

SCIENTIFIC EVIDENCE ON THE ENVIRONMENTAL AND HEALTH EFFECTS OF
LAND APPLICATION OF BIOSOLIDS

A THESIS IN
Environmental and Urban Geosciences

Presented to the Faculty of the University
of Missouri-Kansas City in partial fulfilment of
the requirements of the degree

MASTER OF SCIENCE

by
HARRIS GBOMINA JR

B. Sc., University of Agriculture, Abeokuta, Nigeria, 2006

Kansas City, Missouri
2015

SCIENTIFIC EVIDENCE ON THE ENVIRONMENTAL AND HEALTH EFFECTS
OF LAND APPLICATION OF BIOSOLIDS

Harris Gbomina Jr, Candidate for the Master of Science Degree

University of Missouri-Kansas City, 2015

ABSTRACT

The study is an objective evaluation of the controversy on whether the practice of land application of biosolids for soil enrichment and restoration poses significant harm to the environment, human and animal health. Over the years, many review articles have concluded that the majority of research show that the practice poses less harm as compared to the benefits. This in turn made the United States Environmental Protection Agency to promote its use for soil enrichment and restoration. In an attempt to obtain an objective evaluation, based on reliable scientific evidence of the controversy, Google Scholar search was conducted using the phrase “environmental and health effects of land application of sewage sludge/biosolids”. The search result yielded 86 research articles directly related to the topic. The 86 articles were then comprehensively studied and grouped into three categories: those research findings that proved that land application of biosolids poses significant harm to the environment, human and animal health, those that proved that the practice does not pose significant harm to the environment, human and animal health and those that were inclusive and suggest precaution in using biosolids for soil enrichment and restoration.

Out of the total of 86 research articles studied, 42 or about 49% found that land application of biosolids posed significant harm to the environment, human and animal health as opposed to 33 or about 38% concluding no significant harm. Furthermore, when research conducted in the U.S. were extracted from the 86 global research articles, about 51% found that land application of biosolids posed significant harm to the environment, human and animal health as opposed to about 36% concluding no significant harm. The U.S. articles numbered 47 or about 55% of the total articles reviewed. Based on these statistics from the current study, it is evident that majority of the studies conducted over the past 15 years suggest that land application of biosolids for soil enrichment and restoration poses significant harm to the environment, human and animal health.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of the College of Arts and Sciences, have examined the thesis titled “Scientific Evidence on the Environmental and Health Effects of Land Application of Biosolids” presented by Harris Gbomina Jr, candidate for the Master of Science degree, and certify that in their opinion it is worthy of acceptance.

Supervisory Committee

Syed E. Hasan, Ph.D., Committee Chair
Department of Geosciences

Jimmy Adegoke, Ph.D.
Department of Geosciences

James B. Murowchick, Ph.D.
Department of Geosciences

CONTENTS

ABSTRACT	iii
APPROVAL PAGE	v
ACKNOWLEDGEMENTS	ix
Chapter	
1: INTRODUCTION	1
1.1 Background	1
1.2 Motivation for the Research Study.....	4
1.3 Aim and Objectives of the Study	6
2: LITERATURE REVIEW	7
2.1 Introduction.....	7
2.2 Wastewater Treatment Technologies	7
2.2.1 Anaerobic Digestion	13
2.2.2 Aerobic Digestion	15
2.3 Characteristics of Sewage Sludge	15
2.4 Biosolids Utilization/Disposal	17
2.5 Laws Regulating Biosolids Use in the U.S. and other countries	17
3: STUDY METHODOLOGY.....	23
3.1 Introduction.....	23
3.2 Library Research	23
4: SUMMARY OF RESEARCH FINDINGS	26

4.1 Introduction.....	26
4.1.0 Persistent Toxic Organic Pollutants (POPs) in Biosolids and their fate in the Environment	26
4.1.1 Persistent Toxic Organic Pollutants (POPs) in Biosolids and their fate in the Environment: scientific evidence in support of harmful effects	27
4.1.2 Persistent Toxic Organic Pollutants (POPs) in Biosolids and their fate in the Environment: scientific evidence in support of negligible or no harmful effect	35
4.1.3 Persistent Toxic Organic Pollutants (POPs) in Biosolids and their fate in the Environment: scientific evidence that do not support either side of the controversy but suggest caution.....	41
4.2.0 Environmental and health implication from land application of biosolids	44
4.2.1 Environmental and health implications from land application of biosolids: scientific evidence that support harmful effects.....	44
4.2.2 Environmental and health implications from land application of biosolids: scientific evidence that support negligible or no harmful effects	48
4.2.3 Environmental and health implications from land application of biosolids: scientific evidence that do not support either side of the controversy but suggest cautious approach	51
4.3.0 Effect of Land Application of Biosolids from Heavy Metals, Soil, Air and Surface and Groundwater	51

4.3.1	Effect of Land Application of Biosolids from Heavy Metals, Soil, Air and Surface and Groundwater: scientific evidence in support of harmful effects.....	52
4.3.2	Effect of Land Application of Biosolids from Heavy Metals, Soil, Air and Surface and Groundwater: scientific evidence in support of negligible or no harmful effects.....	57
4.3.3	Effect of Land Application of Biosolids from Heavy Metals, Soil, Air and Surface and Groundwater: scientific evidence that do not support either side of the controversy.....	63
5:	DISCUSSION OF RESULTS	67
5.1	Introduction.....	67
6:	CONCLUSION AND RECOMMENDATIONS.....	80
	Appendix 1.....	82
	Environmental Protection Agency Part 503 Biosolids Rules.....	82
	Subpart A (General Requirements for Biosolids Use)	82
	Subpart A of the rule covers general provisions, such as the purpose and applicability of the rule, the compliance period, and exclusion from the rule. These general provisions apply to each of the three biosolids disposal practices.	82
	Subpart B (Requirements for Land Application)	82
	Subpart D (Requirement for Pathogen and Vector Attraction Reduction	85
	REFERENCES	87
	VITA	109

LIST OF ILLUSTRATIONS

Figure	Page
Figure 2.1: Simplified flow diagram for wastewater treatment	9
Figure 2.2: Four main stages in anaerobic digestion process.....	14
Figure 5.1: Pie chart showing the percentage of research articles that presented scientific evidence on POPs in biosolids applied on land and their impact on the environment .	69
Figure 5.2: Pie chart showing the percentage of research articles that presented scientific evidence on health effects from land application of biosolids	71
Figure 5.3: Pie chart showing the percentage of research articles that presented scientific evidence on the effect of land application of biosolids in respect to heavy metals, soil, air and surface and groundwater pollution	73
Figure 5.4: Pie chart showing total percentage of scientific evidence from all three categories on the environmental and health effects of land application of biosolids	76
Figure 5.5: Pie chart showing total percentage of scientific evidence from research conducted in the U.S. on the environmental and health effects of land application of biosolids	79

LIST OF TABLES

Table	Page
Table 2.1: Main Available Sludge Stabilization Technologies.....	11
Table 2.1: Table 2.1 Continued.....	12
Table 5.1: Research articles that presented scientific evidence on the fate of POPs in biosolids applied on land and their impact on the environment	68
Table 5.2: Research articles that presented scientific evidence on health effects from land application of biosolids	70
Table 5.3: Scientific evidence on the effect of land application of biosolids in respect to heavy metals, soil, air and surface and groundwater pollution	72
Table 5.4: List of all research articles studied on the environmental and health effects of land application of biosolids	74
Table 5.5: Scientific evidence from research conducted in the U.S. on the environmental and health effects of land application of biosolids	77

ACKNOWLEDGEMENTS

I would like to express my highest gratitude to Dr. Syed E. Hasan for his mentorship throughout the course of the study. I am equally grateful to my other committee members- Drs. James B. Murowchick and Jimmy Adegoke for being part of the team in undertaking the study. I would like to acknowledge the financial aid in form of a scholarship received from the American Society of Civil Engineers-the Association of Environmental and Engineering Geologists (ASCE-AEG) through the Department of Geosciences which immensely helped in completing the study.

My special thanks go to Mr. Timothy M. Walters, Agronomist and Farm Manager of the Kansas City Birmingham Farms who worked with me from the beginning of the study up to the point when the methodology and scope of the study was changed. Biosolids application data from the Birmingham Farms owned and operated by the city of Kansas City, Missouri were initially part of the original study and were provided to me by Mr. Walters.

Last but not the least, I am grateful to my wife, Ololade Gbomina and our two handsome boys, Jumodeh and Pontiwai Gbomina and other family members and friends who one-way or the other contributed to the successful completion of the thesis.

CHAPTER 1

INTRODUCTION

1.1 Background

Sewage sludge in a strict sense can be defined as the solid, semi-solid, or liquid by-product generated during the treatment of wastewater at sewage treatment facility. Sewage sludge include scum or solids removed in primary, secondary, or advanced wastewater treatment processes and any material derived from sewage sludge. However, blended sewage sludge and /or fertilizer products are also included by the industries under the term “sewage sludge” but does not include grit separated during the screening or process generated by firing of sewage sludge in an incinerator. The treated sewage sludge which meets United States Environmental Protection Agency (USEPA) standards for land application is called “biosolids” by the USEPA and the wastewater industry (USEPA, 1993; USEPA, 2002). Biosolids which are mostly organic solid materials are known to be rich in nutrients that can be recycled and applied as fertilizer to improve and maintain productive soils and stimulate plant growth (USEPA, 2012). Due to the highly variable nature of the inflow sources, the composition of the sludge can vary considerably, but in general raw sludge consists of water and its solid components. The solid part of sludge contains substances such as organic pollutants, heavy metals and pathogens that are potentially harmful to both living organisms and the environment at large, but at the same time containing nutritional substances and energy which are valuable and can be recovered.

This dual nature of biosolids has generated a lot of controversy over the decades between those who support its beneficial use and those who oppose it. On the one hand, there are those who believe that the use of biosolids for soil enrichment

and restoration is harmful to the environment, human and animal health even when treated, processed and utilized as required by USEPA Title 40 Code of Federal Regulation Part 503 (40 CFR 503) and similar environmental regulations and guidelines around the globe; pointing out the possibility of pathogens and other harmful substances somehow escaping the treatment process and ending up in the environment (Bunger et al., 2000; Burton & Trout 1999; Clark et al., 1984; Clarke et al., 2008; Fannin et al., 1980; Johnson et al., 1980; McBride, 2003; Rylander, 1999; Schlosser et al., 1999; Spinosa and Veslind, 2001). On the other hand, there are those who support its use as long as it is manufactured and utilized in accordance with current regulations and guidelines, also arguing that the harmful effect might be negligible or nonexistence when compared to its benefits (Agrawal and Singh, 2009; Krause, 1985; Lindsay and Logan, 1998; Moss et al., 2002; Oades and Tisdall, 1982; USEPA, 1999). This latter view has been endorsed by the USEPA and other professional groups as well as a considerable number of agricultural and environmental scientists (National Research Council, 1996).

There is therefore a critical need to evaluate each assertion in order to provide factual and up to date information on the age-old controversy over the beneficial use and potential harm of biosolids to the environment and living organisms. This study contributes to the current controversy with a clear intent of providing fact-based evidence on the environmental and health effect of biosolids for use in soil enrichment and restoration.

The problem associated with human waste management has existed from the beginning of human existence. Jewell and Seabrook, (1979) indicated that in ancient Greek and Roman times, public sanitation, the efficient removal of wastes by running water, and even land application of wastewaters were practiced. Shortly after this time and until the early 1800s, public sanitation was almost non-existent. There were explicit

sights of unsanitary conditions in densely populated areas of European cities. Large piles of human excrement were allowed to accumulate between closely spaced houses; and, when convenient, these wastes were either carried to fields to be used as fertilizers or they were washed into the rivers and streams. According to King, (1911) historical records showed Chinese use of sewage sludge called “nightsoil” to fertilize soil for plant growth thousands of years ago.

Before the advent of the modern practice of wastewater treatment, municipal wastewater was raw and untreated, and biosolids did not exist. In the United States (U.S.), federal legislation aimed at controlling water pollution first appeared in 1899 (The Rivers and Harbors Appropriation Act of 1899) and has been strengthened during each decade since the 1950s. The Federal Water Pollution Control Act Amendments of 1972 (PL 92-500, 1972), which placed further restrictions on the discharge of pollutants into the nation’s waterways and encouraged beneficial uses such as land application, marked the beginning of mass production of biosolids that needed to be disposed of (Jewell and Seabrook, 1979).

During the decades that followed the Federal Water Pollution Control Act Amendments of 1972, there has been a tremendous change in the way sewage sludge is treated and disposed. The strict wastewater treatment requirements coupled with advanced treatment technology in the U.S. and other countries in the developed world, as well as growing global population in recent years, have led to a global increase in production of biosolids. For example, in the U.S., the production of dry biosolids is about 17.8 million tons per year (56 kg/person/year), in the EU dry biosolids production is about 9 million tons per year (18 kg/person/year), and in the U.K., dry biosolids production is about 1.05 million tons per year (15.7 kg/person/year). In South Africa, dry biosolids production is about 1 million tons per year (18 kg/person/year), while in Australia dry biosolids production is about 0.36 million tons per year (1.6

kg/person/year) and Japan dry biosolids production is about 2.2 million tons per year (17.3 kg/person/year) (ADB, 2012).

A report from the National Research Council (NRC, 2002) pointed out that since the early 1970s, the USEPA and the wastewater treatment industry have been promoting recycling of biosolids for its beneficial use apparently based on research conducted by the USEPA that proved it could be used for that purpose with negligible adverse effect on living organisms and the environment (USEPA, 2002). However, the same NRC report of 2002 also indicated that although biosolids are potential valuable resource, toxic chemicals, infectious organisms, and endotoxins or cellular material may all be present in them. The report highlights studies that have reported toxic exposure, viral infection, bacteria and protozoan infection leading to gastrointestinal illness and irritation and allergic reaction for sewage sludge workers; and to those who use biosolids for agricultural and or other land-application purposes. However, citing limited epidemiological studies as an impediment, the report declined to conclusively state that biosolids used for soil enrichment and restoration is harmful to the environment and living organisms and that such practice should be abolished.

1.2 Motivation for the Research Study

In recent years, the controversy over the use of biosolids for its beneficial use on agricultural farms and restoration of degraded lands on the one hand, and its potential harmful effects on the other hand has intensified for reasons previously mentioned. A quick google search with a phrase like “controversy over biosolids beneficial use” brings up huge online media stories about the issue; also websites owned by environmental organizations, governments and other institutions all have posted one or more project reports on the issue.

Obviously there have been numerous studies on the components of biosolids and the potential harm and benefits they pose to ecosystems at large. At the same time studies on the use of biosolids on agricultural lands and its potential adverse effects on human health are becoming well-known (Adair et al., 2014; Jenkins et al., 2007; Joshua et al., 1998; OEEB, 2005; Sanchez-Monedero et al., 2003; Shoher et al., 2003; Sidhu and Toze, 2012;).

There are also review studies on the subject but they have always concentrated on specific aspects of biosolids uses and effects. For example the following reviews titled: “the value of sewage sludge to agriculture and effects of the agricultural use of sludges contaminated with toxic elements” (Lester and Sterritt, 1980); “the potential impact of veterinary and human therapeutic agents in manure and biosolids on plants grown on arable land” (Jjemba, 2002); “health effects of biosolids odor: a literature review and analysis” (WERF, 2004); “recycling biosolids to pasture-based animal production systems in Australia: a review of evidence on the control of potentially toxic metals and persistent organic compounds recycled to agricultural land” (Hill, 2005); “occurrence and fate of pharmaceuticals and personal care products (PPCPs) in biosolids” (Xia et al., 2005); “human pathogens and their indicators in biosolids” (Sidhu and Toze, 2009); and “fate of endocrine-active compounds during municipal biosolids treatment” etc. (Citulski and Farahbakhsh, 2010), and many more.

However, to the best of the author’s knowledge, no comprehensive review has been conducted to objectively examine studies on the environmental and health effect of land application of biosolids, with the view of providing factual evidence contrary to or in support to public perceptions and opinions and in some cases, serious disagreement among environmental scientists on the use of biosolids for soil enrichment and restoration. This study, therefore offers a unique, unbiased prospective; whereby various studies on both the beneficial uses of biosolids and

potential harmful effects to the environment and living organisms have been painstakingly studied, to determine whether the use of biosolids for soil enrichment and restoration poses significant or negligible harm to living organisms and the environment, in the context of current environmental regulations and guidelines governing biosolids use in the U.S. and other countries of the world.

1.3 Aim and Objectives of the Study

This research provides an objective evaluation on whether the practice of land application of biosolids for soil nutrient enrichment and soil restoration is a safe practice in respect to the health of living organisms and the overall environment, or if the assertions of its potential harm to the environment and living organisms are valid under the circumstances argued. The following are the specific objectives:

- 1 To review published peer-reviewed research studies on the environmental and health effects resulting from land application of biosolids in an attempt to provide science-based evidence on their ecological impact.
- 2 To make such information handy for decision makers: (a) in regard to the protection of the environment, human and animal health, and (b) growing crops and restoring degraded land.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In recent years, sewage sludge treatment and disposal has been on the spotlight due to the expansion of municipal wastewater treatment systems and increasing stringent environmental regulations aimed at protecting the environment and living organisms (Gu et al., 2013). Proper sewage sludge management is a key objective for the development of an integrated strategy for treating domestic wastewater. In fact, the treatment and disposal and/ or utilization of sewage sludge from wastewater treatment plants account for up to 60%, of the total cost of wastewater treatment (Wei et al., 2003). In this section, a review of relevant literature discussing wastewater treatment technologies, characteristics of sludge, utilization/disposal of sludge and environmental regulations governing the use of sludge in the context of this research are presented.

2.2 Wastewater Treatment Technologies

Generally, wastewater treatment process includes physical, chemical, and biological processes to remove physical, chemical and biological contaminants and produces two end products: effluent, and water slurries which are usually referred to as sludges. There are three kinds of sludge: sewage sludge from municipal treatment works, septage pumped from septic tanks, and industrial sludges. While the clean water component is disposed of directly into the environment, it is not feasible,

environmentally or economically, to do so with the sludge generated by wastewater treatment processes. The raw sludge produced from the wastewater treatment processes needs to be stabilized, as appropriate, for its intended end-use and or disposal route in order to comply with public health and safety, environmental regulations, and economic considerations (Girovich, 1996; Hope, 1986).

