderson, S. Bulman, J. Horswell, N. Dickinson, and B. Robinson. 2016. Biowaste mixtures affecting the growth and elemental composition of Italian ryegrass (*Lolium multiflorum*). *J. Environ. Qual.* 45:1054–1061. doi:10.2134/jeq2015.09.0459
- Evanylo, G.K. 2009. Agricultural land application of biosolids in Virginia: Managing biosolids for agricultural use. *Publ.* 452-303. Virginia Coop. Ext., Blacksburg.
- Fetzner, S. 2000. Biodegradation of xenobiotics. In: H.W. Doelle, S. Rokem, and M. Berovic, editors, *Biotechnology: Fundamentals in Biotechnology*. Vol. X. Eolss Publishers, Oxford, UK. p. 215–246.
- Gartler, J., B. Robinson, K. Burton, and L. Clucas. 2013. Carbonaceous soil amendments to biofortify crop plants with zinc. *Sci. Total Environ.* 465:308–313. doi:10.1016/j.scitotenv.2012.10.027
- Gary M.K., Brooks J.P., Brown S., Gerba C. 2011. Land application of organic residuals: Public health threat or environmental benefit? *Am. Soc. Microbiol.*, Washington, DC.
- Gerwing, J.J., J.S. Johns, and E. Vidal. 1996. Reducing waste during logging and log processing: Forest conservation in eastern Amazonia. *FAO Corporate Document Repository, Rome.*
- Gholz, H.L., D.A. Wedin, S.M. Smitherman, M.E. Harmon, and W.J. Parton. 2000. Long-term dynamics of pine and hardwood litter in contrasting environments: Toward a global model of decomposition. *Glob. Change Biol.* 6:751–765. doi:10.1046/j.1365-2486.2000.00349.x
- Gilmour J., and V. Skinner. 1998. Estimating plant-available nitrogen in biosolids. In: W.E. Sabbe, editor, *Arkansas soil fertility studies 1997*. Res. Ser. 459. Arkansas Agric. Exp. Stn., Fayetteville. p. 29–33.
- GW. 2015. Sludge management: Opportunities in growing volumes, disposal restrictions and energy recovery. *Global Water Intelligence, Austin, TX.*
- Haering K.C., Daniels W.L., Feagley S.E. 2000. 24. Reclaiming mined lands with biosolids, manures, and papermill sludges. In: R.I. Barnhisel, R.G. Darmody, and W.L. Daniels, editors, *Reclamation of drastically disturbed lands*. Agron. Monogr. 41. ASA, CSSA, SSSA, Madison, WI. p. 615–644. doi:10.2134/agronmonogr41.c24
- Handreck, K.A. 1990. Extractants for assessing the availability of copper to *Chrysanthemum morifolium* cultivar 'Yellow Mandalay' growing in soil-less media. *Sci. Hortic. (Amsterdam)* 44:323–334. doi:10.1016/0304-4238(90)90133-Y
- Harmayani, K.D., and A.H.M.F. Anwar. 2012. Adsorption of nutrients from stormwater using sawdust. *Int. J. Environ. Sci. Dev.* 3:114–117. doi:10.7763/IJESD.2012.V3.199
- Haynes, R.J., G. Murtaza, and R. Naidu. 2009. Inorganic and organic constituents and contaminants of biosolids: Implications for land application. In: D.L. Sparks, editor, *Advances in agronomy*. Vol. 104. Elsevier, Amsterdam, the Netherlands. p. 165–267.
- Henry, C., M. Van Ham, M. Grey, N. Cowley, and R. Harrison. 2000. Field method for biosolids N mineralization using porous ceramic cups. *Water Air Soil Pollut.* 117:123–131. doi:10.1023/A:1005140911712
- Henry, C.L., D.W. Cole, and R.B. Harrison. 1994. Use of municipal sludge to restore and improve site productivity in forestry: The pack forest sludge research program. *For. Ecol. Manage.* 66:137–149. doi:10.1016/0378-1127(94)90153-8
- Hina, K., P. Bishop, A.M. Camps, R. Calvelo-Pereira, J.A. Macia-Agullo, J. Hindmarsh et al. 2010. Producing biochars with enhanced surface activity through alkaline pretreatment of feedstocks. *Aust. J. Soil Res.* 48:606–617. doi:10.1071/SR10015
- Israel, S., A. Rosenov, G. Tredoux, and N. Jovanovic. 2014. In situ nitrate removal from groundwater using freely available carbon material at an industrially polluted site. In: J. Cobbing, S. Adams, I. Dennis, and K. Riemann, editors, *Assessing and managing groundwater in different environments*. CRC Press, Boca Raton, FL. p. 207–223.