Sewage sludge treatment steps may include preliminary treatment, primary treatment, secondary treatment, and tertiary treatment. Preliminary treatment removes large objects, such as sticks, paper, sand and grit, which are typically landfilled and do not become part of sewage sludge. Primary treatment involves gravity sedimentation for removing solid material that settles out and flotation processes that remove oil, grease, wood, and vegetative matter. Secondary treatment is a biological process in which naturally occurring microorganisms are used to degrade (break down or digest) suspended and dissolved organic material in the wastewater. Tertiary treatment includes steps designed to further reduce plant nutrients (nitrogen and phosphorus), pathogens, suspended solids, or biological oxygen demand (BOD) in the wastewater. Preliminary, primary, secondary, and sometimes tertiary treatments are often combined in any given publicly owned treatment works (POTW) (USEPA, 2009).

The main objectives of treating sewage sludge are to stabilize the organics, eliminate odors, destroy pathogens, reduce amount of solids and enhance de-watering. This reduces the volume of the sludge and improves its characteristics thereby reducing the associated health problem. The treatment process therefore reduces the water content, transforms the highly putrescible organic matter into a relatively stable or inert organic and inorganic residue and makes it meet disposal limits required by environmental regulations (Appels et. al, 2008).

There are three types of sludge produced from wastewater treatment: primary sludge, secondary sludge and mixed primary and secondary sludge. Primary sludge

comes from primary sedimentation to remove settleable solids that are readily thickened by gravity. Secondary sludge is biological sludge consisting of the conversion products from soluble wastes in primary effluent and particles escaping primary treatment. Treatment processes such as activated sludge, trickling filter and rotating biological contactors produce secondary sludges. Sludges produced from combination of primary and secondary sludges will have properties that are approximately proportional to their respective compositions (WEF/ASCE, 1992a).

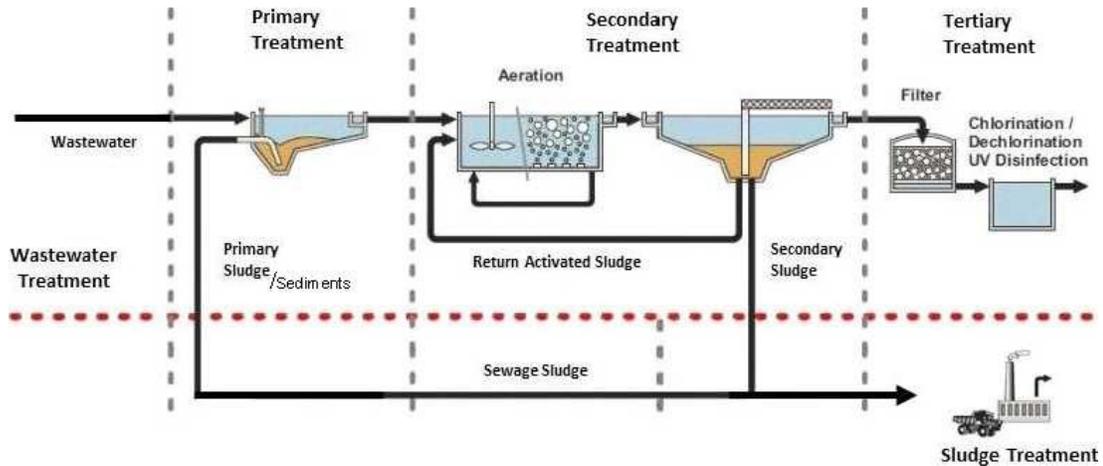


Figure 2.1: Simplified flow diagram for wastewater treatment after (Xu, 2014)

Sewage sludge treatment processes also remove contaminants from wastewater. The water purification part of wastewater treatment process commonly comprise a pre-treatment to remove about 50-60% of the suspended solids and 30-40% of the biochemical oxygen demand (BOD). The settled primary sludge contains mainly water (between 97% and 99%) and separates mostly organic matter that is highly putrescible (Eddy and Metcalf, 2003; Qasim, 1999). The pre-treatment is followed by a biological step, where aerobic microorganisms remove the remaining (or

nearly total) BOD and suspended solids. Nitrogen (N) and phosphorus (P) are commonly removed simultaneously, although N is more usually and easily targeted first. A secondary clarifier produces the dischargeable effluent as overflow and a bottom sludge (98–99% water), partly recycled to the biology to maintain the concentration of the microorganisms at the required level, and partly evacuated to the sludge treatment units of the (Wastewater Treatment Plant) WWTP. If a pretreatment is present, primary and secondary sludge are generally combined and thickened to undergo further treatment (Appels et. al., 2008).

After many years of development and practice, many technologies exist that can be used to treat the sludge produced from wastewater treatment. The main available sludge treatment options commonly in use are compiled in Table 2.1.

The most widespread stabilization processes in sludge treatment are the biological treatment processes of anaerobic digestion (Hall, 1995) and aerobic digestion which are further discussed in details in this section.

Table 2.1: Main Available Sludge Stabilization Technologies (Adapted from: Land and Soh, 2013)

Main Category	Sub-Category	Biosolids Classification
Aerobic Digestion	Conventional Aerobic Digestion	Class B
	High Purity Oxygen Aerobic Digestion	Class B
	Cryophilic Aerobic Digestion	Class B
	Aerobic/Anoxic Digestion	Class B
	Autothermal Thermophilic Aerobic Digestion (ATAD)	Class B
	Vertical Shaft Autothermal Thermophilic Digestion (VERTAD)	Class B
Aerobic Digestion with Pretreatment	Sonication Followed by Aerobic Digestion	Class B
Anaerobic Digestion	Conventional Mesophilic Anaerobic Digestion	Class B
	Conventional Thermophilic Anaerobic Digestion	Class A
	Anaerobic Baffled Reactor (ABR)	Minimum Class B
	Columbus Biosolids Flow-Through Thermophilic Treatment (CBFT3)	Class A
	High-Rate Plug Flow BioTerminator 24/85	Minimum Class B
	Temperature Phased Anaerobic Digestion (TPAnD)	Class A
	Two-Phase Acid Gas Anaerobic Digestion (2PAD)	Typically Class B
Anaerobic Digestion with Pre-treatment	Thermal Hydrolysis (CAMBI/Biothelyse Followed by Anaerobic Digestion)	Class A
	Sonication Followed by Anaerobic Digestion	Class A/B
	Electric Pulsation Followed by Anaerobic Digestion (OpenCEL TM)	Class A/B
	MicroSludge TM	Class A/B
	CROWN	Class A/B
	Dual Digestion	Class A
	Eco-Therm TM	Class A
Anaerobic Digestion with Post-treatment	Anaerobic Digestion Followed by Ozonation	Class A

Table 2.1: Table 2.1 Continued.

Chemical Treatment	Standard Alkaline Stabilization	Class A/B
	N-Viro TM	Class A
	CleanB TM	Class B
	VitAG (patented chemical with nutrient addition)	Class A
Alkaline Stabilization with Pasteurization	EnVessel Pasteurization TM (EVP)	Class A
Conventional Solidification		Typically Class A
Composting	Windrow	Class A
	Aerated Static Pile (ASP)	Class A
	In-Vessel	Class A
	Vertical Plug Flow System	
	Horizontal Plug Flow System	
	Agitated Bed System	
	Static Pod	TBC
Vermicomposting		
Thermal Drying	Standard Direct Drying	Class A
	Standard Indirect Drying	Class A
	Combination of Direct and Indirect Drying (e.g. INNODRY 2E)	Class A
	Vacuum Thermal Drying (e.g. Dry Vac TM)	Class A
Solar Drying		Class A
Disinfection	Ferrate Addition	Class A
	Irradiation	TBC
	Electron-Irradiation	
	Gamma-Irradiation	Class A
Neutralizer		
Incineration: Combustive Incineration	Fluidized Bed Incinerator	Class A
	Multiple Hearth Incinerator	Class A
	Electric Incinerator	Class A
	Rotary Kiln Incinerator	Class A
	Plasma Assisted Sludge Oxidation (PASO)	Class A
Incineration: Thermal Gasification	Conventional Gasification	Class A
	Plasma Gasification	Class A
Pyrolysis		Class A
Wet Oxidation (e.g. ZIMPRO and LOPROX)		Class A
Supercritical Water Oxidation (SCWO) (e.g. AquaCritox)		Class

TBC: to be confirmed

2.2.1 Anaerobic Digestion

Anaerobic digestion is one of the oldest processes used for the stabilization of sludges. It offers significant advantages over aerobic systems, such as low energy consumption, reduced solids formation, low nutrient requirement and potential energy recovery from the methane produced (Stewart et al., 1995). This process is now widely used in many environmental applications in different configurations and modes of operation.

Anaerobic digestion process uses microbes in the absence of oxygen to stabilize organic wastes and produces biogas, a mixture of methane and carbon dioxide, new biomass and inorganic products (Halls, 2000). It is most suitable for wastewaters with chemical oxygen demand (COD) concentrations in the high strength range (>2000 mg/L).

The anaerobic digestion process involves four key stages as shown in the diagram on the next page: hydrolysis, acidogenesis, acetogenesis, and methanogenesis.

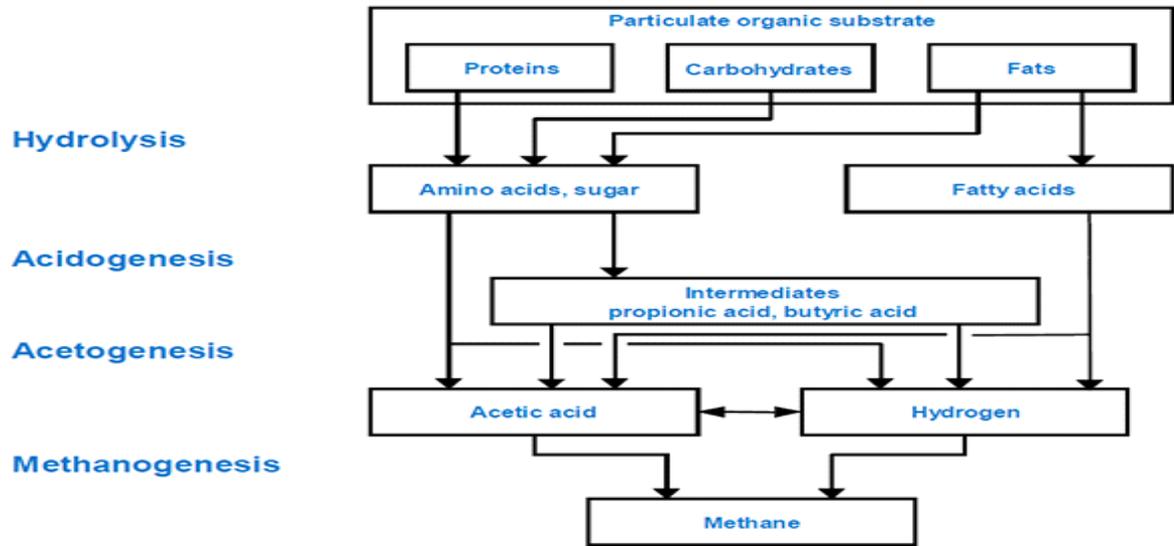


Figure 2.2: Four main stages in anaerobic digestion process Source: Waste-to-Energy Research and Technology Council (Available at: <http://www.wtert.eu/default.asp?Menu=13&ShowDok=12>. Accessed September, 2014)

The first stage is the hydrolysis process which involves the conversion of insoluble high molecular compounds like lignin, carbohydrates and fats into lower molecular compounds like sugars, amino acids and fatty acids that are available for bacteria. The second stage is the acidogenesis; here bacteria convert these soluble organic molecules into acetic acid, volatile fatty acids, hydrogen, and carbon dioxide. Acetogenesis is the third stage, and the rest of the acidogenesis products, i.e. the propionic acid, butyric acid and alcohols are transformed by acetogenic bacteria into hydrogen, carbon and acetic acid. Hydrogen plays an important intermediary role in the acetogenesis process, as the reaction will only occur if the hydrogen partial pressure is low enough to thermodynamically allow the conversion of all acids. The fourth and final stage is called methanogenesis. During this final stage, microorganisms convert the hydrogen and acetic acid formed by the acid formers to methane gas and carbon dioxide (Ahring, 2003; Baily, 2009; Mata-Alvarez, 2003; Verma, 2002; Williams, 2005).

2.2.2 Aerobic Digestion

Aerobic digestion is a bacterial decomposition process that occurs in the presence of oxygen. During this process, sewage sludge is biochemically oxidized by bacteria. To supply these aerobic microorganisms with enough oxygen, either the sewage sludge must be agitated by a mixer, or air must be forcibly injected. Under proper operating conditions, the volatile solids in sewage sludge are converted to carbon dioxide, water, and nitrate nitrogen (USEPA, 2003).

Aerobic bacteria are very efficient in breaking down waste products. Accordingly, aerobic treatment usually yields better effluent quality than obtained in anaerobic processes. The aerobic pathway also releases a substantial amount of energy, portion of which is used by the microorganisms for synthesis and growth of new microorganisms. Compared to anaerobic digestion, simplicity of process and lower capital costs are the advantages of aerobic process. It has also been a popular option for small or medium-sized wastewater treatment plants because of these advantages (Barbusinski and Koscielniak, 1997; Bernard and Gray, 2000).

2.3 Characteristics of Sewage Sludge

Sewage sludge is produced from wastewater treatment plants operated by municipalities. Wastewater may contain domestic wastes (soaps, human excrement, food, detergents, and household hazardous waste), pretreated industrial wastes, and or stormwater runoff. Sludge is defined as wastewater end-product that contains more than 0.5% solids by weight. Unprocessed sewage sludge is generally 93 to 99.5% water and contains substances that were present in the wastewater or that were added or produced by the wastewater treatment process. Untreated sewage sludge contains organic solids, nutrients (e.g., nitrogen, phosphorus, and micronutrients), pathogens

(e.g., bacteria, viruses, protozoa, and eggs of parasitic worms), and trace amounts of organic chemicals and inorganic chemicals such as heavy metals (Basta, 1995) and Pharmaceuticals and Personal Care Products (PPCPs). The type of plant, the operational method, and the physical and chemical characteristics of sludge can vary depending on source of the sewage.

Sewage is mainly water (including free water, interstitial water and bound water), microorganisms and mineral components but after the wastewater is treated, the particulate and colloidal matter is concentrated to form sludge (Cezac and Vaxelaire, 2004; Qi et al., 2011). Treated sludge characteristics that are important to land application include water content, degree of stabilization, and pH (the negative log of the activity of the hydrogen ion in an aqueous solution). The water content determines transportation costs and the method of application; stabilization influences biodegradability, pathogen destruction and odor potential; and pH determines the potential for leaching metals from the soil/biosolids and subsequent metals uptake by crops. Beneficial biosolids constituents include nitrogen, phosphorus, potassium and certain trace metals that act as fertilizer nutrients, and organic material that serves as a soil conditioner.

According to the USEPA, there are two classes of biosolids based on characteristics, Class A and Class B biosolids. Biosolids destined for beneficial use through land application must meet pathogen reduction criteria for either Class A or Class B according to Part 503 rules (USEPA, 2012). Class A biosolids typically are treated by a "Processes to Further Reduce Pathogens" (PFRP) such as composting, pasteurization, drying or heat treatment, advanced alkaline treatment, or by testing and meeting the pathogen density limits in Part 503. Class A pathogen reduction reduces the level of pathogenic organisms in the biosolids to a level that does not pose a risk of infectious disease transmission through casual contact or ingestion. Class B

biosolids typically are treated using a “Process to Significantly Reduce Pathogens” (PSRP) such as aerobic digestion, anaerobic digestion, air drying, and lime stabilization. As an alternative, producers may document compliance by analyzing the material for fecal coliform levels. When Class B requirements are met, the level of pathogenic organisms is significantly reduced, but pathogens are still present. In this case, other precautionary measures required by the Part 503 rule, i.e., site and crop harvesting restrictions are implemented for protection of public health.

2.4 Biosolids Utilization/Disposal

After treatment and processing, biosolids are commonly used in a number of ways. These include the following: application of sludge to agricultural and non-agricultural lands; sale or give-away of sludge for use in home gardens (often referred to as distribution and marketing of sludge); disposal of sludge in municipal landfills, sludge-only landfills (known as monofills), surface disposal site; and incineration of sludge (USEPA, 1993).

In 2004, 49% of biosolids produced in the U.S. were beneficially used (applied to land for agronomic, silviculture, or land restoration purposes), while 45% were disposed and 6% were stored, or their final use or disposal was not reported. It is likely that most of the 6% reported as “stored” was also destined for beneficial uses making beneficial use of biosolids in the U.S. in 2004 to be about 55% (NEBRA, 2007).

2.5 Laws Regulating Biosolids Use in the U.S. and other countries

The creation of sewage sludge is inevitable and for good reason. They are the byproduct of processes that clean our sewage before the cleaned water is discharged

into the streams and estuaries or other water body. The principal objective of wastewater treatment is to convert polluted wastewater into clean water but in the process it creates solid waste disposal problem. Unlike pollution created by unnecessary or accidental releases, municipal solid waste disposal is essential to industrialized society; however, alternatives for their disposal are limited due to enacted regulations that protect other aspects of the environment (Perez-Elvira et al., 2006; Harrison et al., 1999; Robinson et al., 2012).

In the U.S., there are established federal and states regulations that govern the use and or management of biosolids. In order for sewage sludge to become biosolids it must be treated to meet the standards established in federal and state regulations for use of biosolids for land application, marketing, storage, and or distribution in any form. These regulations require that the sewage sludge is properly treated complying with established treatment and management practices to meet pathogen control levels, vector attraction reduction, and lowering concentrations of regulated metals below established limits.

In 1978 the USEPA established pretreatment specifications (40 CFR Part 403), (USGPO, 2006) that required industries to limit the concentrations of certain pollutants, including trace elements and organic chemicals, in wastewater discharged to a treatment facility. An improvement in the quality of biosolids over the years has largely been due to pretreatment and pollution prevention programs (Evanylo, 1999).

Until 1990, sewage sludge was disposed of into the ocean. Following the U.S. government ban on ocean dumping due to pollution concerns, the amount of sludge sent to landfills quickly increased (Logan, 1995). To further compound the problem, the amendment of the Clean Water Act (CWA) in 1987 established quality standards for wastewater treatment resulting in additional municipal sludge generation. These pressures and the on-going recognition of the values of nutrients and organic matter in

sewage sludge, led to increased efforts to pretreat biosolids for recycling to land (Robinson et al., 2012). In compliance with the Clean Water Amendments Act of 1987, the USEPA issued the “Standard for the Use and Disposal of Sewage Sludge” in 40 CFR Part 503. The rule defined the management practices and numerical criteria for the three major use and disposal options: land application, incineration, and surface disposal, to protect public health and the environment. In addition to limiting where and when biosolids can be applied, the rule requires processes to kill pathogens and strictly limits amounts of metals that can be applied to any piece of land.