- Janos P., L. Zavadzka, J. Lesny, and S. Krizenecka. 2011. Young brown coals for environmental applications composition, acid-base, ion-exchange and sorption properties of selected central European coals. *NOVA Science Publishers, Hauppauge, NY.*
- Jones-Lepp, T.L., and R. Stevens. 2007. Pharmaceuticals and personal care products in biosolids/sewage sludge: The interface between analytical chemistry and regulation. *Anal. Bioanal. Chem.* 387:1173–1183. doi:10.1007/s00216-006-0942-z
- Karczewska, A., T. Chodak, and J. Kaszubkiewicz. 1996. The suitability of brown coal as a sorbent for heavy metals in polluted soils. *Appl. Geochem.* 11:343–346. doi:10.1016/0883-2927(95)00043-7
- Kim, H.H., E.A. Seagren, and A.P. Davis. 2003. Engineered bioretention for removal of nitrate from stormwater runoff. *Water Environ. Res.* 75:355–367. doi:10.2175/106143003X141169
- Knowles, O.A., B.H. Robinson, A. Contangelo, and L. Clucas. 2011. Biochar for the mitigation of nitrate leaching from soil amended with biosolids. *Sci. Total Environ.* 409:3206–3210. doi:10.1016/j.scitotenv.2011.05.011
- Korboulesky, N., S. Dupouyet, and G. Bonin. 2002. Environmental risks of applying sewage sludge compost to vineyards: Carbon, heavy metals, nitrogen, and phosphorus accumulation. *J. Environ. Qual.* 31:1522–1527. doi:10.2134/jeq2002.1522
- Kucerik J., Pekar M., Klucakova M. 2003. South-Moravian lignite-potential source of humic substances. *Petroleum and Coal* 45:58–62.
- Kunhikrishnan, A., N.S. Bolan, R. Naidu, and W.I. Kim. 2013. Recycled water sources influence the bioavailability of copper to earthworms. *J. Hazard. Mater.* 261:784–792. doi:10.1016/j.jhazmat.2012.10.015
- Kwiatkowska, J., M.R. Provenzano, and N. Senesi. 2008. Long term effects of a brown coal-based amendment on the properties of soil humic acids. *Geoderma* 148:200–205. doi:10.1016/j.geoderma.2008.10.001
- Laghari, M., R. Naidu, B. Xiao, Z.Q. Hu, M.S. Mirjat, M. Hu et al. 2016. Recent developments in biochar as an effective tool for agricultural soil management: A review. *J. Sci. Food Agric.* 96:4840–4849. doi:10.1002/jsfa.7753
- Laidlaw, W.S., S.K. Arndt, T.T. Huynh, D. Gregory, and A.J.M. Baker. 2012. Phytoextraction of heavy metals by willows growing in biosolids under field conditions. *J. Environ. Qual.* 41:134–143. doi:10.2134/jeq2011.0241
- Lavado, R.S. 2006. Effects of sewage-sludge application on soils and sunflower yield: Quality and toxic element accumulation. *J. Plant Nutr.* 29:975–984. doi:10.1080/01904160600685611
- LeBlanc, R.J., P. Matthews, and R.P. Richard, editors. 2008. *Global atlas of excreta, wastewater sludge, and biosolids management: Moving forward the sustainable and welcome uses of a global resource*. UN Human Settlements Programme, Nairobi, Kenya.