The rule applies to any person who applies biosolids to the land or fires biosolids in a biosolids incinerator, and to the owner/operator of a surface disposal site, or to any person who is a preparer of biosolids for use, incineration, or disposal.

For a comprehensive guide and details on the rules governing the use of biosolids in the U.S., “A Plain English Guide to the USEPA Part 503 Biosolids Rule” of 1994 written by the USEPA is a primary source (USEPA, 2012). Part 503 rule as written by the USEPA comprises five subparts: general provisions, requirements for land application; surface disposal; pathogen and vector attraction reduction; and incineration. For each of the regulated use or disposal practices, Part 503 standard includes general requirements, pollutant limits, management practices, operational standards, and requirements for the frequency of monitoring, recordkeeping, and reporting. Details of the subparts are included in Appendix 1.

Several other federal laws have also influenced biosolids management. The Resource Conservation and Recovery Act of 1976 (Public Law 94-580) and the Marine Protection, Research and Sanctuaries Act of 1972 (Public Law 92-532) are some of the federal laws that provide grants for the construction of municipal wastewater treatment plants, including sludge processing and management facilities

In the European Union (EU), during the last decades there has been a major change in the ways biosolids are handled and disposed of due to the passage of various directives aimed at protecting the environment and human health. Like the USEPA, the EU emphasizes the beneficial use of recycling the nutritional value of biosolids; and thus seeks to find the best balance of applying biosolids to the land and the cost of reducing the risks from pathogens and contaminants in biosolids affecting human health and the environment (Iranpour et al. 2004). Accordingly, this has led to the passage of regulations or directives by the EU to control the quantity, composition and use of biosolids one way or the other: the Waste Framework Directive (WFD) of 1975, the Sludge Directive of 1986 (86/278/EEC), the Urban Waste Water Treatment Directive of 1991 (91/271/EEC), Nitrates Directive of 1991 (91/676/EEC), and the Waste Incineration Directive of 2000 (2000/76/EC) are regulations/directives that have affected the fates of biosolids directly or indirectly in terms of land application across the EU.

The Waste Framework Directive (WFD) is the “basic law” of the EU Waste Policy. It dates back to 1975 and was revised in 2006. The directive was amended and merged with the Hazardous Waste Directive and the Waste Oil Directive. The WFD required Member States (MS) to manage waste by encouraging prevention and environmentally friendly disposal. The directive lays down the basic hierarchy of waste management and waste treatment and contains basic requirements for waste treatment facilities. The WFD applies to all waste streams with the notable exception of nuclear waste and other specific waste streams. It establishes the so-called waste hierarchy, sets out rules for waste management planning, qualified waste collection and treatment, and calls for obligatory permitting procedures for waste treatment plants (IEEP, 2009).

Also in mid-1980, a legislative item referred to as the “cornerstone” legislature on issues concerning wastewater and sludge treatment and management called the Sewage Sludge Council Directive of 1986 (86/278/EEC) was enacted to regulate the use of biosolids on agricultural lands. This directive in author’s opinion is the equivalence of the 40 CFR Part 503, U.S. law that regulates the use of biosolids programs in the U.S. The sludge council directive defined treated sludge as one that has undergone biological, chemical, or thermal treatment; and has undergone long-term storage or any other appropriate process so as to significantly reduce its ability to ferment and the health hazards associated with its use (Milieu Ltd, WRc and RPA, 2010). The directive aims at avoiding the accumulation of toxic substances, especially heavy metals that might reach excessive levels in the soil after a number of applications of biosolids on agricultural lands (Meozzi et al., 1997). The directive like previous directives on waste disposal, specifically seeks to protect the environment, and in particular the soil when biosolids are used in agricultural activities. The directive requires that sewage sludge be treated before it is used in agriculture; however it states that MS may authorize the injection or working of untreated sludge in soil in certain conditions, as long as human and animal health is not at risk (CEC, 1986).

The Urban Waste Water Treatment Directive (UWWTD) (Council Directive 91/271/EEC) was adopted on 21 May 1991. In 2005 the directive came into force thereby setting stringent quality standards for wastewaters. Article 14 in the UWWTD specifically addressed how biosolids arising from wastewater treatment should be disposed; and set 1998 as the deadline for MS to phase out ocean dumping, discharge from pipelines or by other means. Its objective is to protect the environment from adverse effects of urban wastewater discharges and discharges from certain industrial sectors and concerns the collection, treatment and discharge of domestic wastewater, mixture of wastewater and wastewater from certain industrial sectors (CEC, 1991).

The Nitrates Directive of 1991 (91/676/EEC) aims to protect water quality across Europe by preventing nitrates from agricultural sources polluting ground and surface waters and by promoting the use of good farming practices. While nitrogen is a vital nutrient that helps plants and crops to grow, high concentrations are harmful to people and nature as it can lead to eutrophication (CEC, 1991). Biosolids is used on agricultural lands across the EU, like in other countries of the world, because of its richness in nitrogen and other nutrients essential for plant growth. However the Nitrates Directive seeks to prevent eutrophication of water bodies from excess nitrogen from unregulated biosolids used on agricultural lands.

The Waste Incineration Directive (2000/76/EC) aimed at measures to prevent or reduce air, water and soil pollution caused by incineration or co-incineration of waste, as well as the resulting risk to human health. These measures specifically require that a permit be obtained for incineration and co-incineration plants and limits emission of certain pollutants released into the air or water. The directive affect sludge disposal by setting limiting values for emissions of pollutants into the air due to waste incineration.

The establishment of the directives discussed above makes it clear that the EU directives on biosolids use as well as biosolids related operations and other disposal methods have the ultimate aim of protecting the environment and human health.

CHAPTER 3

STUDY METHODOLOGY

3.1 Introduction

Studies on the environmental effects of land application of biosolids take considerably long period of time to fully understand their impacts. Conducting epidemiological studies to determine the health effects on grazing animals and those that work and live on and around lands applied with biosolids are even more difficult to undertake due to the high cost in conducting such studies as well as the long duration required, since the effects of contamination in the affected populations sometimes do not show up for many years. Based on this premise and considering the limited time for this study, and the fact that a good body of data, in the form of peer-reviewed articles are available, a systematic review of individual studies on the environmental and health effects of land application of biosolids was conducted.

3.2 Library Research

A modified systematic review after Lichtenstein et al., (2009) of individual studies was conducted in the summer of 2014 to answer the question: does land application of biosolids for soil enrichment and restoration poses significant harm to the health of human, animal and the environment?

The phrase “environmental and health effects of land application of sewage sludge/biosolids” was used to search Google Scholar. Google Scholar as a scholarly search tool has been proven to be a comparatively accurate and reliable source for accessing scholarly articles. Studies have shown that search results obtained using Google Scholar search are similar in most cases when compared to a variety of different science databases, including PubMed, BIOSIS Previews, SciFinder, Chemical

Abstracts Service (CAS), Web of Science (WoS), PsycINFO, Scopus and many others, especially when searching articles published after 1996 (Adriaanse and Renleigh, 2011; Garcia-Perez, 2010; Levine-Clark and Kraus, 2007; Mikki, 2010).

An initial search of Google Scholar retrieved over 300 journal articles. Each study was then evaluated to determine whether the study specifically focused on the impact of biosolids application on land. For articles to be included in detailed evaluation, they were required to have researched the impact of biosolids on human and animal health and the environment when land applied—this narrowed the number of relevant articles down to 86. The search result was limited to articles published from 1999 to 2014 to eliminate repetition of studies conducted by the National Research Council on land application of biosolids which resulted in their 1996 and 2002 renowned reports; and also to access current findings on the issue within the past 15 years.

The 86 articles retained were comprehensively reviewed and divided into three categories based on the issues at the center of the controversy as determined from studying the research findings. The three categories with percentages of the articles retrieved are:

1. Toxic organic compounds: persistent toxic organic chemicals and their fate in the environment following land application of biosolids totaled 34 or 39.1% of the total articles.
2. Pathogens: presence of pathogens and vector in biosolids and their health implications for grazing animals and human within closed contact with biosolids-amended soil comprised 18 or 20.7% of the total articles
3. Heavy metals: concern over heavy metals/trace elements and aerosols in biosolids and their effects on air/soil/nutrient, surface and groundwater quality accounted for 35 or 40.2% of total articles.

The articles retrieved from the Google Scholar search were painstakingly studied to determine what percentage in each category and overall percentage support or refute the claim that land application of biosolids poses significant danger to the environment, human and animal health. This is important since the environmental and health implications of land application of biosolids are at the core of the controversy on beneficial use of biosolids.

In chapter four, the research articles findings are summarized under the three categories listed below. Each article was critically reviewed to determine whether the articles:

1. Support the claim that land application of biosolids poses significant harm to the environment, human and animal health under current environmental regulations: these articles are designated (SPH)
2. Support the claim that land application of biosolids does not pose significant harm to the environment, human and animal health under current environmental regulations: these are denoted with (SPNH)
3. Are inconclusive on the issue under investigation, i.e. they do not say categorically if land application is harmful or not harmful but rather based on their findings recommend caution in the usage of biosolids for soil amendment: such articles are denoted with (INC).

The results of the review are presented in form of summary discussion and percentages for those scientific evidence that support or refute the claim that land application of biosolids is harmful to the environment, animal and human health, as well as those that are inclusive.

CHAPTER 4

SUMMARY OF RESEARCH FINDINGS

4.1 Introduction

This chapter presents summaries of the research findings from published peer reviewed articles studied on the issues at the core of the controversy, on whether land application of biosolids poses significant harm to the environment, human and animal health or not, as currently allowed by USEPA 40 CFR Part 503, all U.S. states and other countries of the world that regulate land application of biosolids in one form or the other.

4.1.0 Persistent Toxic Organic Pollutants (POPs) in Biosolids and their fate in the Environment

Persistent organic pollutants are chemicals that persist in the environment, bioaccumulates through the food web, and pose a risk of causing adverse effects to human and animal health and the environment when introduced into the environment (USEPA, 2009). Studies have shown that biosolids contain trace levels of persistent organic contaminants and thus the use of biosolids for soil amendment has been controversial due to safety concerns. Organic chemicals discharged in urban wastewater from industrial and domestic sources, or those entering through atmospheric deposition onto paved areas via surface run-off, are predominantly lipophilic in nature and therefore become concentrated in sewage sludge, with potential implications for the agricultural use of biosolids as soil amendment. Because they can be transported by wind and water, most POPs generated in one country can and do affect people and wildlife far from where they are used and released. They persist for

long periods of time in the environment and can accumulate and pass from one species to the next through the food chain (USEPA, 2009).

4.1.1 Persistent Toxic Organic Pollutants (POPs) in Biosolids and their fate in the Environment: scientific evidence in support of significant harmful effects

The following paragraphs present summaries of research evidence in support that POPs and other dangerous chemicals found in biosolids are harmful to the environment, human and animal health when introduced into the environment through land application of biosolids.

In a study Venkatesan et al., (2014) conducted in the U.S. to determine the persistence of brominated flame retardants (BFRs) in U.S. biosolids showed BFRs to persist in soil for years with little attenuation observable (<1% in 3 years). The study concluded that though polybrominated diphenyl ethers (PBDEs) are being phased-out in the U.S., the replacement chemicals novel brominated flame retardants (NBFRs) have similar structural properties since they share undesirable properties of traditional BFRs, such as environmental persistence and accumulation potential and suggested that there should be regulation to protect human health and the environment against such chemicals being released in the environment from biosolids land application (Venkatesan et al., 2014).

Sepulvado et al., (2011) conducted a study to investigate the occurrence and fate of perfluorochemicals (PFCs) from land applied biosolids by evaluating the levels, mass balance, desorption, and transport of PFCs in soils receiving application of biosolids at various loading rates. Their study was the first to report levels of PFCs in agricultural soils amended with typical municipal biosolids. They found that

perfluorooctane sulfonate (PFOS) was the dominant PFC in both biosolids (80 219 ng/g) and biosolids-amended soil (2 483 ng/g). They also found that concentrations of all PFCs in soil increased linearly with increasing biosolids loading rate. Laboratory desorption experiments indicated that the leaching potential of PFCs decreases with increasing chain length and that previously derived organic-carbon normalized partition coefficients may not be accurate predictors of the desorption of long-chain PFCs from biosolids-amended soils. Trace levels of PFCs were also detected in soil cores from biosolids-amended soils to depths of 120 cm, suggesting potential movement of these compounds within the soil profile over time and confirming the higher transport potential for short-chain PFCs in soils amended with municipal biosolids. The overall data from the study suggested that though the risk to groundwater is uncertain, transport of PFCs from soils amended with municipal biosolids is possible (Sepulvado et al., 2011).

Bioaccumulation of pharmaceuticals and other organic anthropogenic waste indicators (AWIs) in earthworms were studied by Kinney et al., (2008) from agricultural soil amended with biosolids to measure the presence and potential for transfer of 77 AWIs from land-applied biosolids to earthworms. The study found that when AWIs are present in source materials that are land applied, such as biosolids, AWIs can be transferred to earthworms with serious ecological implication (Kinney et al., 2008).

In a similar study to their early work, Kinney et al., (2012), used earthworm bioassays and seedling emergence to monitor toxicity, aging and bioaccumulation of anthropogenic waste indicator compounds in biosolids-amended soil to investigate the influence of biosolids and biosolids aging on earthworm (*Eisenia fetida*) reproduction and survival and lettuce (*Lactuca sativa*) seedling emergence. The study found that when biosolids were applied to soils at levels above 3%, the toxic components were lethal. Furthermore, AWIs content in the exposed earthworms along with bioaccumulation factor (BAF) values suggested that aging may alter the bioavailability

and bioaccumulation of many AWIs as well as the toxicity of biosolids (Kinney et al., 2012).

The potential for PPCPs to enter the plant presents concerns for their phytotoxicity. In another study by D' Abrosca et al., (2008), the uptake of PPCPs by soybean plants from soils applied with biosolids and irrigated with contaminated water was investigated and the researchers found that it was possible for plants to uptake PPCPs from soils that have been applied with biosolids or irrigated with PPCPs contaminated water (Wu et al., 2010). Negative effects to plants have been observed for several pharmaceuticals at environmentally relevant concentrations (Aristilde et al., 2010), in addition, accumulation of PPCPs through the food chain could also pose potential risks to species consuming plant parts, including humans.

Wu et al., (2012), in a similar study investigated the uptake of carbamazepine, diphenhydramine, and triclocarban (TCC) by five vegetable crop plants in a field experiment. They found again that even in actual field conditions, human and livestock exposure to PPCPs by way of consuming the crops grown on biosolids land-applied fields is possible, especially when heavily contaminated biosolids are used as amendments.

O'Connor and Snyder, (2013) also assessed the risk of land-applied biosolids-borne TCC using literature-derived and most recent measured data at the time to characterize screening-level "worst case" and "100-year" biosolids application scenarios adapted from the Part 503 Biosolids Rule risk assessment (USEPA, 1995) for 16 human and ecological exposure pathways. They identified an unacceptable risk associated with PPCPs compound in land-applied biosolids, and recommended additional research work to fill several remaining data deficiencies, before current guidelines could be modified to protect the most sensitive species (O'Connor and Snyder, 2013).

An outdoor mesocosm study was conducted by Walters et al., (2010) in Baltimore, Maryland, U.S.A to explore the fate of 72 PPCPs over the course of three years. PPCPs were placed in plastic containers made from polyvinylchloride and kept exposed to ambient outdoor conditions. The study results showed that PPCPs were readily biotransformable and could persist in soils for extended periods of time when applied through biosolids. The study provided the first experimental data on the persistence of PPCPs in biosolids-amended soils that included: ciprofloxacin, diphenhydramine, doxycycline, 4-epitetracycline, gemfibrozil, miconazole, norfloxacin, ofloxacin, and thiabendazole (Walters et al., 2010).

Kookana and Ying, (2007) conducted a study in Australia to investigate the occurrence of triclosan (TCS) in effluents, biosolids and surface waters, and its fate in WWTPs. They concluded from preliminary risk assessment based on the worst-case scenario that the TCS concentrations in surface waters might lead to risks to aquatic organisms such as algae. And that based on the TCS levels in the biosolids; application of biosolids on agricultural land could also cause adverse effects in the soil environment (Kookana and Ying, 2007).

Sertraline is a widely-used antidepressant that is one of the selective serotonin reuptake inhibitors (SSRIs). SSRIs are the most commonly prescribed antidepressants (de Jonghe and Swinkels, 1997). They can ease symptoms of moderate to severe depression, are relatively safe and generally cause fewer side effects than other types of antidepressant. Sertraline has been found to persist in agricultural soils following biosolids application, with major dissipation pathways including the production of non-extractable soil-bound residues, and accumulation of hydroxylated transformation products (Li et al., 2013). Studies have shown the potential environmental and public health impact of such chemical to be fatal (Boxall and Monteiro, 2010; Fent et al., 2006; Kolpin et al., 2002; Li et al., 2010).

Nanoparticles (NPs) from the rapidly increasing number of consumer products that contain manufactured nanomaterials are being discharged into waste streams (Judy et al., 2011). Increasing evidence suggest that several classes of nanomaterials may accumulate in sludge derived from wastewater treatment and ultimately in soil following land application as biosolids. A study, investigating evidence for biomagnification of gold nanoparticles within a terrestrial food chain from land application of biosolids using model organisms *Nicotiana tabacum* L. cv *Xanthi* and *Manduca sexta* (tobacco hornworm) found that there are important implications for risks associated with nanotechnology, including the potential for human exposure (Judy et al., 2011).

Cha and Cupples, (2009) investigated the occurrence of the antimicrobials TCC and TCS in agricultural soils following land application of biosolids using liquid chromatography-tandem mass spectrometry (LC-MS-MS) with negative ion multimode ionization. The method detection limits were 0.58 ng TCC/g soil, 3.08 ng TCC/g biosolids, 0.05 ng TCS/g soil and 0.11 ng TCS/g biosolids and the average recovery from all of the sample matrices was >95%. Antimicrobial concentrations in biosolids from three Michigan wastewater treatment plants (WWTPs) ranged from 4890 to 9280 ng/g, and from 90 to 7060 ng/g, for TCC and TCS respectively. Antimicrobial analysis of soil samples, collected over two years, from ten agricultural sites previously amended with biosolids, indicated TCC was present at higher concentrations (1.24–7.01 ng/g and 1.20–65.10 ng/g in 2007 and 2008) compared to TCS (0.16–1.02 ng/g and from the method detection limit, <0.05–0.28 ng/g in 2007 and 2008). The study concluded that such information is important because approximately 50% of U.S biosolids are land applied; therefore, any downstream effects of antimicrobial are likely to be widespread (Cha and Cupples, 2009).

In response to the U.S. National Academies' call for a better assessment of chemical pollutants contained in the approximately 7 million dry tons of digested municipal sludge produced annually in the U.S., the mean concentration of 72 PPCPs were determined in 113 biosolids samples collected by the USEPA in its 2001 national sewage sludge survey (USEPA, 2007). Composite samples of archived biosolids, collected at 94 U.S. wastewater treatment plants from 32 states and the District of Columbia, were analyzed by liquid chromatography tandem mass spectrometry using USEPA method 1694. Thirty-eight (54%) of the 72 analytes were detected in at least one composite sample at concentrations ranging from 0.002 to 48 mg kg⁻¹ dry weight. Triclocarban and triclosan were the most abundant analytes with mean concentrations of 36 ± 8 and 12.6 ± 3.8 mg kg⁻¹ (n = 5), respectively, accounting for 65% of the total PPCP mass found. The loading to U.S. soils from nationwide biosolids recycling was estimated at 210–250 metric tons per year for the sum of the 72 PPCPs investigated. The results of this nationwide reconnaissance of PPCPs in archived U.S. biosolids mirror in contaminant occurrences, frequencies and concentrations, those reported by the USEPA for samples collected in 2006 to 2007. Overall, the study reemphasizes the significance of biosolids recycling as a mechanism for the release of PPCPs into the environment. Based on the mean concentrations of all analytes detected, it is estimated that the total loading to U.S. soils from nationwide biosolids recycling is on the order of 210–250 metric tons per year for the 72 PPCPs investigated here (Halden and McClellan, 2010).

Rhind et al., (2013) investigated short and long-term temporal changes in soil concentrations of selected endocrine disrupting compounds (EDCs) following single or multiple applications of biosolids to pastures, found temporal changes in soil burdens of selected EDCs when sewage sludge or inorganic fertilizer was applied. Soil polycyclic aromatic hydrocarbon and polychlorinated biphenyl concentrations were not

altered. Changes in concentrations of diethylhexyl phthalate (DEHP) and PBDEs 47 and 99 differed with season but concentrations remained elevated for more than three weeks after application, when grazing animals are normally excluded from pasture. The study concluded based on its findings that single applications of sewage sludge can increase soil concentrations of some, but not all classes of EDCs, possibly to concentrations sufficient to exert biological effects when different chemicals act in combination, but patterns of change depend on season and soil temperature. Analysis of soil from pasture subjected to repeated sludge applications, over 13 years, provided preliminary evidence of greater increases in soil burdens of all of the EDC groups measured, including all of the PBDE congeners measured (Rhind et al., 2013).

Multimedia fate modeling and comparative impact on freshwater ecosystems of pharmaceuticals from biosolids-amended soils was done by Morais et al., (2013). The study modeled the impact on freshwater ecosystems of pharmaceuticals detected in biosolids following application on agricultural soils. The detected sulfonamides and hydrochlorothiazide displayed comparatively moderate retention in solid matrices and, therefore, higher transfer fractions from biosolids to the freshwater compartment. However, the residence times of these pharmaceuticals in freshwater were estimated to be short due to abiotic degradation processes. They found that the non-steroidal anti-inflammatory mefenamic acid had the highest environmental impact on aquatic ecosystems. The estimation of the solid-water partitioning coefficient was generally the most influential parameter of the probabilistic comparative impact assessment.

Alkylphenol ethoxylates, widely used in commercial and household detergents in the U.S., can degrade during the wastewater treatment process to more toxic, estrogenic, and lipophilic compounds (Guardia et al., 2001). These include octylphenol (OP), nonylphenols (NPs), nonylphenol monoethoxylates (NP1EOs), and nonylphenol diethoxylates (NP2EOs). These compounds have received considerable attention due

to their acute toxicity and ability to disrupt the endocrine system. In Europe, regulations have been established to control their impact on the environment. In a study, biosolids derived from all 11 U.S. wastewater treatment plants examined contained detectable levels of OP, NPs, NP1EOs, and NP2EOs. Nine exceeded the current Danish land application limit (30 mg/kg; sum of NPs, NP1EOs, and NP2EOs) by 6-33 \times . NPs were the major component, and their concentrations ranged from 5.4 to 887 mg/kg (dry weight). OP, reportedly 10- 20 \times more estrogenic than NP, was detected in these same nine biosolids at levels up to 12.6 mg/kg. Three biosolids were also subjected to the U.S. Environmental Protection Agency Toxicity Characteristic Leaching Procedure (TCLP) Method 1311 test. NPs and NP1EOs were both detected in the leachate; the former at concentrations from 9.4 to 309 μ g/ L. On the basis of effect levels published in the literature, alkylphenol ethoxylate degradates in U.S. biosolids may cause adverse environmental impacts (Guardia et al., 2001).

On-farm assessment of biosolids effects on soil and crop tissue quality by Shober et al., (2003) was designed to assess the effects of long-term commercial-scale application of biosolids on soils and crop tissue sampled from 18 production farms throughout Pennsylvania, U.S.A. At the end of the study there were no differences in the concentrations of measured nutrients or trace elements in the crop tissue grown on treated or control fields at any time during the study period. Commercial-scale biosolids application resulted in soil trace element increases that were in line with expected increases based on estimated trace element loading. They however found excess NO₃ and apparent P buildup and recommend the need to reassess biosolids nutrient management practices (Shober et al., 2003).

4.1.2 Persistent Toxic Organic Pollutants (POPs) in Biosolids and their fate in the Environment: scientific evidence in support of negligible or no harmful effect

The following paragraphs present summaries of research evidence in support that POPs and other dangerous chemicals found in biosolids pose negligible or no adverse effects to the environment, human and animal health when introduced into the environment through land application of biosolids.

In a study to evaluate runoff of pharmaceuticals and personal care products following application of dewatered municipal biosolids (DMB) to an agricultural field, Sabourin et al., (2012) applied DMB at commercial rate using broadcast application followed by incorporation. They simulated precipitation at 1, 3, 7, 21 and 34 days following the application on 2m² microplots shortly after application of a commercial rate of DMB to evaluate surface runoff of PPCPs, namely atenolol and carbamazepine. Their findings showed that a number of PPCPs were detected in artificial runoff, but all compounds were present at concentrations that were below effects concentrations for a variety of acute toxicological endpoints. On a mass basis, analytes with octanol/water partition coefficients (K_{ow}) values greater than 3 had little transport potential in surface runoff. On the basis of the very low detected concentrations and the transient nature of exposure from runoff drainage, they concluded that the risk of known acute effects is low for organisms exposed in adjacent aquatic environments to the PPCPs measured in the study, should they be entrained in runoff (Sabourin et al., 2012).

Smith (2014) studied organic contaminants in biosolids and their significance for agricultural recycling and found that scientific literature on the potential environmental and health impacts of organic contaminants (OCs) in sludge indicates that the presence of a compound in sludge, or of seemingly large amounts of certain

compounds used in bulk volumes domestically and by industry, does not necessarily constitute a hazard when the material is recycled to farmland. Furthermore, he found that the chemical quality of sludge is continually improving and concentrations of potentially harmful and persistent organic compounds have declined to background values. Thus, recycling biosolids on farmland was not constrained by concentrations of OCs found in contemporary biosolids (Smith, 2014).

Jones et al., (2014) measured concentrations of trace substances in biosolids in a survey of 28 wastewater treatment works (WWTWs) in the United Kingdom (U.K.) over a period of 12 months. Approximately 250 samples were analyzed for more than 40 trace contaminants, including trace metals, pharmaceuticals, polycyclic aromatic hydrocarbons (PAHs), 'emerging' and regulated organic pollutants. All substances investigated were found to be present in at least some of the biosolids sampled. Concentrations were relatively homogenous across all the WWTWs, irrespective of the treatment process, influent and effluent concentrations, and the location of the sludge sampling point within each works. Analysis of the results against existing regulatory and proposed thresholds suggested that levels are mostly below the limits set in the Sewage Sludge Directive, and proposed new limits for sludge used in agriculture. Predicted soil concentrations after application of sewage sludge to land were below the predicted no effect concentrations (PNEC) for all determinants. Predicted concentrations of pharmaceuticals in soil were also below thresholds deemed to indicate negligible environmental risk (Jones et al., 2014).

Yang et al., (2011) studied the environmental risk of PBDEs. PBDEs are organobromine compounds that are used as flame retardant. PBDEs include the commercial versions of pentabromodiphenyl ether (c-pentaBDE), octabromodiphenyl ether (c-octaBDE), and decabromodiphenyl ether (c-decaBDE). The environmental concern for flame retardant chemicals is due to their high lipophilicity and high

resistance to degradation processes. The critical endpoint of concern for human health is neurobehavioral effects. Various PBDEs have also been studied for ecotoxicity in mammals, birds, fish, and invertebrates. Studies conducted to investigate whether flame retardants are migrating from the indoor environment to the outdoor environment through land application of biosolids and the environmental risk pose by PBDEs in biosolids from land application in Italy, China and the U.S.; found that PBDEs are indeed entering the outdoor environment but pose low risk to the environment (Alessandra et al., 2012; Yang et al., 2011).

A study by Bright and Healey, (2003) examined the potential for environmental risks due to organic contaminants at biosolids application sites and documented metals and various potential organic contaminants (volatile organics, chlorinated pesticides, PCBs, dioxins/furans, extractable petroleum hydrocarbons, PAHs, phenols, and others) in biosolids production from five wastewater treatment plants (WWTPs) within the Greater Vancouver Regional District (GVRD). Another objective was to evaluate the extent to which management of biosolids re-use based on metal/metalloid levels coincidentally minimizes environmental risks from organic contaminants. The study found that with the exception of petroleum hydrocarbon constituents or their microbial metabolites, the mixing of biosolids with uncontaminated soils during land application- and based on the known metal concentrations in biosolids from the Greater Vancouver WWTPs investigated-provides adequate protection against the environmental risks associated with organic substances such as dioxins and furans, phthalate esters, or volatile organics (Bright and Healey, 2003).

Xia et al., (2010) conducted a study to evaluate the levels of TCC, TCS, 4-nonylphenol (4-NP), and polybrominated diphenyl PBDEs in biosolids from 16 WWTPs and in soils from field plots receiving annual applications of biosolids for 33 years. All of the four contaminants evaluated were detected in most of the biosolids at

concentrations ranging from 100s of mg/kg to over 1,000 mg/kg (dry wt basis). They were detected at mg/kg levels in the biosolids-amended soil, but their concentrations decreased sharply with increasing soil depth for 4-NP, PBDEs, and TCC, indicating limited soil leaching of those compounds. However, potential leaching of TCS in the biosolids-amended soils was observed. The levels of all four compounds in the surface soil increased with increasing biosolids application rate. Compared with the estimated 33 years cumulative input to the soil during the 33 years consecutive biosolids application, most of the PBDEs and a small percentage of 4-NP, TCC, and TCS remained in the top 120-cm soil layer. The observations suggest slow degradation of PBDEs but rapid transformation of 4-NP, TCC, and TCS in the biosolids-amended soils (Xia et al., 2010).

A probabilistic risk assessment for linear alkylbenzene sulfonate (LAS) was developed for biosolids used on agricultural soil in the U.K., by Schowanek et al., (2007) to assess exposure and effects for LAS in biosolids and soil. Their findings, backed up by relevant field evidence, are that LAS in anaerobic biosolids does not represent a significant ecological risk.

Best Management Practices (BMPs) is used to minimize the risk of contamination of adjacent water resources with chemical or microbial agents that are of public or environmental health concern according to current USEPA regulations. Topp et al., (2008) conducted a field study to investigate runoff of PPCPs following application of biosolids to an agricultural field. They found that injection of biosolids slurry below the soil surface could effectively eliminate surface runoff of PPCPs thereby posing less risk to the environment (Topp et al., 2008).

Langdon et al., (2012) studied field dissipation of 4-nonylphenol, 4-t-octylphenol, triclosan and bisphenol A (BPA) following land application of biosolids treatments under field conditions in South Australia. The pattern of dissipation was

assessed to determine if a first-order or a biphasic model better described the data. The field dissipation data was compared to previously obtained laboratory degradation data. The concentrations of 4-nonylphenol, 4-t-octylphenol and BPA decreased during the field study, whereas the concentration of triclosan showed no marked decrease. The time taken for 50% of the initial concentration of the compounds in the two biosolids to dissipate (DT50), based on a first-order model, was 257 and 248 d for 4-nonylphenol, 231 and 75 d for 4-t-octylphenol and 289 and 43 d for BPA. These field DT50 values were 10- to 20-times longer for 4-nonylphenol and 4-t-octylphenol and 2.5-times longer for BPA than DT50 values determined in the laboratory. A DT50 value could not be determined for triclosan as this compound showed no marked decrease in concentration. The biphasic model provided a significantly improved fit to the 4-t-octylphenol data in both biosolids treatments, however, for 4-nonylphenol and BPA it only improved the fit for one treatment. The study showed that the use of laboratory experiments to predict field persistence of compounds in biosolids amended soils may greatly overestimate degradation rates and inaccurately predict patterns of dissipation (Langdon et al., 2012).

The presence of antimicrobial chemicals triclocarban (TCC) and triclosan (TCS) in municipal biosolids has raised concerns about the potential impacts of these chemicals on soil ecosystems following land application of municipal biosolids (Higgins et al., 2011). The relative persistence of TCC and TCS in agricultural fields receiving yearly applications of biosolids at six different loading rates over a three-year period was investigated. Soil and biosolids samples were collected, extracted, and analyzed for TCC and TCS using liquid chromatography tandem mass spectrometry. In addition, the potential for bioaccumulation of TCC and TCS from the biosolids-amended soils was assessed over 28 days in the earthworm *Eisenia foetida*. Standard 28 days bioaccumulation tests were conducted for three biosolids loading rates from two sites,

representing agronomic and twice the agronomic rates of biosolids application plots as well as control plots receiving no applications of biosolids. Additional bioaccumulation kinetics data were collected for the soils receiving the high biosolids loadings to ensure attainment of quasi-steady state conditions. The results indicate that TCC is relatively more persistent in biosolids-amended soil than TCS. In addition, TCC bioaccumulated in *E. foetida*, reaching body burdens of 25 ± 4 and 133 ± 17 ng/g wet weight in worms exposed for 28 days to the two soils amended with biosolids at agronomic rates. The 28 days organic carbon and lipid normalized biota soil accumulation factors (BSAFs) were calculated for TCC and ranged from 0.22 ± 0.12 to 0.71 ± 0.13 . Their findings suggest that TCC bioaccumulation is somewhat consistent with the traditional hydrophobic organic contaminant (HOC) partitioning paradigm. However, the data also suggest substantially reduced bioavailability of TCC in biosolids amended soils when compared to HOC partitioning theory (Higgins et al., 2011).

PBDEs were determined in sewage sludge samples collected from eight Italian wastewater treatment plants (WWTPs) between June 2009 and March 2010 (Cincinelli et al., 2012). Total PBDE concentrations ranged from 158.3 to 9427 ng g⁻¹ dry weight, while deca-BDE (BDE-209) (concentrations ranging from 130.6 to 9411 ng g⁻¹ dry weight) dominated the congener profile in all the samples, contributing between 77% and 99.8% of total PBDE. The suitability of using a magnetic particle enzyme-linked immunoassay (ELISA) to analyze PBDEs in sewage sludge was also tested. The ELISA results, expressed as BDE-47 equivalents, were well correlated with those obtained by gas chromatography-negative chemical ionization-mass spectrometry (GC-NCI-MS), with correlation coefficients (r^2) of 0.899 and 0.959, depending on the extraction procedure adopted. The risk assessment of PBDEs in sewage sludge addressed to land application was calculated. Predicted environmental concentration soil (PECsoil) values compared to the relative predicted no effect concentration soil

(PNECsoil) for penta and deca-BDE suggests that there is a low risk to the soil environment.

4.1.3 Persistent Toxic Organic Pollutants (POPs) in Biosolids and their fate in the Environment: scientific evidence that do not support either side of the controversy but suggest caution

The following paragraphs present summaries of research evidence that do not categorically state whether or not POPs and other dangerous chemicals found in biosolids are harmful to the environment, human, and animal health when introduced into the environment through land application of biosolids.

Jjemba (2002) conducted a review of the potential impact of veterinary and human therapeutic agents in manure and biosolids on plants grown on arable land. He found that most of the phytotoxicity studies have been conducted in vitro and few conducted in soil, and all suggest that phytotoxicity varies between species. He also found that the bioavailability of these compounds is greatly dependent on the sorption kinetics of the respective compound, soil organic matter, and soil pH. Furthermore, the review found that they are potential pollutants in the environment although their concentrations in soils need to be investigated. Once introduced into soil, the mobility and sorption of these compounds also greatly influence their availability for uptake by plants. Sorption is greatly dependent on soil organic matter. They concluded that it seems reasonable to standardize sorption measurements by computing the distribution coefficient and normalizing it to the organic carbon (i.e. *K_{oc}* values) to make comparisons between soil types easier (Jjemba, 2002).

Persistence of PBDEs in agricultural soils after biosolids applications was studied by Andrade et al., (2010) to examine the levels and trends in biosolids from a

WWTP, and evaluate potential factors governing PBDEs concentrations and the fate in agricultural soils fertilized by biosolids. The study found that soil environment is difficult to model and the fate of these chemicals depends on their interaction with all environmental compartments and on agricultural management practices. They recommended more controlled experiments, which would include repeated soil sampling of a field, repeated sampling of fields with different types of soil, and incorporation of sorption, biodegradation, volatilization, and photodegradation studies, to better estimate the half-life of these chemicals and to better understand their disappearance in the soil environment (Andrade et al., 2010).

To help fill the gaps in knowledge regarding the presence and concentration of organic chemicals in biosolids Harrison et al., (2006) examined peer-reviewed papers and official governmental reports. Data were found for 516 organic compounds which were grouped into 15 classes. Concentrations were compared to USEPA risk-based soil screening limits (SSLs) where available. For 6 of the 15 classes of chemicals identified, there were no SSLs. For the 79 reported chemicals which had SSLs, the maximum reported concentration of 86% exceeded at least one SSL. Eighty-three percent of the 516 chemicals were not on the USEPA established list of priority pollutants and 80% were not on the USEPA's list of target compounds. Thus analyses targeting these lists detected only a small fraction of the organic chemicals in sludges. Analysis of the reported data showed that more data has been collected for certain chemical classes such as pesticides, PAHs and PCBs than for others that may pose greater risk such as nitrosamines. The results of the study reinforced the need for a survey of organic chemical contaminants in sewage sludges and for further assessment of the risks they pose (Harrison et al., 2006).