- Liu, Z.-h., Y. Kanjo, and S. Mizutani. 2009. Removal mechanisms for endocrine disrupting compounds (EDCs) in wastewater treatment- physical means, biodegradation, and chemical advanced oxidation: A review. *Sci. Total Environ.* 407:731–748. doi:10.1016/j.scitotenv.2008.08.039
- Lu Q., Z.L. He, and P.J. Stoffella. 2012. Land application of biosolids in the USA: A review. *Appl. Environ. Soil Sci.* 2012:201462. doi:10.1155/2012/201462
- Magesan, G.N., and H. Wang. 2003. Application of municipal and industrial residuals in New Zealand forest: An Overview. *Aust. J. Soil Res.* 41:557–569. doi:10.1071/SR02134
- Majumder, R., S.J. Livesley, D. Gregory, and S.K. Arndt. 2014. Biosolid stockpiles are a significant point source for greenhouse gas emissions. *J. Environ. Manage.* 143:34–43. doi:10.1016/j.jenvman.2014.04.016
- Marchaim, U. 2017. Chapter six: Aerobic versus anaerobic wastewater treatment. In: *Biogas processes for sustainable development*. FAO, Rome.
- Martin, B.C., S.J. George, C.A. Price, M.H. Ryan, and M. Tibbett. 2014. The role of root exuded low molecular weight organic anions in facilitating petroleum hydrocarbon degradation: Current knowledge and future directions. *Sci. Total Environ.* 472:642–653. doi:10.1016/j.scitotenv.2013.11.050
- McBride, M.B., B.K. Richards, T. Steenhuis, and G. Spiers. 1999. Long-term leaching of trace elements in a heavily sludge-amended silty clay loam soil. *Soil Sci.* 164:613–623. doi:10.1097/00010694-199909000-00001
- McLaren, R.G., and K.C. Cameron. 1996. *Soil science: Sustainable production and environmental protection*. Oxford Univ. Press, Auckland, New Zealand.
- McLaughlin, H., F. Shields, J. Jagiello, and G. Thiele. 2012. Analytical options for biochar adsorption and surface area In: *Proceedings of the 2012 US Biochar conference*. Biochar Conference, Rohnert Park, CA. 29 July–1 Aug. 2012. US Biochar Initiative, Portland, OR.
- Michalk, D.L., M.S. Whatmuff, G.J. Osborne, and T.S. Gibson. 2004. Benefits and risks associated with biosolids application to agricultural production systems: Experiences from New South Wales, Australia. In: A.L. Juhász, G. Magesan, and R. Naidu, editors, *Waste management*. Science Publishers, Enfield, NH. p. 157–201.

- Mileski, G.J., J.A. Bumpus, M.A. Jurek, and S.D. Aust. 1988. Biodegradation of pentachlorophenol by the white rot fungus *Phanerochaete chrysosporium*. *Appl. Environ. Microbiol.* 54:2885–2889.
- Miller-Robbie, L., B.A. Ulrich, D.F. Ramey, K.S. Spencer, S.P. Herzog, T.Y. Cath et al. 2015. Life cycle energy and greenhouse gas assessment of the co-production of biosolids and biochar for land application. *J. Clean. Prod.* 91:118–127. doi:10.1016/j.jclepro.2014.12.050
- Mizera, J., G. Mizerova, V. Machovic, and L. Borecka. 2007. Sorption of cesium, cobalt and europium on low-rank coal and chitosan. *Water Res.* 41:620–626. doi:10.1016/j.watres.2006.11.008
- Mohan, D., and S. Chander. 2006. Removal and recovery of metal ions from acid mine drainage using lignite: A low cost sorbent. *J. Hazard. Mater.* 137:1545–1553. doi:10.1016/j.jhazmat.2006.04.053
- Mok, H.-F., R. Majumder, W.S. Laidlaw, D. Gregory, A.J.M. Baker, and S.K. Arndt. 2013. Native Australian species are effective in extracting multiple heavy metals from biosolids. *Int. J. Phytoremediation* 15:615–632. doi:10.1080/15226514.2012.723063
- Nash, D., C. Butler, J. Cody, and M.S.J. Warne. 2011. Effects of biosolids application on pasture and grape vines in Southeastern Australia. *Appl. Environ. Soil Sci.* 2011:342916. doi:10.1155/2011/342916
- NZWWA. 2003. Guidelines for the safe application of biosolids to land in New Zealand. N.Z. Water and Wastes Assoc., Wellington.
- O'Connor, G.A., H.A. Elliott, N.T. Basta, R.K. Bastian, G.M. Pierzynski, R.C. Sims, and J.E. Smith. 2005. Sustainable land application: An overview. *J. Environ. Qual.* 34:7–17. doi:10.2134/jeq2005.0007
- O'Kelly, B.C. 2005. Sewage sludge to landfill: Some pertinent engineering properties. *J. Air Waste Manag. Assoc.* 55:765–771. doi:10.1080/10473289.2005.10464670
- Ogilvie, D. 1998. National study of the composition of sewage sludge. Drainage Managers Group, N.Z. Water and Wastes Assoc., Wellington.