In a review of 'emerging' OCs in biosolids and assessment of international research priorities for the agricultural use of biosolids, Clarke and Smith (2011)

reviewed selected 'emerging' OCs in biosolids of potential concern for land application based upon human toxicity, evidence of adverse effects on the environment, and endocrine disruption. To identify research priorities the selected chemicals were ranked using an assessment matrix approach. Compounds were evaluated based upon environmental persistence, human toxicity, evidence of bioaccumulation in humans and the environment, evidence of ecotoxicity and the number and quality of studies focused on the contaminant internationally. The identified chemicals of concern were ranked in decreasing order of priority: perfluorinated chemicals (PFOS, PFOA); polychlorinated alkanes (PCAs), polychlorinated naphthalenes (PCNs); organotins (OTs), PBDEs, TCS, TCC; benzothiazoles; antibiotics and pharmaceuticals; synthetic musks; bisphenol A, quaternary ammonium compounds (QACs), steroids; phthalate acid esters (PAEs) and polydimethylsiloxanes (PDMSs). The study concluded that, though research on OCs in biosolids has been undertaken for over 30 years and the increasing body of evidence demonstrates that the majority of compounds studied do not place human health at risk when biosolids are recycled to farmland; a number of 'emerging' OCs (PFOS, PFOA and PCAs) were identified for priority attention that are environmentally persistent and potentially toxic with unique chemical properties, or are present in large concentration in sludge, that make it theoretically possible for them to enter human and ecological food-chains from biosolids-amended soil (Clarke and Smith, 2011).

Eriksson et al., (2008) identified potential priority pollutants in biosolids applied to agricultural land in Sweden. Their study revealed that there are potential hazardous compounds in biosolids applied to agricultural land.

4.2.0 Environmental and health implication from land application of biosolids

There is a growing need for better assessment of health risks associated with land applied of biosolids. Fertilization of land with biosolids, which often contain low levels of pathogens, endotoxins, and trace amounts of industrial and household chemicals, has become common practice in Western Europe, the U.S. and Canada. Local governments, however, are increasingly restricting or banning the practice in response to residents reporting adverse health effects (Lewis et al., 2002). However, there are still others vigorously advocating their use citing minimum adverse effects to human and animals. Scientific evidence in respect to the issue is presented below.

4.2.1 Environmental and health implications from land application of biosolids: scientific evidence that support harmful effects

The following paragraphs present summaries of research evidence that support the claim that land application of biosolids pose adverse effect to the environment, human and animal health.

Measurement of aerosolized endotoxin from land application of Class B biosolids in southeast Arizona was done by Brooks et al., (2006) in a study to determine aerosolized endotoxin concentrations downwind of a biosolids land application site. The study evaluated the presence of aerosolized endotoxin from the land application of biosolids and showed that the levels were within ranges for concern as it relates to adverse effect to the environment, human and animal health.

Alleged health incidents associated with land application of biosolids after residents near application site reported illnesses, symptoms of more than 328 people involved in 39 incidents in 15 states investigated by Harrison and Oakes, (2002). The

study found that analysis of the limited data suggests that surface-applied Class B biosolids posed the greatest risk and should be eliminated. And that even under less risky application scenarios, the potential for off-site movement of chemicals, pathogens, and biological agents suggests that their use should be eliminated.

Also in a health survey of residents living near farm fields permitted to receive biosolids in Wood County, OH, U.S.A, 607 households were mailed health questions (Khuder et al., 2007). The survey results from the study revealed that some reported health-related symptoms were statistically significantly elevated among the exposed residents, including excessive secretion of tears, abdominal bloating, jaundice, skin ulcer, dehydration, weight loss, and general weakness. The frequency of reported occurrence of bronchitis, upper respiratory infection, and giardiasis were also statistically significantly elevated. The findings suggest an increased risk for certain respiratory, gastrointestinal, and other diseases among residents living near farm fields on which the use of biosolids was permitted (Khuder et al., 2007).

Also Lowman et al., (2013) conducted an in-depth interview with neighbors of land application sites and qualitative analytic software and team-based methods were used to analyze interview transcripts and identify themes. Thirty-four people in North Carolina, South Carolina, and Virginia responded to interviews. Key themes were health impacts, environmental impacts, and environmental justice. Over half of the respondents attributed physical symptoms to application events. Most noted offensive sludge odors that interfere with daily activities and opportunities to socialize with family and friends (Lowman et al., 2013).

In another study to investigate interactions of pathogens and irritant chemicals in land-applied biosolids, 48 individuals at 10 sites in the U.S. and Canada were questioned about their environmental exposures and symptoms by Lewis et al., (2002). The study found that affected residents lived within approximately 1 km of land

application sites and generally complained of irritation (e.g., skin rashes and burning of the eyes, throat, and lungs) after exposure to winds blowing from treated fields. A prevalence of *Staphylococcus aureus* infections of the skin and respiratory tract was also found. Approximately 1 in 4 of 54 individuals was infected, including 2 mortalities (septicemia, pneumonia). The study concluded that their result was consistent with the prevalence of *S. aureus* infections accompanying diaper rashes in which the organism, which is commonly found in the lower human colon, tends to invade irritated or inflamed tissue (Lewis et al., 2002).

Decay of enteric microorganisms in biosolids amended soil under wheat (*Triticum aestivum*) cultivation was studied by Schwarz et al., (2014) to investigate in-situ decay of seeded human adenovirus (HAdV), *Salmonella enterica*, *Escherichia coli*, and bacteriophage (MS2) in biosolids-amended soil under wheat cultivation. In the study, no notable decline in HAdV numbers (PCR detectable units) was observed in both biosolids-amended and the un-amended soils at the three sites studied. The HAdV decay time ($T_{90} \geq 180$ days) in biosolids-amended and un-amended soils was significantly higher than MS2 ($T_{90} = 22\text{--}108$ days). The results of the study suggest that adenovirus could survive for a longer period of time (>180 days) during the winter in biosolids-amended soil. The study concluded that the stability of adenovirus suggests that consideration towards biosolids amendment frequency, time, rates, and appropriate withholding periods are necessary for risk mitigation (Schwarz et al., 2014).

Lind et al., (2010) exposed pregnant ewes to multiple endocrine disrupting pollutants through biosolids-fertilized pastures to determine effects on maternal and fetal bone structures, density and mechanical properties of exposure to environmental concentrations of multiple EDCs and heavy metal pollutants. They found that ewes grazing pasture fertilized with biosolids exhibited an anti-estrogenic effect on their trabecular bone in the form of reduced mineral content and density, despite increased

body weight. It is suggested that human exposure to low levels of multiple EDCs may have implications for bone structure and human health (Lind et al., 2010).

Also Hombach-Klonisch et al., (2013) studied ewe's periconceptual changes in maternal exposure to biosolids chemicals and found that biosolids chemical disturbed fetal thyroid gland development. After ewes were maintained on biosolids-fertilized pastures twice annually with thermally dried digested biosolids, the researchers found that periconceptual low-dose in utero exposure to a relevant complex mixture of environmental chemicals adversely affected cell proliferation, thyrocyte differentiation and the formation of intact angio-follicular units in the fetal thyroid. Their conclusion was that the changes may have long-term consequences for thyroid function during postnatal life (Hombach-Klonisch et al., 2013).

Muchuweti et al., (2006) conducted a study in Zimbabwe to look at the health implications of heavy metal content of vegetables irrigated with mixtures of wastewater and biosolids. The crops analyzed in the study were found to be heavily contaminated with the four regulated elements: cadmium (Cd), copper (Cu), lead (Pb) and zinc (Zn). The study highlights the potential risks involved in the cultivation and consumption of vegetables on plots irrigated with biosolids, a practice which they claimed may place at risk the health of the urban population who consume these vegetables (Muchuweti et al., 2006).

4.2.2 Environmental and health implications from land application of biosolids: scientific evidence that support negligible or no harmful effects

The following paragraphs present summaries of research evidence that support the claim that land application of biosolids pose negligible or no adverse effect to the environment, human and animal health.

Ziemba et al., (2013) results from modelling human off-site aerosol exposure to polybrominated flame retardants emitted during the land application of biosolids suggest that while the amount of PBDEs aerosolized during the land application process is small compared to aerosol emissions associated with product use, the application of biosolids onto U.S. soils constitutes a major source of PBDEs entering the outdoor environment. However, the overall finding of the study was that the inhalation of PBDE aerosols from biosolids-applied fields does not represent a significant contribution to human exposure compared to other common indoor exposures (Ziemba et al., 2013).

Also, a national study on the residential impact of biological aerosols from the land application of biosolids was conducted by Brooks et al., (2005) to evaluate the community risk of infection from bioaerosols to residents living near biosolids land application sites. The study evaluated the overall incidence of aerosolized microorganisms from the land application of biosolids and subsequently determined that microbial risks of infection from bioaerosol operations exposure poses little community risk based on the study findings.

Tanner et al., (2005) also studied bioaerosol emission rates and plume characteristics of bioaerosols generated during land application of liquid Class B biosolids. They compared the rate of aerosolization of coliphages and total coliform

bacteria during land application of liquid Class B biosolids to the rate of aerosolization during land application of groundwater inoculated with similar concentrations of *Escherichia coli* and coliphage MS2. In conclusion, they found that aerosolized microorganisms were not detectable during land application of liquid Class B biosolids near Tucson, Arizona, U.S.A. Land application of seeded water was a useful experimental tool and demonstrated that the aerosol plume generated during land application is detectable from a stationary point for no more than 1 min per “pass” of the applicator. Thus, exposure to bioaerosols containing coliform bacteria and coliphages resulting from land application of liquid class B biosolids is discrete and occurs at low concentrations. The study also suggests that exposure to aerosolized pathogenic microorganisms is lower than previously estimated (Tanner et al., 2005).

Also a research to investigate the occupational risk from bioaerosols generated during land application of class B biosolids at various locations in the U.S. found risks from aerosolized microorganisms to be lower than those at wastewater treatment plants, based on previously reported literature (Tanner et al., 2007).

Aryal and Reinhold (2011) researched the phytoaccumulation of antimicrobials, the effects of plant growth on migration of antimicrobials to water resources, and relevance of phytoaccumulation in human exposure to antimicrobials by growing pumpkin, zucchini and switch grass in soil columns to which biosolids were applied. Results from the trials indicated that plants can reduce leaching of antimicrobials to water resources. Potential human exposure to triclocarban from consumption of pumpkin or zucchini was substantially less than exposure from product use, but was greater than exposure from drinking water consumption. Consequently, the study concluded that pumpkin and zucchini may beneficially impact the fate of antimicrobials in agricultural fields, while presenting minimal acute risk to human health (Aryal and Reinhold, 2011).

Staphylococcus aureus is an important human pathogen both within the hospital setting and as a community-acquired infection. Rusin et al., (2003) conducted a study to investigate the concern that land applied biosolids may transmit *S. aureus* and reported that biosolids are not a likely source of *S. aureus* human exposure or infection.

Jenkins et al., (2007), reviewed available scientific evidence on the health effect of land application of biosolids and concluded that there does not seem to be strong evidence of serious health risks when biosolids are managed and monitored appropriately.

McFarland et al., (2012) conducted a study at sites located near Columbus, Georgia, U.S.A to evaluate whether the present regulatory limits established for biosolids pollutants (e.g., heavy metals) were sufficiently protective of human health associated with potential groundwater consumption using a new USEPA risk assessment tool. Application of a computer-based biosolids groundwater risk characterization screening tool (RCST) to two biosolids land application sites predicted that biosolids could be safely applied at rates of at least 90 Mg ha⁻¹ with the regulated biosolids pollutant concentration as large as 10 times the current regulatory limit (Part 503 Ceiling Concentration limits) with no apparent non-carcinogenic human effects associated with groundwater consumption. The study concluded that the absence of a significant human health risk predicted from biosolids land application modeling efforts support maintaining current regulatory requirements (McFarland et al., 2012).

In a similar study, Rhind et al., (2011) researched effect of duration of exposure to biosolids-treated pastures on liver tissue accumulation of persistent EDCs in sheep. Liver tissue concentrations of selected polychlorinated biphenyls (PCBs), PBDEs and polycyclic aromatic PAHs were determined in groups of Texel ewes and lambs following exposure to pastures fertilized with either biosolids (Treated; T) or inorganic

fertilizer (Control; C). It was concluded that the increases in tissue concentrations with increased duration of exposure were unlikely to be sufficient to be of concern to consumers and that tissue burdens cannot be linked, easily, with the physiological effects reported previously for animals similarly exposed (Rhind et al., 2011).

4.2.3 Environmental and health implications from land application of biosolids: scientific evidence that do not support either side of the controversy but suggest cautious approach

The paragraph below presents summary of a research evidence that neither support nor oppose the claim that land application of biosolids pose adverse effect to the environment, human and animal health.

Zaleski et al., (2005) reviewed studies on the survival, growth, and regrowth of enteric indicator and pathogenic bacteria in biosolids, compost, soil, and land applied biosolids to show if after biosolids are treated and land applied, there is the possibility of enteric indicators and pathogenic bacteria resurfacing. This is important since the presence of such are linked to potential health problems to human and animals. The review found that studies evaluating the regrowth of *Salmonella* and indicators in biosolids amended soil have shown mixed results. However experiments done with indigenous *Salmonella* showed that regrowth to only low concentrations was observed (Zaleski et al., 2005).

4.3.0 Effect of Land Application of Biosolids from Heavy Metals, Soil, Air and Surface and Groundwater

Land application of biosolids has been defended as beneficial use by some scientists and regulators (Agrawal and Singh, 2009; Moss et al., 2002; USEPA, 1999),

based on the premise that the behavior of any toxins accumulated in soils from this practice is reasonably well understood and will not have detrimental agronomic or environmental impacts into the foreseeable future. Likewise other scientists and environmental activists (Clarke et al., 2008; McBride, 2003; Spinosa and Veslind, 2001) have strongly opposed the practice of land application of biosolids for soil amendment based on the facts that it contained potentially harmful substances.

4.3.1 Effect of Land Application of Biosolids from Heavy Metals, Soil, Air and Surface and Groundwater: scientific evidence in support of harmful effects

The following paragraphs present summaries of research evidence that support the claim that land application of biosolids has adverse effect on the environment, human and animal health.

Phosphorus solubility in biosolids-amended farm soils in the Mid-Atlantic Region of the U.S. was studied to investigate the influence of current N-based land application practices for biosolids on soil P. The Findings from the study suggest that adding biosolids according to current N-based guidelines will lead to an accumulation of P in soils with serious long-term ecological consequence (Maguire et al., 2000).

Also, a field plot experiment in a calcareous soil with wheat and maize rotation was carried out for 2 years to investigate the effects of biosolids application on nitrogen N and P accumulation in soils. Results from the study showed that heavy application of biosolids to agricultural soils based on the N requirement of a wheat-maize rotation cropping system will oversupply P with long-term adverse environmental effects (Qiong et al., 2012).

Also, a study evaluated the environmental hazard of biosolids compost applied at 10, 30, and 90 Mg ha⁻¹ fresh weight in a vineyard in southeastern France and concluded that in the long run, P will accumulate in the soil and may reach concentrations that will pose a risk to surface waters and groundwater from land application of biosolids (Korboulewsky et al., 2002).

Lindstrom et al., (2011) investigated the application of biosolids and resulting PFCs such as perfluorooctanoic acid (PFOA) and PFOS contamination of surface and well water in Alabama, U.S.A. A situation in Decatur, Alabama where PFC contaminated biosolids from local municipal wastewater treatment facility, that had received waste from local fluorochemical facilities were used as a soil amendment in local agricultural fields for as many as 12 years. Ten target PFCs were measured in surface and groundwater samples. The findings showed that surface and well water in the vicinity of these fields had elevated PFC concentrations, with 22% of the samples exceeding the USEPA Provisional Health Advisory level for PFOA in drinking water of 400ng/L. Water/soil concentration ratios as high as 0.34 for perfluorohexanoic acid, 0.17 for perfluoroheptanoic acid, and 0.04 for PFOA verify decreasing mobility from soils with increasing chain length while indicating that relatively high transport from soils to surface and well water was possible (Lindstrom et al., 2011).

Latare et al., (2014) evaluated the effect of sewage sludge on yield of rice, soil fertility and heavy metals accumulation in grain and straw in a glass house. The study found significant increase in straw and grain yields of both the crops with application of biosolids. Soil pH in post-harvest rice soil increased with the application of biosolids, however, it decreased in post-harvest wheat soil at higher levels of biosolids application. Increase in available nutrients content of soil was also recorded with increasing levels of biosolids application after harvest of rice and wheat crops. Most importantly, the application of biosolids also increased the heavy metals contents in

soil and plant above the Indian safe limit at 20 t ha⁻¹ or higher levels of biosolids application. The study also found significant buildup of P, S, Zn, Fe, and Mn in post-harvest wheat soil at 40 t ha⁻¹ biosolids application (Latare et al., 2014).

Mobilization of endocrine disrupting chemicals and estrogenic activity in rainfall runoff from land-applied biosolids was simulated in a study by Giudice and Young (2011) to characterize the mobilization of selected EDCs, heavy metals, and total estrogenic activity in rainfall runoff from land-applied biosolids. The study found possible environmental risk in rainfall runoff for copper, nickel, and TCS and concluded that based on the findings current limits on metals concentrations in biosolids may not be sufficiently protective with respect to either metal or TCS in runoff.

Waterhouse et al., (2014) examined the effects of biosolids on endemic earthworms following the use of biosolids in mine soil rehabilitation. The study reported 100% of earthworm mortality in biosolids-amended soil, and concluded that biosolids and endemic earthworms can play an important role in ecological restoration but thorough ecotoxicological testing of biosolids should be undertaken prior to their use in mined land rehabilitation on a large scale.

In a study titled "Life cycle assessment of biosolids land application and evaluation of the factors impacting human toxicity through plant uptake", Sablayrolles et al., (2010) studied the environmental impacts of two types of biosolids (dried and composted, from the same wastewater treatment plant) from the dehydration step to biomass production in the field. Overall, it was found that dried biosolids were found to be more harmful to the environment than the composted biosolids for 6 out of the 8 impact categories (abiotic resources depletion, global warming, acidification, eutrophication, ozone depletion, summer smog, ecotoxicity, and human toxicity) of the life cycle assessment (Sablayrolles et al., 2010).