- Ozores-Hampton, M., and D.R.A. Peach. 2002. Biosolids in vegetable production systems. *Horttechnology* 12:336–340.
- Paramashivam, D., T.J. Clough, A. Carlton, K. Gough, N. Dickinson, J. Horswell et al. 2016a. The effect of lignite on nitrogen mobility in a low-fertility soil amended with biosolids and urea. *Sci. Total Environ.* 543:601–608. doi:10.1016/j.scitotenv.2015.11.075
- Paramashivam, D., T.J. Clough, N.M. Dickinson, J. Horswell, O. Lense, L. Lucas, and B.H. Robinson. 2016b. Effect of pine waste and pine biochar on nitrogen mobility in biosolids. *J. Environ. Qual.* 45:360–367. doi:10.2134/jeq2015.06.0298
- Park, J.H., G.K. Choppala, N.S. Bolan, J.W. Chung, and T. Chuasavathi. 2011. Biochar reduces the bioavailability and phytotoxicity of heavy metals. *Plant Soil* 348:439–451. doi:10.1007/s11104-011-0948-y
- Pehlivan, E., and G. Arslan. 2007. Removal of metal ions using lignite in aqueous solution: Low cost biosorbents. *Fuel Process. Technol.* 88:99–106. doi:10.1016/j.fuproc.2006.09.004
- Pehlivan, E., A. Richardson, and P. Zuman. 2004. Electrochemical investigation of binding of heavy metal ions to Turkish lignites. *Electroanalysis* 16:1292–1298. doi:10.1002/elan.200302949
- Pereira Calvelo, R., J. Kaal, M.C. Arbertain, R. Pardo Lorenzo, W. Aitkenhead, M. Hedley et al. 2011. Contribution to characterisation of biochar to estimate the labile fraction of carbon. *Org. Geochem.* 42:1331–1342. doi:10.1016/j.orggeochem.2011.09.002
- Piveteau, P., F. Fayolle, J.P. Vandecasteele, and F. Monot. 2001. Biodegradation of tert-butyl alcohol and related xenobiotics by a methylotrophic bacterial isolate. *Appl. Microbiol. Biotechnol.* 55:369–373. doi:10.1007/s002530000545
- Pope, C.G. 1984. Lignite porosity study by kinetics of gas adsorption. *Fuel* 63:1681–1686. doi:10.1016/0016-2361(84)90100-5
- Prasad R., and J.F. Power. 1997. Soil fertility management for sustainable agriculture. CRC Press, Boca Raton, FL.
- Raghab, S.M., A.M. Abd El Meguid, and H.A. Hegazi. 2013. Treatment of leachate from municipal solid waste landfill. *HBRC J.* 9:187–192. doi:10.1016/j.hbrj.2013.05.007
- Rajendram W., A. Surapaneni, and G.L. Smith. 2011. From waste to soil to plant to feed: The fate of biosolids nutrients and contaminants in a real farm situation. Australia and New Zealand Biosolids Partnership. <https://www.biosolids.com.au/wp-content/uploads/From-Waste-to-Soil-to-Plant-to-Feed.pdf> (accessed 15 Aug. 2016).
- Ramamoorthy, K., F. Wang, I.C. Chen, S. Safe, J.D. Norris, D.P. McDonnell et al. 1997. Potency of combined estrogenic pesticides. *Science* 275:405–406. doi:10.1126/science.275.5298.405
- Rigby, H., and S.R. Smith. 2013. Nitrogen availability and indirect measurements of greenhouse gas emissions from aerobic and anaerobic biowaste digestates applied to agricultural soils. *Waste Manag.* 33:2641–2652. doi:10.1016/j.wasman.2013.08.005
- Robertson, W.D., and J.A. Cherry. 1995. In-situ denitrification of septic system nitrate using reactive porous media barriers- field trials. *Ground Water* 33:99–111. doi:10.1111/j.1745-6584.1995.tb00266.x
- Rouch, D.A., V.A. Fleming, S. Pai, M. Deighton, J. Blackbeard, and S.R. Smith. 2011. Nitrogen release from air-dried biosolids for fertilizer value. *Soil Use Manag.* 27:294–304 doi:10.1111/j.1475-2743.2011.00338.x
- Rynk, R., and N. Goldstein. 2003. Reducing odor impacts at land application sites. *BioCycle* 44:54–58.