A study to establish whether the repeated application of biosolids to an acid forest soil (*Dystric cambisol*) would lead to short-term groundwater contamination was done by Egiarte et al., (2008). The study found that the alkalinity of the biosolids was not able to buffer the acidity generated by nitrification and by the high leaching conditions of the system. Also the drinking water standards for Cd and Ni were surpassed in all treatments. Control plots were contaminated by groundwater flow despite the existence of buffer zones between plots.

The USEPA Part 503 rule did not directly specify the amount of biosolids-borne P that can be applied but allowed application rates based on the recommended N requirement of a crop (Schroder et al., 2008). A study on the effect of long-term annual application of biosolids on soil properties, phosphorus and metals found that the repeated long-term application of biosolids above the N agronomic rate should be avoided and application should be based on other criteria such as an agronomic P threshold, an environmental P threshold, or a P site index following increased micronutrients to level of concern (Schroder et al., 2008).

Land (2012) conducted a study into the Chesapeake Bay nutrient pollution problem and found that the land application of biosolids was the cause of the pollution. He concluded that the ban of land application of biosolids in Virginia, U.S.A was long overdue. He further stated that biosolids was such an inefficient “fertilizer” because it takes time for microbes to decompose the organic material and release the nutrients for crop growth.

Esseili et al., (2012) used genetic as well as traditional methods to investigate the impact of rainfall on the offsite drainage of *Escherichia coli* from agricultural fields during biosolids application. Their study results showed that heavy rainfall following biosolids application to agricultural fields induced the offsite transport of biosolids-

associated *E. coli*, potentially compromising the quality of water draining through the watershed.

Mantovi et al., (2005) conducted a study to evaluate the effects of repeated biosolids applications in comparison to mineral fertilizers on a winter wheat–maize–sugar beet rotation, in a field experiment on a silty-loam soil, in the Eastern Po Valley (Italy), since 1988. Results from the study showed that with the higher rate of liquid and dewatered biosolids, excessive N supply was harmful, leading to wheat lodging and poor quality of sugar beet and wheat crops. Lodging is a term used to describe regions or sometimes entire field of cereal falling flat on the ground. It was also found that biosolids increased organic matter (OM), total N, and available P in the soil and reduced soil alkalinity, with more evident effects at the highest rate. Significant accumulations of total Zn and Cu were detected in amended topsoil, but not of other heavy metals (Cd, [chromium] Cr, [nickel] Ni, Pb), whose total concentration remained well below the hazard limits. Biosolids applications significantly increased the content of N, P, Zn, and Cu in wheat grain, N and Cu in sugar beet roots, and only Cu in maize grain. The application of biosolids brought about notable benefits to soil fertility but it was associated with possible negative effects on water quality due to increased P availability and on soil ecology due to Zn accumulation (Mantovi et al., 2005).

Wang et al., (2008) conducted field experiments to study the effect of biosolids application on the heavy metal content in soils and grasses from Northern Shenyang WWTP, China, and applied at 0, 15, 30, 60, 120 and 150t ha⁻¹. The experimental results showed that nutrient content of the soil, especially organic matter, increased after biosolids application. The grass biomass was increased and the grass growing season was longer. Heavy metal concentrations in the soil also increased; however, the Zn content did not exceed the stringent Chinese environmental quality standard for soil. Pb and Cu did not exceed the standard for B grade soil, but Cd concentration in soil

amended by biosolids exceeded the B grade standard. Therefore, it was suggested that the sewage sludge produced from the wastewater treatment plant should not be applied to farmland, for which B grade soil or better is required (Wang et al., 2008).

Katanda et al., (2007) conducted a study in 2005 at Crowborough and Firle farms (near Harare, Zimbabwe) to assess effect of Cd on microbial biomass and activity and effect of biosolids and effluent on soybean (*Glycine max* L (Merr)) nodulation, and uptake of Zn and Cu by lettuce (*Lactuca sativa* L.), mustard rape (*Brassica juncea* L.), covo (*Brassica napus*) and star grass (*Cynodon nlemfuensis*); following 30 years of biosolids application. The study found that long-term application of biosolids to soil has negative effects on soil microorganisms, including rhizobia and that mustard rape and lettuce can accumulate Zn and Cu beyond toxic limits without apparent reduction in growth thereby posing a serious concern to the food chain (Katanda et al., 2007).

4.3.2 Effect of Land Application of Biosolids from Heavy Metals, Soil, Air and Surface and Groundwater: scientific evidence in support of negligible or no harmful effects

The following paragraphs present summaries of research evidence that support the claim that land application of biosolids pose negligible or no adverse effect on the environment, human and animal health.

Hazard et al., (2014) investigated the effects of biosolids on arbuscular mycorrhizal fungi (AMF) communities in grassland and arable agroecosystems, in the context of the natural seasonal dynamics of AMF community composition and diversity. A pasture and arable system under commercial farming management were amended annually with two different types of biosolids, applied at levels meeting current European Union regulations, in a factorial, replicated field-scale plot experiment. AMF

root colonization and community composition were measured in *Lolium perenne* roots from the pasture and *Trifolium repens* roots growing in arable soil across the seasons of two years. AMF community compositions were assessed by terminal-restriction fragment length polymorphism analyses. The study found no significant effect on AMF root colonization or community composition in either agroecosystem in respect to biosolids application (Hazard et al., 2014).

Since the mid-1990s, a *Pinus radiata* (D. Don) plantation growing on a sandy, low fertility soil at Rabbit Island near Nelson, New Zealand received aerobically digested liquid biosolids. An experimental research trial by Wang et al., (2004) was established on the site to investigate the effects of biosolids applications on tree growth, nutrition, and soil and groundwater quality. The study showed that biosolids application significantly increased tree growth. Soil analysis indicated that biosolids application have not caused significant changes in concentrations of most nutrients. However, biosolids treatments significantly increased available P. Of the heavy metals only total Cu concentrations in the soil increased after biosolids application. Groundwater quality, which was monitored quarterly, was not affected by biosolids application. The concentrations of nitrate and heavy metals in groundwater were also found to be well below the maximum acceptable values in drinking water standards. The overall study results showed that application of biosolids to a plantation forest can significantly improve tree nutrition and site productivity without resulting in any measurable adverse effect on the receiving environment (Wang et al., 2004).

Zerzghi et al., (2010) evaluated the influence of 20 annual land applications of Class B biosolids on the soil microbial community. The potential benefits and hazards of land application were evaluated by analysis of surface soil samples collected following the 20th land application of biosolids. The study was initiated in 1986 at the University of Arizona Marana Agricultural Center, Tucson, AZ, U.S.A. The study

showed that land application of Class B biosolids had no significant long-term effect on indigenous soil microbial numbers including bacteria, actinomycetes, and fungi compared to un-amended control plots. Importantly, no bacterial or viral pathogens were detected in soil samples collected from biosolids-amended plots 10 month after the last land application, demonstrating that pathogens introduced via Class B biosolids only survived in soil transiently. However, plots that received biosolids had significantly higher microbial activity or potential for microbial transformations, including nitrification, sulfur oxidation, and dehydrogenase activity, than control plots and plots receiving inorganic fertilizers. The researchers concluded that the 20 annual land applications showed no long-term adverse environmental effects (Zerzghi et al., 2010).

The effects of biosolids application rate and history on soil potential carbon (C) and N mineralization were measured over 112 day's laboratory incubation. Soils were collected from a large-scale biosolids recycling operation that surface-applies anaerobically digested Class B biosolids for commercial forage production. The study found no significant differences in potential C and N mineralization between controls and soils amended at the lowest rate for 8 or 25 years which suggests that biosolids applications at $22 \text{ Mg ha}^{-1} \text{ y}^{-1}$ are sustainable over the long-term (Jin et al., 2011).

Also, a review of research work was done with the objective to evaluate the sustainability of land application of Class B biosolids by evaluating the fate and transport of potential biological and chemical hazards within biosolids, and the influence of long-term land application on the microbial and chemical properties of the soil (Pepper et al, 2008). The study found direct risks to human health posed by pathogens in biosolids to be low and risks from indirect exposure such as aerosolized pathogens or microbially contaminated groundwater to be also low. A long-term land application showed enhanced microbial activity with no adverse toxicity effects on the soil microbial community; increased soil macronutrients including C, N, and, in

particular, P were found. Available soil metal concentrations remained low over the 20 years land application period due to the low metal content of the biosolids and a high soil pH. Soil salinity increases were not detected due to the low salt content of biosolids and irrigation rates in excess of consumptive use rates for cotton. The study conclusion was that long-term land application of Class B biosolids was therefore sustainable (Pepper et al., 2008).

To determine the prevalence of antibiotic-resistant bacteria and endotoxin in soil after land application of biosolids, a study was conducted by Brooks et al., (2007). Soil samples collected over a 15 month period following land application of biosolids, and antibiotic resistance was ascertained using clinically relevant antibiotic concentrations. Ampicillin, cephalothin, ciprofloxacin, and tetracycline resistance were all monitored separately for any changes throughout the 15 month period. Overall, the study found that land application of biosolids did not increase the percentage of antibiotic-resistant culturable bacteria above background soil levels. Likewise, land application of biosolids did not significantly increase the concentration of endotoxin in soil (Brooks et al., 2007).

Surface water chemistry (NO_3^- , NH_4^+ , and total P, Cd, Cu, and [mercury] Hg) was monitored for 31 years from 1972 to 2002 in a 6000-ha watershed at Fulton County, Illinois, U.S.A where the Metropolitan Water Reclamation District of Greater Chicago was restoring the productivity of strip-mined land using biosolids: The study was conducted to evaluate the long-term impacts from using biosolids to restore degraded land. Results from the study showed that application of biosolids for land reclamation at high loading rates from 1972 to 2002, with adequate runoff and soil erosion control, had only a minor impact on surface water quality (Tian et al., 2006).

Also, Tian et al., (2013) studied the impact of biosolids application on soil organic matter (SOM) stability-which contributes to soil C sequestration-soil samples

were collected in 2006 at plow layer from fields that received liquid and dry biosolids application from 1972 to 2004 at the cumulative rate of 1416Mgha⁻¹ in mined soil and 1072Mgha⁻¹ in non-mined soil and control fields that received chemical fertilizer at Fulton County, Western Illinois, U.S.A. The findings from the study showed that biosolids application increased the soil microbial biomass C (SMBC) by 5-fold in mined soil and 4-fold in non-mined soil. Biosolids-amended soils showed a high amount of basal respiration and N mineralization, but low metabolic quotient, and low rate of organic C and organic N mineralization. There was a remarkable increase in mineral-associated organic C from 6.9 g kg⁻¹ (fertilizer control) to 26.6 g kg⁻¹ (biosolids-amended) in mined soil and from 8.9 g kg⁻¹ (fertilizer control) to 23.1 g kg⁻¹ (biosolids-amended) in non-mined soil. The amorphous Fe and Al, that can improve SOM stability, were increased by 2–7 folds by the long-term biosolids application. The study results showed that biosolids-modified SOM resists decomposition more than that in the fertilizer treatment, thus long-term biosolids application could increase SOM stability (Tian et al., 2013).

Gaskin et al., (2003) conducted a study on the long-term application of biosolids that periodically contained elevated metal concentrations raising questions about potential effects on animal health. In the study, metal (As, Cd, Cu, Pb, Hg, Mo, Ni, Se, and Zn) concentrations were determined in both soil and Bermuda grass (*Cynodon dactylon* (L.) Pers.) forage from 10 fields in the following categories of biosolids application: six or more years (>6YR), less than six years (<6YR), and no applications (NS). The study found that toxic levels of metals did not accumulate in the soils due to long-term biosolids application and that overall forage quality from the biosolids-amended fields was similar to that of commercially fertilized fields.

A study by Contin et al., (2012) measured and compared methane oxidation rates of arable and grassland soils that received 7.5 t ha⁻¹ y⁻¹ of non-contaminated

aerobically treated biosolids for 10 years and found that long-term continuous application of sewage sludge with characteristics within the threshold limits did not impair methane oxidation capacities of both arable and grassland soils. Moreover, the soil receiving 10 times the allowed amount of biosolids was more resistant to additions of Pb and Zn. The increase of soil organic matter increased the proportion of Pb and especially Zn retained as sulfur bound and organic matter forms which are well known to be less toxic. The methanotrophic community was therefore temporarily protected against Pb and Zn pollution events. However, the work also demonstrated that the potential to emit (PTE) contamination (namely Pb and Zn) have a negative effect on microbial communities (Contin et al., 2012).

Roig et al., (2012) analyzed the systematic and periodical use, for 16 years, of anaerobically digested biosolids as an agricultural fertilizer by assessing the effects on the physical, chemical, functional, and ecotoxicological properties of some soils. The results showed that the input of biosolids enhanced soil properties proportionally to the application doses and/or frequency. The organic amendments increased the organic matter content and its aromaticity, the soil nitrogen, and the microbial activity, improving carbon and nitrogen mineralization processes and some enzymatic functions (Roig et al., 2012).

PPCPs in groundwater, subsurface drainage, soil, and wheat grain, following a high single application of municipal biosolids to a field was studied in October 2008 by Gottschall et al., (2012). Over 80 PPCPs were analyzed of which the following were analyzed in depth: antibiotics (tetracyclines, fluoroquinolones), bacteriocides (triclosan, triclocarban), beta-blockers (atenolol, propranolol, metoprolol), antidepressants (fluoxetine, citalopram, venlafaxine, sertraline), antifungals (miconazole), analgesics (acetaminophen, ibuprofen) and anticonvulsants (carbamazepine). The study found that despite the relatively high rates of biosolids applied at the site (22 Mg dw ha⁻¹),

there was no significant impact on the quality of either tile drainage or groundwater. Additionally, there were no observed PPCPs in the grain of wheat planted the spring following application. The study showed that the application did not pose a significant risk to surface or groundwater resources at the site (Gottschall et al., 2012).

A similar study on land application of biosolids was conducted on an agricultural field in fall 2008 at a rate of 22 Mg dry weight (dw) ha⁻¹ to investigate possible tile and groundwater contamination from hormone, sterol and fecal found in biosolids. The study found that despite the high rate of biosolids application and the relative persistence of hormones and sterols in biosolids aggregates incorporated in the soil following land application, tile and groundwater contamination was limited (Gottschall et al., 2013).

4.3.3 Effect of Land Application of Biosolids from Heavy Metals, Soil, Air and Surface and Groundwater: scientific evidence that do not support either side of the controversy.

The following paragraphs present summaries of research evidence that neither support nor oppose the claim that land application of biosolids pose adverse effect on the environment, human and animal health.

The increasing use of engineered nanoparticles (NPs) in industrial and household applications will very likely increase the release of such materials into the public sewer systems. During the wastewater treatment process, some fraction of NPs would always be concentrated in the biosolids. When biosolids is applied on the agricultural land, NPs are introduced into the soil matrix. In a study, Shah et al., (2014) investigated the influence of five different metal nanoparticles present in biosolids on soil microbial community as a function of time. Results indicate that ZnO and Zero

Valent Cu NPs were not toxic to soil bacterial community. Biosolids mixed with Ag NPs 10 and TiO₂ (both anatase and rutile phase) in contrast changed the bacterial richness and composition in wavering pattern as a function of time. Based on the observations made in the study, the researchers suggest caution when interpreting the toxicity of NPs based on single time point study.

An ecotoxicological effects study was conducted by Carbonell et al., (2009) for representative soil organisms on agricultural soil applied with biosolids in order to assess the fate and the effects in a microcosm multi-species soil system (MS3). The MS3 columns were filled with spiked soil at three different doses: 30, 60 and 120 t ha⁻¹ fresh wt. Seed plants (*Triticum aestivum*, *Vicia sativa* and *Brassica rapa*) and earthworms (*Eisenia fetida*) were introduced into the systems. After a 21 day exposure period, a statistically significant increase for Cd, Cu, Zn and Hg concentrations was found for the soils treated with the highest application rate. Dose- related increase was observed for Ni concentrations in leachates. Plants and earthworm metal body burden offer much more information than metal concentrations and help to understand the potential for metal accumulation. Bioaccumulation factor (BAF plant soil) presented a different behavior among species and large differences for BAF earthworm soil, from control or biosolids-amended soil, for Cd and Hg were found. *B. rapa* seed germination was reduced. Statistically significant decrease in fresh biomass was observed for *T. aestivum* and *V. sativa* at the highest application rate, whereas *B. rapa* biomass decreased at any application rate. Enzymatic activities (dehydrogenase and phosphatase) as well as respiration rate on soil microorganisms were enlarged. The complexity of the responses is very high and produces contradictory driving forces in related pathways and parameters, resulting in unclear dose response. The study showed that there can be environmental risk from micropollutants if the proper dose is not used (Carbonell et al., 2009).

A study was conducted by Hollert and Oleszczuk, (2011) to determine the influence of different soils (sandy, loamy and Organization for Economic Co-operation and Development [OECD] soil) on biosolids toxicity in relation to plants (*Lepidium sativum*, *Sorghum saccharatum*, and *Sinapis alba*) and an invertebrate species (*Heterocypris incongruens*). Results from the study demonstrated that in the practical evaluation of biosolids usability, biosolids dose is not the only determining element, soil type being also significant. Biosolids toxicity can significantly differ depending on the soil type and this may lead to an underestimation or overestimation of the hazard relating to the application of biosolids for agricultural purposes (Hollert and Oleszczuk, 2011).

In a review, McBride (2003) used the case of toxic metals in biosolids applied to agricultural land to illustrate that metal behavior in soils and plant uptake is difficult to generalize because it is strongly dependent on the nature of the metal, biosolids, soil properties and crop. Nevertheless, permitted agricultural loadings of toxic metals from biosolids are typically regulated using the sole criterion of total metal loading or concentrations in soils. Several critical generalizing assumptions about the behavior of sludge-borne metals in soil-crop systems, built into the USEPA risk assessment for metals, have tended to underestimate risks and are shown not to be well justified by published research. He concluded that in the absence of a basic understanding of metal behavior in each specific situation, a more precautionary approach to toxic metal additions to soils is warranted (McBride, 2003).

In a pot trial, Adair et al., (2014) grew two oilseed crop species, *Brassica napus* and *Camellia sativa* in soil amended with two levels biosolids and soil amended with urea. Seed yield and oil content were compared between soil treatments, and effects on soil chemistry, activity of microfauna, and bacterial and fungal community structure were quantified. The study results suggested that biosolids could effectively fertilize

oilseed crops and may enhance soil health, but impacts of heavy metals needed to be considered.

CHAPTER 5

DISCUSSION OF RESULTS

5.1 Introduction

This chapter presents discussion on the articles reviewed. As indicated before, one of the main goals of this study is to investigate whether land application of biosolids as currently practiced in the U.S. and other countries of the world poses significant harm to animal, human health and the environment. Summaries of scientific evidences presented in chapter 4 on the controversy are presented in this chapter in tables and pie charts according to the three categories to provide clearer picture of the findings. The author's perspective on the controversy and the conclusion of the study are also presented here.