- Samaras, V., C.D. Tsadilas, and S. Stamatiadis. 2008. Effects of repeated application of municipal sewage sludge on soil fertility, cotton yield, and nitrate leaching. *Agron. J.* 100:477–483. doi:10.2134/agronj2007.0162
- Sanchez-Monedero, M.A., C. Mondini, M. de Nobili, L. Leita, and A. Roig. 2004. Land application of biosolids. Soil response to different stabilization degree of the treated organic matter. *Waste Manag.* 24:325–332. doi:10.1016/j.wasman.2003.08.006
- Schipper, L.A., and M. Vojvodic-Vukovic. 2000. Nitrate removal from groundwater and denitrification rates in a porous treatment wall amended with sawdust. *Ecol. Eng.* 14:269–278. doi:10.1016/S0925-8574(99)00002-6
- Schmidt, J.M., W.L. Daniels, R.S. Li, and D. McFaden. 2001. Determining optimal sawdust/biosolids mixtures to manage nitrate leaching in reclaimed disturbed soils. In: Proceedings of the 2001 Meeting of the American Association for Surface Mining and Reclamation, Albuquerque, NM. 3–7 June 2001. Am. Soc. for Surface Mining and Reclamation, Lexington KY. p. 429–436.
- Shinbrot, X. 2012. Biosolids or biohazards? *Pesticides and You* 32(3):9–15.
- Shukla, A., Y.H. Zhang, P. Dubey, J.L. Margrave, and S.S. Shukla. 2002. The role of sawdust in the removal of unwanted materials from water. *J. Hazard. Mater.* 95:137–152. doi:10.1016/S0304-3894(02)00089-4
- Simmler, M., L. Ciadamidaro, R. Schulin, P. Madejón, R. Reiser, L. Clucas et al. 2013. Lignite reduces the solubility and plant uptake of cadmium in pasturelands. *Environ. Sci. Technol.* 47:4497–4504. doi:10.1021/es303118a
- Singh, R.P., and M. Agrawal. 2008. Potential benefits and risks of land application of sewage sludge. *Waste Manag.* 28:347–358. doi:10.1016/j.wasman.2006.12.010
- Smith S.R. 1995. Agricultural recycling of sewage sludge and the environment. Oxford Univ. Press, Oxford, UK.
- Song, C.S., and H.H. Schobert. 1996. Non-fuel uses of coals and synthesis of chemicals and materials. *Fuel* 75:724–736. doi:10.1016/0016-2361(95)00295-2
- Sopper W.E., and E.M. Seaker. 1990. Long-term effects of a single application of municipal sludge on abandoned mine land. In: J. Skousen, J. Sencindiver, and D. Samuel, editors, Proceedings of the 1990 Mining and Reclamation Conference and Exhibition, Charleston, WV. 23–26 Apr. 1990. West Virginia Univ., Morgantown, WV. p. 579–588.
- Spokas, K., J. Bogner, J.P. Chanton, M. Morect, C. Aran, C. Graff et al. 2006. Methane mass balance at three landfill sites: What is the efficiency of capture by gas collection systems? *Waste Manag.* 26:516–525. doi:10.1016/j.wasman.2005.07.021
- Spokas, K.A., W.C. Koskinen, J.M. Baker, and D.C. Reicosky. 2009. Impacts of woodchip biochar additions on greenhouse gas production and sorption/ degradation of two herbicides in a Minnesota soil. *Chemosphere* 77:574–581. doi:10.1016/j.chemosphere.2009.06.053
- Stoffella, P.J., M. Ozores-Hampton, N.E. Roe, Y.C. Li, and T.A. Obreza. 2003. Compost utilization in vegetable crop production systems. In: K. Mirami, C. Andreoli, and W.M. Nascimento, editors, Proceedings of the 9th International Symposium on Timing of Field Production in Vegetable Crops, São Paulo, Brazil. 20–24 May 2001. Int. Soc. Hort. Sci., Leuven, Belgium. p. 125–128.