Table 5.1: Research articles that presented scientific evidence on the fate of POPs in biosolids applied on land and their impact on the environment

SPH	SPNH	INC
Morais et al., 2013	Jones et al., 2014	Jjemba, 2002
Smith, 2009	Rhind et al., 2013	Andrade et al., 2010
Laguardia et al., 2001	Sabourin et al., 2009	Eriksson et al., 2008
McClellan and Halden, 2010	Xia et al., 2010	Harrison et al., 2006
Cha and Cupples, 2009	Langdon et al., 2012	Clarke and Smith, 2011
Sepulvado et al., 2011	Topp et al., 2008	
Judy et al., 2011	Schowaneck et al., 2007	
Li et al., 2013	Bright and Healey, 2003	
Ying and Kookana, 2006	Higgins et al., 2011	
Walters et al., 2010	Yang et al., 2011	
Snyder and O'Connor, 2013	Cincinelli et al., 2012	
Davis et al., 2012		
Wu et al., 2012		
Kinney et al., 2008		
Kinney et al., 2012		
Wu et al., 2010		
Venkatesan and Halden, 2014		
Shober et al., 2003		

*SPH= research articles that support the controversy that the use of biosolids for soil enrichment and restoration poses significant harm to the environment, human and animals health

*SPNH=research articles that support the controversy that the use of biosolids for soil enrichment and restoration do not pose significant harm to the environment, human and animal health

*INC=research articles that are inconclusive on the controversy that the use of biosolids for soil enrichment and restoration is beneficial or harmful to the environment, human and animal health effect of land application of biosolids

Table 5.1 shows the list of peer-reviewed research articles that were studied for this work. They provide scientific evidence on the fate of persistent organic pollutants (POPs) and other toxic chemicals found in biosolids. These chemicals can be introduced into the environment through land application of biosolids.

Out of the total of 34 peer-reviewed research articles studied, 18 or about 53% support the claim that land application of biosolids is harmful to the environment, human and animal health. There were 11 or about 32% of the articles that support the claim

that land application of biosolids poses negligible or no harm to the environment, human and animal health. On the other hand, 5 articles or about 15% of the articles do not categorically say that land application of biosolids is harmful or not harmful. Those researches that do not reach definite conclusion on the subject under discussion recommended caution in dealing with land application of biosolids for soil enrichment.

The breakdown on the findings from the articles studied in respect to POPs and other toxic chemicals and their fate in the environment are presented Figure 5.1.

Percentages of Research Findings

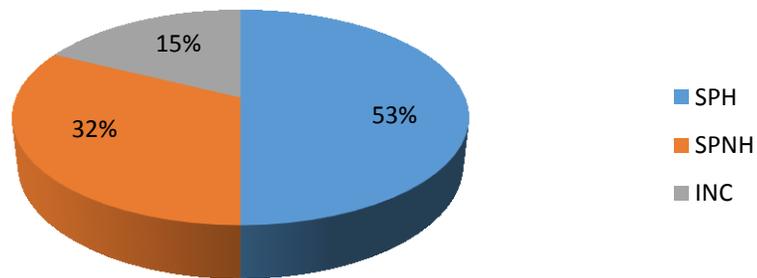


Figure 5.1: Pie chart showing the percentage of research articles that presented scientific evidence on POPs in biosolids applied on land and their impact on the environment

Table 5.2: Research articles that presented scientific evidence on health effects from land application of biosolids

SPH	SPNH	INC
Lowman et al., 2013	Ziamba et al., 2013	Zaleski et al., 2005
Lewis et al., 2002	Tanner et al., 2008	
Harrison and Oakes, 2002	Brooks et al., 2005	
Brooks et al., 2006	McFarland et al., 2012	
Schwarz et al., 2014	Aryal and Reinhold, 2011	
Muchuweti et al., 2006	Rusin et al., 2003	
Lind et al., 2010	Rhind et al., 2011	
Hombach-Klonisch et al., 2013	Jenkins et al., 2007	
Khuder et al., 2007		

*SPH= research articles that support the controversy that the use of biosolids for soil enrichment and restoration poses significant harm to the environment, human and animals health

*SPNH=research articles that support the controversy that the use of biosolids for soil enrichment and restoration do not pose significant harm to the environment, human and animal health

*INC=research articles that are inconclusive on the controversy that the use of biosolids for soil enrichment and restoration is beneficial or harmful to the environment, human and animal health effect of land application of biosolids

Table 5.2 shows the list of peer-reviewed research articles that were studied for the purpose of this work. The articles provided scientific evidence on the health implications from land application of biosolids.

A total of 18 peer-reviewed research articles were studied in respect to the health implications from applying biosolids to farm land. Out of the 18 research work studied, 9 or 50% support the claim that land application of biosolids poses considerable health risk to people and animal in proximity to sites where biosolids has been land applied. Also there were 8 or about 44% of the articles that support the claims that land application of biosolids pose negligible or no health risk to animal and people in proximity to sites that are enriched from biosolids application. Also 1 or about 6% of the articles could not categorically say that land application of biosolids pose serious

health risk or not to human and animals in proximity to sites where biosolids is land applied.

The breakdown on the findings from the articles studied in respect to health risk to human and animals from land application of biosolids are presented Figure 5.2.



Figure 5.2: Pie chart showing the percentage of research articles that presented scientific evidence on health effects from land application of biosolids

Table 5.3: Scientific evidence on the effect of land application of biosolids in respect to heavy metals, soil, air and surface and groundwater pollution

SPH	SPNH	INC
Latare et al., 2014	Benjamin et al., 2005	Carbonell et al., 2009
Lindstrom et al., 2011	Hazard et al., 2014	Adair et al., 2014
Giudice & Young, 2011	Tian et al., 2006	McBride, 2003
Waterhouse et al., 2014	Tian et al., 2013	Oleszczuk & Hollert, 2011
Sablayrolles et al., 2010	Wang et al., 2004	Shah et al., 2014
Egiarte et al., 2008	Zerzghi et al., 2010	
Schroder et al., 2008	Pepper et al., 2008	
Qiong et al., 2012	Brooks et al., 2007	
Land, 2012	Gaskin et al., 2013	
Esseili et al., 2012	Contin et al., 2012	
Korboulewsky et al., 2002	Gottschall et al., 2012	
Mantovi et al., 2005	Gottschall et al., 2013	
Maguire et al., 2000	Roig et al., 2012	
Wang et al., 2008	Jin et al., 2011	
Katanda et al., 2007		

*SPH= research articles that support the controversy that the use of biosolids for soil enrichment and restoration poses significant harm to the environment, human and animals health

*SPNH=research articles that support the controversy that the use of biosolids for soil enrichment and restoration do not pose significant harm to the environment, human and animal health

*INC=research articles that are inconclusive on the controversy that the use of biosolids for soil enrichment and restoration is beneficial or harmful to the environment, human and animal health effect of land application of biosolids

Table 5.3 shows the list of peer-reviewed research articles that were studied for the purpose of this work. The articles provide scientific evidence on the effect of land application of biosolids as it relate to heavy metals concentration in soil, air and surface and groundwater pollution.

A total of 34 peer-reviewed research articles were studied in respect to the danger of land-applying biosolids for soil enrichment as it relates to heavy metals concentration, soil, air and surface and groundwater pollution. Out of the 34 research articles studied, 15 or about 44% support the claim that land application of biosolids can lead to air pollution, heavy metals concentration in the soil with consequent soil

surface and groundwater pollution. Also, there were 14 or about 41% of the articles that support the claim that land application of biosolids does not significantly lead to air pollution, or heavy metal concentration in soil. They also reported little or no serious pollution problems to surface and groundwater from land application of biosolids. A total of 5 or about 15% of the articles could not categorically say that land application of biosolids can lead to substantial heavy metal concentration, air pollution and pollution of surface and groundwater.

The breakdown on the findings from the articles studied in respect to heavy metal concentration, air pollution and surface and groundwater pollution from land application of biosolids are presented in the pie chart below (Figure 5.3).

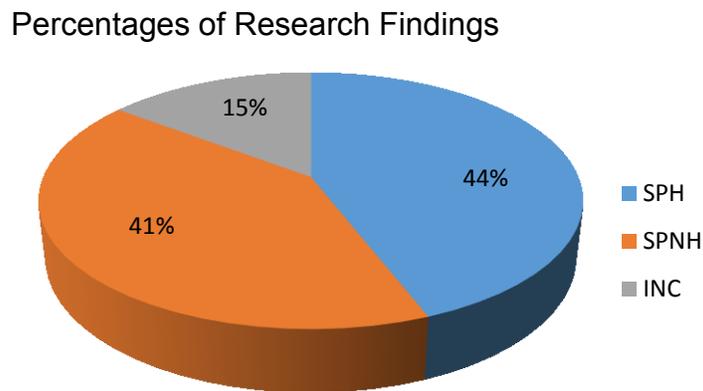


Figure 5.3: Pie chart showing the percentage of research articles that presented scientific evidence on the effect of land application of biosolids in respect to heavy metals, soil, air and surface and groundwater pollution

Table 5.4: List of all research articles studied on the environmental and health effects of land application of biosolids

SPH	SPNH	INC
Morais et al., 2013	Jones et al., 2014	Jjemba, 2002
Smith, 2009	Rhind et al., 2013	Andrade et al., 2010
Laguardia et al., 2001	Sabourin et al., 2009	Eriksson et al., 2008
McClellan and Halden, 2010	Xia et al., 2010	Harrison et al., 2006
Cha and Cupples, 2009	Langdon et al., 2012	Clarke and Smith, 2011
Sepulvado et al., 2011	Topp et al., 2008	Zaleski et al., 2005
Judy et al., 2011	Schowaneck et al., 2007	Carbonell et al., 2009
Li et al., 2013	Bright and Healey, 2003	Adair et al., 2014
Ying and Kookana, 2006	Higgins et al., 2011	McBride, 2003
Walters et al., 2010	Yang et al., 2011	Oleszczuk & Hollert, 2011
Snyder and O'Connor, 2013	Cincinelli et al., 2012	Shah et al., 2014
Davis et al., 2012	Ziemba et al., 2013	
Wu et al., 2012		
Kinney et al., 2008	Tanner et al., 2008	
Kinney et al., 2012	Brooks et al., 2005	
Wu et al., 2010	McFarland et al., 2012	
Venkatesan and Halden, 2014	Aryal and Reinhold, 2011	
Shober et al., 2003	Rusin et al., 2003	
Lowman et al., 2013	Rhind et al., 2011	
Lewis et al., 2002	Jenkins et al., 2007	
Harrison and Oakes, 2002	Benjamin et al., 2005	

*SPH= research articles that support the controversy that the use of biosolids for soil enrichment and restoration poses significant harm to the environment, human and animals health

*SPNH=research articles that support the controversy that the use of biosolids for soil enrichment and restoration do not pose significant harm to the environment, human and animal health

*INC=research articles that are inconclusive on the controversy that the use of biosolids for soil enrichment and restoration is beneficial or harmful to the environment, human and animal health effect of land application of biosolids

Table 5.4 shows the list of all the peer-reviewed research articles that were studied for the purpose of this work.

In all, a total of 86 peer-reviewed research articles were studied to investigate the environmental and health implications from land application of biosolids. This investigation was conducted in an attempt to provide scientific evidence on whether

land application of biosolids poses substantial danger to the environment, and the people, and other living organisms that live near such operational sites.

Table 5.4: Continued.

SPH	SPNH	INC
Brooks et al., 2006	Hazard et al., 2014	
Schwarz et al., 2014	Tian et al., 2006	
Muchuweti et al., 2006	Tian et al., 2013	
Lind et al., 2010	Wang et al., 2004	
Hombach-Klonisch et al., 2013	Zerzghi et al., 2010	
Khuder et al., 2007	Pepper et al., 2008	
Latare et al., 2014	Brooks et al., 2007	
Lindstrom et al., 2011	Gaskin et al., 2013	
Giudice & Young, 2011	Contin et al., 2012	
Waterhouse et al., 2014	Gottschall et al., 2012	
Sablayrolles et al., 2010	Gottschall et al., 2013	
Egiarte et al., 2008	Roig et al., 2012	
Schroder et al., 2008	Jin et al., 2011	
Qiong et al., 2012		
Land, 2012		
Esseili et al., 2012		
Korboulewsky et al., 2002		
Mantovi et al., 2005		
Maguire et al., 2000		
Wang et al., 2008		
Katanda et al., 2007		

*SPH= research articles that support the controversy that the use of biosolids for soil enrichment and restoration poses significant harm to the environment, human and animals health

*SPNH=research articles that support the controversy that the use of biosolids for soil enrichment and restoration do not pose significant harm to the environment, human and animal health

*INC=research articles that are inconclusive on the controversy that the use of biosolids for soil enrichment and restoration is beneficial or harmful to the environment, human and animal health effect of land application of biosolids

Out of a total of 86 research articles studied, 42 or about 49% support the assertion that land application of biosolids pose substantial harm to the environment,

human and animal health. Also, 33 or about 38% of the articles studied support the assertion that land application of biosolids does not pose significant harm to the environment, human and animal health. A total of 11 or about 13% of the articles could not categorically say that land application of biosolids can lead to substantial harm to the environment, human and animal health.

The breakdown on the findings from the articles studied in respect to the environmental, human and animal health implications from applying biosolids to land for soil restoration and enrichment are summarized in the pie chart in Figure 5.3.

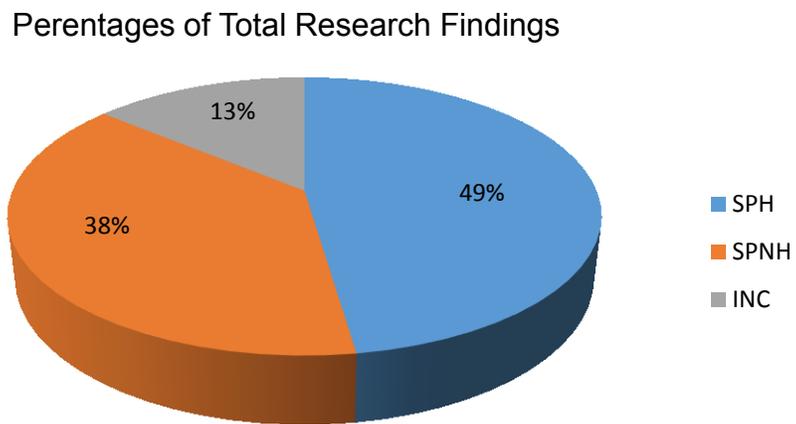


Figure 5.4: Pie chart showing total percentage of scientific evidence from all three categories on the environmental and health effects of land application of biosolids

Table 5.5: Scientific evidence from research conducted in the U.S. on the environmental and health effects of land application of biosolids

SPH	SPNH	INC
Shober et al., 2003	Ziemba et al., 2013	Harrison et al., 2006
Lowman et al., 2013	Benjamin et al., 2005	Zaleski et al., 2005
Lindstrom et al., 2011	Tanner et al., 2008	McBride, 2003
Venkatesan et al., 2014	Higgins et al., 2011	Andrade et al., 2010
Giudice & Young, 2011	Tian et al., 2006	Jjemba, 2002
Wu et al., 2010	Tian et al., 2013	Shah et al., 2014
Kinney et al., 2012	Zerzghi et al., 2010	
Lewis et al., 2002	Pepper et al., 2008	
Davis et al., 2012	Brooks et al., 2005	
Snyder & O'Connor, 2013	Brooks et al., 2007	
Harrison & Oakes, 2002	Gaskin et al., 2003	
Walters et al., 2010	Xia et al., 2010	
Judy et al., 2011	McFarland et al., 2012	
Schroder et al., 2008	Aryal & Reinhold, 2011	
Brooks et al., 2006	Rusin et al., 2003	
Sepulvado et al., 2011	Jenkins et al., 2007	
Cha & Cupples, 2009	Jin et al., 2011	
McClellan & Halden, 2010		
Land, 2012		
Laguardia et al., 2001		
Esseili et al., 2012		
Maguire et al., 2000		
Khuder et al., 2007		
Kinney et al., 2008		

*SPH= research articles that support the controversy that the use of biosolids for soil enrichment and restoration poses significant harm to the environment, human and animals health

*SPNH=research articles that support the controversy that the use of biosolids for soil enrichment and restoration do not pose significant harm to the environment, human and animal health

*INC=research articles that are inconclusive on the controversy that the use of biosolids for soil enrichment and restoration is beneficial or harmful to the environment, human and animal health effect of land application of biosolids

Table 5.5 shows all U.S. peer-reviewed research articles that were studied for the purpose of this work. These articles are included in the total of the 86 articles studied for the entire thesis.

After comprehensively reading through the 86 articles and classifying them into the three categories of significantly harmful to the environment, human and animal health (SPH), not significantly harmful (SPNH) and inconclusive (INC), as earlier mentioned, about 49% of the articles supported the assertion that land application of biosolids poses significant harm to the environment, human and animal health as opposed to about 38% which supports that biosolids poses insignificant harm to the environment, human and animal health. The high percentage of support for harmful effect led me to separate the U.S. articles for further examination. My prediction was that the result could be different since I assumed the U.S. biosolids regulations were stringent as compared to the rest of the world thereby resulting in lesser environmental effect, but the results proved me wrong.

A total of 47 studies were conducted in the U.S. Out of the 47 studies, 24 or about 51% support the assertion that land application of biosolids poses substantial harm to the environment, human and animal health. While 17 or about 36% of the articles support the assertion that land application of biosolids do not pose significant danger to the environment, human and animal health. On the other hand and following the same pattern, 6 or about 13% of the articles also could not categorically say that land application of biosolids can lead to substantial harm to the environment, human and animal health.

The breakdown on the findings from review of the U.S. articles studied in respect to the environmental, human and animal health implications of land application of biosolids is shown in Figure 5.5.