- Sullivan, T.S., M.E. Stromberger, M.W. Paschke, and J.A. Ippolito. 2006. Long-term impacts of infrequent biosolids applications on chemical and microbial properties of a semi-arid rangeland soil. *Biol. Fertil. Soils* 42:258–266. doi:10.1007/s00374-005-0023-z
- Taghizadeh-Toosi, A., T.J. Clough, L.M. Condon, R.R. Sherlock, C.R. Anderson, and R.A. Craigie. 2011. Biochar incorporation into pasture soil suppresses in situ nitrous oxide emissions from ruminant urine patches. *J. Environ. Qual.* 40:468–476. doi:10.2134/jeq2010.0419
- Taghizadeh-Toosi, A., T.J. Clough, R.R. Sherlock, and L.M. Condon. 2012. Biochar adsorbed ammonia is bioavailable. *Plant Soil* 350:57–69. doi:10.1007/s11104-011-0870-3
- Tella, M., M.N. Bravin, L. Thuries, P. Cazevielle, C. Chevassus-Rosset, B. Collin et al. 2016. Increased zinc and copper availability in organic waste amended soil potentially involving distinct release mechanisms. *Environ. Pollut.* 212:299–306. doi:10.1016/j.envpol.2016.01.077
- Trolove, S.N., and J.B. Reid. 2003. A field growing system to reduce sulphur uptake of a crop grown in a moderately high sulphur soil- preliminary report. *Agron. N. Z.* 32:51–59.

- Uchimiya, M., I.M. Lima, T. Klasson, S. Chang, L.H. Wartelle, and J.E. Rodgers. 2010. Immobilization of heavy metal ions (CuII, CdII, NiII, and PbII) by broiler litter-derived biochars in water and soil. *Agric. Food Chem.* 58:5538–5544. doi:10.1021/jf9044217
- Uggetti, E., I. Ferrer, S. Nielsen, C. Arias, H. Brix, and J. García. 2012. Characteristics of biosolids from sludge treatment wetlands for agricultural reuse. *Ecol. Eng.* 40:210–216. doi:10.1016/j.ecoleng.2011.12.030
- UNEP. 2016. Practices in Europe and North America: Waste disposal versus resource utilisation. *Freshwater Manage. Ser. no. 1.* UN Environ. Programme, Nairobi, Kenya.
- Wang, H., K. Lin, Z. Hou, B. Richardson, and J. Gan. 2010. Sorption of the herbicide terbuthylazine in two New Zealand forest soils amended with biosolids and biochars. *J. Soils Sediments* 10:283–289. doi:10.1007/s11368-009-0111-z
- Wang, H.L., M.O. Kimberley, and M. Schlegelmilch. 2003. Biosolids-derived nitrogen mineralization and transformation in forest soils. *J. Environ. Qual.* 32:1851–1856. doi:10.2134/jeq2003.1851
- WCC. 2008. Landfill charges. Wellington City Council, Wellington, New Zealand.
- WEC. 2010. Survey of energy resources. World Energy Council, London.
- Werther, J., and T. Ogada. 1999. Sewage sludge combustion. *Pror. Energy Combust. Sci.* 25:55–116. doi:10.1016/S0360-1285(98)00020-3
- Wilén, C., P. Salokoski, E. Kurkela, and K. Sipilä. 2004. Finnish expert report on best available techniques in energy production from solid recovered fuels. Technical Research Centre of Finland, Espoo, Finland.
- Ye, J., A. Singh, and O.P. Ward. 2004. Biodegradation of nitroaromatics and other nitrogen-containing xenobiotics. *World J. Microbiol. Biotechnol.* 20:117–135. doi:10.1023/B:WIBI.0000021720.03712.12
- Zhang, H., K. Lin, H. Wang, and J. Gan. 2010. Effect of *Pinus radiata* derived biochars on soil sorption and desorption of phenanthrene. *Environ. Pollut.* 158:2821–2825. doi:10.1016/j.envpol.2010.06.025
- Zhang, H., R.P. Voroneya, and G.W. Price. 2015. Effects of temperature and processing conditions on biochar chemical properties and their influence on soil C and N transformations. *Soil Biol. Biochem.* 83:19–28. doi:10.1016/j.soilbio.2015.01.006