Percentages of U.S Research Findings

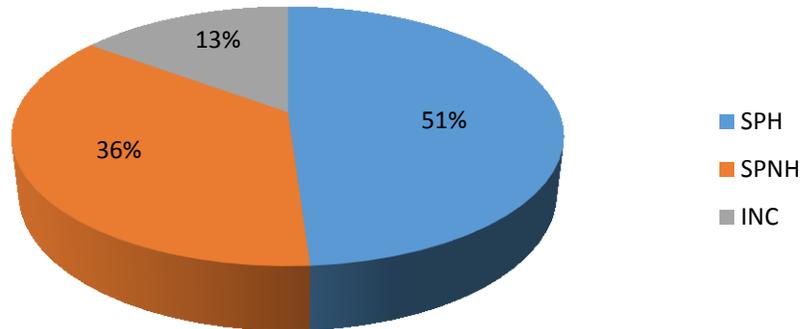


Figure 5.5: Pie chart showing total percentage of scientific evidence from research conducted in the U.S. on the environmental and health effects of land application of biosolids

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

The study involved comprehensive review of scientific literature, covering a 15-year period from 1999 to 2014, on the practice of land application of biosolids and its impact on the environment, human and animal health. The objective of the study was to provide scientific evidence on whether the use of biosolids for soil restoration and enrichment poses significant harm to the environment, human and animal health. The study was also undertaken to make such information handy for decision makers for recommending use of biosolids to provide the much needed soil nutrients for growing crops and restoring degraded land.

Based on the research articles reviewed and analyzed for this work, it is evident that the majority of the studies suggest that the practice of land application of biosolids poses significant harm to the environment, and other living organisms including human and animals that come in close contact with such sites. This conclusion is supported by about 49% of the 86 articles reviewed from across the globe as compared to 38% that suggest that the practice does not pose significant harm. When research works conducted in the U.S. were extracted from the rest of the studies from across the globe, about 51% also suggest that the practice of land application of biosolids is indeed harmful to the environment, human and animal health as compared to about 36% that suggest that the practice is not so harmful.

After reviewing the 86 research articles on the issue, I am of the opinion that the controversy of whether land application of biosolids is good or bad for the ecosystem would continue at least into the coming decades. When biosolids are land applied, many factors come into play in respect to how its components are released and affect the entire ecosystem. This is because the complex interactions of toxic

chemicals, soil nutrients and other components in biosolids on the environment have not yet been well understood, leading to the controversy.

Based on the findings of this study, it appears that pathogens and PPCPs are the two most critical substances that pose serious threat to the ecosystem from the use of biosolids. Accordingly, it would be prudent to undertake the following studies to:

1. Develop new wastewater treatment process that will detect and remove pharmaceutical products and other harmful substances that are not being trapped or removed by existing wastewater technologies, thereby ending up in the environment, and
2. Improve the current USEPA method of “process to significantly reduce pathogens (PSRPs)”¹ for Class B biosolids. This will further reduce or eliminate pathogens to environmentally-safe level in treated biosolids destined for land application.

¹USEPA, (1999), defines PSRPs as a process that consistently reduces the density of pathogenic bacteria, viruses, and/or parasites (number/gram of biosolids on a dry weight basis) in mixed sludge from a conventional plant by equal to or greater than 1 log (base 10). There are five PSRPs: aerobic and anaerobic digestion, air drying, composting, and lime stabilization. Under Part 503.32(b)(3), sewage sludge meeting the requirements of these processes is considered to be Class B with respect to pathogens. The treatment processes reduce fecal coliform densities to less than 2 million colony-forming unit (CFU) or most probable number (MPN) per gram of total solids (dry weight basis) and reduce *Salmonella* sp. and enteric virus densities in sewage sludge by approximately a factor of 10. Currently, to minimize impact on the environment and to maintain public health, additional restrictions are required for land application of PSRP treated biosolids. Some of these measures include restricting the public’s access to the land application site and preventing crop harvesting for a certain amount of time so that the pathogens naturally attenuate to below the detection limit.

APPENDIX 1

ENVIRONMENTAL PROTECTION AGENCY PART 503 BIOSOLIDS RULES

Subpart A (General Requirements for Biosolids Use)

Subpart A of the rule covers general provisions, such as the purpose and applicability of the rule, the compliance period, and exclusion from the rule. These general provisions apply to each of the three biosolids disposal practices.

Subpart B (Requirements for Land Application)

Options for Land Application of Biosolids under Subpart B:

Subpart B of the rule specifies requirements for biosolids applied to land. The term “apply” means to put biosolids on the land to take advantage of the nutrient content or soil conditioning properties of the biosolids. The requirements for land application also pertain to material derived from biosolids; i.e. biosolids that have undergone a change in quality through treatment (e.g., composting) or by mixing with other materials (e.g., wood chips, municipal solid waste, yard waste).

The biosolids land application requirements, which are explained in detail in Chapter Two of “A Plain English Guide to the USEPA Part 503 Biosolids Rule”, are summarized below. There are several options for land applying biosolids under Subpart B of the Part 503 rule, all of which are equally protective of human health and the environment. This guidance discusses these options in order of increasing regulatory complexity:

Exceptional Quality Biosolids Although not explicitly defined in the Part 503 rule, this document uses the term Exceptional Quality (EQ) to characterize biosolids that meet low-pollutant and Class A pathogen reduction (virtual absence of pathogens) limits and that have a reduced level of degradable compounds that attract vectors.

Once the requirements discussed in detail in Chapter Two are met, EQ biosolids are considered a product that is virtually unregulated for use, whether used in bulk, or sold or given away in bags or other containers.

Pollutant Concentration Biosolids Although not explicitly defined in the Part 503 rule, this document uses the term Pollutant Concentration (PC) to refer to biosolids that meet the same low-pollutant concentration limits as EQ biosolids, but only meet Class B pathogen reduction and/or are subjected to site management practices rather than treatment options to reduce vector attraction properties. Unlike EQ biosolids, PC biosolids may only be applied in bulk and are subject to general requirements and management practices; however, tracking of pollutant loadings to the land is not required.

A majority of the biosolids currently generated in the United States are believed to be EQ or PC biosolids containing low levels of pollutants. The USEPA expects that many municipalities will strive to produce EQ or PC biosolids because of the reduced regulatory requirements and the anticipated improved public perception about using EQ and PC biosolids beneficially. Cumulative levels of pollutants added to land by EQ or PC biosolids do not have to be tracked because the risk assessment has shown that the life of a site would be at least 100 to 300 years under the conservative parameters assumed.

Cumulative Pollutant Loading Rate (CPLR) Biosolids CPLR biosolids typically exceed at least one of the pollutant concentration limits for EQ and PC biosolids but meet the ceiling concentration limits as discussed in Chapter Two. Such biosolids must be applied to land in bulk form. The cumulative levels of biosolids pollutants applied to each site must be tracked and cannot exceed the CPLR.

Annual Pollutant Loading Rate (APLR) Biosolids APLR biosolids are biosolids that are sold or given away in a bag or other container for application to the

land that exceed the pollutant limits for EQ biosolids but meet the ceiling concentration limits as discussed in Chapter Two. These biosolids must meet APLR requirements and must be accompanied by specific biosolids application rate information on a label or handout that includes instructions on the material's proper use.

Options for Using or Disposing of Domestic Septage under Subpart B: If domestic septage is applied to land with a high potential for contact by the public (e.g., public parks, ball fields, cemeteries, plant nurseries, and golf courses), the Part 503 land application requirements apply. However, when domestic septage is applied to nonpublic contact sites (e.g., agricultural land, forests, and reclamation sites), less burdensome requirements may apply. A separate USEPA guidance document, entitled Domestic Septage Regulatory Guidance: A Guide to the USEPA 503 Rule, provides detailed on these requirements.

Subpart C (Requirement for Sewage Sludge Placed on a Surface Disposal Site)

Subpart C of the rule covers requirements for biosolids-including domestic Septage-placed on a surface disposal site.

Placement refers to the act of putting biosolids on a parcel of land at high rates for final disposal rather than using the organic content in the biosolids to condition the soil or using the nutrients in the biosolids to fertilize crops. Placing biosolids in a monofill, in a surface impoundment, on a waste pile, or on a dedicated site is considered surface disposal.

Treatment and storage of biosolids are not considered surface disposal. Treatment is the preparation of biosolids for final use or disposal through such activities as thickening, stabilization, and dewatering. Storage is the placement of biosolids on the land for 2 years or less. Placement on land for longer than 2 years is considered

surface disposal unless the site owner/operator retains written records demonstrating clearly to the permitting authority that the area of land onto which biosolids are placed is not a surface disposal site but rather, based on management or operational practices, constitutes a treatment or temporary storage site.

Surface disposal requirements and the difference between disposal, treatment, and storage of biosolids are explained in Chapter Three of the Plain English Guide to the USEPA Part 503 Biosolids Rule.

Certain materials derived from biosolids, the quality of which has been changed by treating the biosolids or by mixing them with other materials (e.g., wood chips), are subject to the surface disposal requirements in Part 503 with one exception. If biosolids are mixed with nonhazardous solid wastes, the mixture and the land onto which the mixture is placed are subject to the solid waste regulations (40 CFR Part 258) instead of Part 503

Subpart D (Requirement for Pathogen and Vector Attraction Reduction

Subpart D of the Part 503 rule covers requirements for the control of disease-causing organisms, called pathogens, in biosolids and the reduction of the attractiveness of biosolids to vectors, such as flies, mosquitoes, and other potential disease-carrying organisms. These requirements are described in Chapter Five of this document. Pathogen and vector attraction reduction requirements also are briefly described for biosolids applied to land or placed on a surface disposal site in Chapters Two and Three of this document.

Subpart E (Requirements for Sewage Sludge Fired in a Sewage Sludge Incinerator)

Subpart E of the rule covers the requirements for biosolids fired in a biosolids incinerator. The firing of biosolids with auxiliary fuels also is covered by the Part 503

incineration requirements. Auxiliary fuel materials include gas, oil, coal, and other materials that serve as a fuel source.

The co-firing of biosolids in an incinerator with other wastes is generally not regulated under Part 503. It should be noted, however, that wastes either in auxiliary fuel or mixed and co-fired with biosolids are considered to be auxiliary fuel when the weight is less than or equal to 30 percent (by dry weight) of the total biosolids and auxiliary fuel mixture. The requirements in

Subpart E for biosolids incineration are discussed in Chapter Four. The February 25, 1994, amendment to the Part 503 rule states that under certain conditions USEPA will allow continuous monitoring of carbon monoxide emissions from biosolids incinerators as an alternate to continuous monitoring of total hydrocarbons in emissions.

REFERENCES

- Adair, K. L., Wratten, S., Barnes, A. M., Waterhouse, B. R., Smith, M., Lear, G., Weber, P., Pizey, M., Boyer, S. (2014). Effects of biosolids on biodiesel crop and belowground communities. *Ecological Engineering* 68, 270-278.
- ADB (Asia Development Bank), (2012). Promoting beneficial sewage sludge utilization in the People's Republic of China. ISBN 978-92-9092-654-2, (print), 978-92-9092-655-9 (pdf).
- Andrade, N. A., McConnell, L. L., Torrent, A., Ramirez, M. (2010). Persistence of polybrominated diphenyl ethers in agricultural soils after biosolids application. *J. Agric. Food Chem.* 58, 3077-3084.
- Adriaanse, L. S., and Rensleigh, C., (2011). Comparing Web of Science, Scopus and Google Scholar from an environmental sciences perspective. *South African Journal of Library & Information Science.* 77(2), 169-178. Accessed May, 2015. Available at: http://www.sabinet.co.za/abstracts/liasa/liasa_v77_n2_a8.html.
- Appels, L., Baeyes, J., Degreve, J., Dewil, R. (2008). Principles and potential of the anaerobic digestion of waste-activated sludge. *Progress in Energy and Combustion Science* 4, 755-781.
- Aristilde, L., Melis, A., Sposito, G. (2010). Inhibition of photosynthesis by a fluoroquinolone antibiotic. *Environ. Sci. Technol.* 44, 1444-1450.
- Aryal, N., & Reinhold, D. M. (2011). Phytoaccumulation of antimicrobials from biosolids: Impacts on environmental fate and relevance to human exposure. *Water Research* 45, 5545-5552.
- Barbusinski, K., Koscielniak, H. (1997). Activated sludge floc structure during aerobic digestion. *Water Science and Technology* 36(11), 107-114.
- Basta, N. T. (1995). Land application of biosolids: A review of research concerning benefits, environmental impacts, and regulations of applying treated sewage

- sludge. Sewage sludge composition and transformations. Available at: <http://pods.dasnr.okstate.edu/docushare/dsweb/Get/Document-3109/B-808.pdf>. Accessed December, 2013. p. 5.
- Bernard, S. Gray, N. F., (2000). Aerobic digestion of pharmaceutical and domestic wastewater sludges at ambient temperature. *Water Research* 34(3), 725-734.
- Bright, D. A., & Healey, N. (2003). Contaminant risks from biosolids land application: Contemporary organic contaminant levels in digested sewage sludge from five treatment plants in Greater Vancouver, British Columbia. *Environmental Pollution* 126, 39-49.
- Brooks, J. P., Mazwell, S. L., Rensing, C., Gerba, C. P., Pepper, I. L. (2007). Occurrence of antibiotic-resistant bacteria and endotoxin associated with the land application of biosolids. *Canadian Journal of Microbiology* 53(5), 616-622.
- Brooks, J. P., Tanner, B. D., Gerba, C. P., Pepper, I. L. (2006). The measurement of aerosolized endotoxin from land application of Class B biosolids in Southeast Arizona. *Canadian Journal of Microbiology* 52(2), 150-156.
- Brooks, J. P., Tanner, B. D., Josephson, K. L., Gerba, C. P., Haas, C. N., Pepper, I. L. (2005). A national study on the residential impact of biological aerosols from the land application of biosolids. *Journal of Applied Microbiology* 99, 310-322.
- Bunger, J., Antlauf-Lammers, M., Schulz, T. G., Westphal, G. A., Muller, M. M., Ruhnau, P., Hallier, E., (2000). Health complaints and immunological markers of exposure to biosolids among biowaste collectors and compost workers. *Occupational Environmental Medicine* 57(7), 458-464.
- Burton, N. C., Trout, D., (1999). NIOSH health hazard evaluation report: Biosolids land application process, LeSourdsville, Ohio. HETA 98-0118-2748. U.S. department of health and human services, public health service, centers for disease control and prevention, national institute for occupational safety and health.

- Carbonell, G., Pro, J., Gomez, N., Babin, M. M., Fernandez, C., Alonso, E. Tarazona, J. V. (2009). Sewage sludge applied to agricultural soil: Ecotoxicological effects on representative soil organisms. *Ecotoxicological and Environmental Safety* 72, 1309-1319.
- CEC (Council of the European Communities) (1986). Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture. Available at: <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31986L0278>. Accessed March 20, 2014.
- CEC (Council of the European Communities). (1991). Council directive of 21 May 1991 concerning urban wastewater treatment (91/27/EEC). Available at: <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31991L0271>. Accessed April 10, 2014.
- Cha, J., & Cupples, A. M. (2009). Detection of the antimicrobials triclocarban and triclosan in agricultural soils following land application of municipal biosolids. *Water Research* 43, 2522-2530.
- Cincinelli, A., Martellini, T., Misuri, L., Lanciotti, E., Sweetman, A., Laschi, S., Palchetti, I. (2012). PBDEs in Italian sewage sludge and environmental risk of using sewage sludge for land application. *Environmental Pollution* 161, 229-234.
- Citulski, J. A., & Farahbakhsh, K. (2010). Fate of endocrine-active compounds during municipal biosolids treatment: A review. *Environ. Sci. Technol.* 44(22), 8367-8376.
- Clarke, B. O., & Smith, S. R. (2011). Review of 'emerging' organic contaminants in biosolids and assessment of international research priorities for the agricultural use of biosolids. *Environment International* 37, 226-247.

- Clarke, B. O., Porter, N., Symons, R., Marriot, P., Ades, P., Stevenson, G., Blackbeard, J. (2008). Polybrominated diphenyl ethers and polybrominated biphenyls in Austrian sewage sludge. *Chemosphere* 73(6), 980-989.
- Contin, M., Goi, D., De Nobili, M. (2012). Land application of aerobic sewage sludge does not impair methane oxidation rates of soils. *Science of the Total Environment* 441, 10-18.
- D' Abrosca, B., Fiorentino, A., Izzo, A., Cefarelli, G., Pascarella, M. T., Uzzo, P., Monaco, P. (2008). Phytotoxicity evaluation of five pharmaceutical pollutants detected in surface water on germination and growth of cultivated and spontaneous plants. *J. Environ. Sci. Health, Part A: Environ. Sci. Eng. Toxic Hazard Subst. Control* 43, 285-294.
- Davis, E. F., Klosterhaus, S. L., Stapleton, H. M. (2012). Measurement of flame retardants and triclosan in municipal sewage sludge and biosolids. *Environment International* 40, 1-7.
- Davis, R. D., 1996. The impact of EU and U.K. environmental pressures on the future of sludge treatment and disposal. *Journal. CIWEN*. 10, 65-69.
- de Jonghe, F. and Swinkels, J. (1997). Selective Serotonin Reuptake Inhibitors. *CNS Drugs*, 7(6), 452-467.
- Egiarte, G., Pinto, M., Ruiz-Romera, E., Arbostai, M. C. (2008). Monitoring heavy metal concentrations in leachates from a forest soil subjected to repeated application of sewage sludge. *Environmental Pollution* 156, 840-848.
- Eriksson, E., Christensen, N., Schmidt, J. E., Ledin, A. (2008). Potential priority pollutants in sewage sludge. *Desalination* 226, 371-388.
- Esseili, M. A., Kassem, I. I., Sigler, V., Czajkowski, K., Ames, A. (2012). Genetic evidence for the offsite transport of E. coli associated with land application of Class B biosolids on agricultural fields. *Science of the Total Environment* 433, 273-280.

- Evanylo, G. K., (1999). Agricultural land application of Biosolids in Virginia: Regulations. Crop and Soil Environmental Sciences publication 452-302. Available at: <http://poultryems.ag.vt.edu/assessment/biosolids.pdf>. Accessed May, 2014. pp. 1-8.
- Fannin, K. F., Cochran, K. W., Lamphiear, D. E., Monto, A. S., (1980). Acute illness differences with regard to distance from the Tecumseh, Michigan, wastewater treatment plant. pp. 117-135 in wastewater aerosols and disease proceedings of a symposium, September 19-21, 1979, H.R Pahren and W. Jakubowski, eds. USEPA-600/9-80-028. NTIS PB81169864. Health effects research laboratory, office of research and development, U.S. Environmental Protection Agency, Cincinnati, OH.
- Fent, K., Weston, A. A., Caminada, D. (2006). Ecotoxicology of human pharmaceuticals. *Aquat. Toxicol.*, 76, 122-159.
- IEEP (Institute for European Environmental Policy), (2009). A report on the implementation of Directive 75/442/EEC on waste. Available at: http://ec.europa.eu/environment/waste/reporting/pdf/Waste_Framework_Directive.pdf. Accessed April, 2014. p. 1-85.
- Iranpour, R., Cox, J. H. H., Kearney, R. J., Clark, H. J., Pincince, A. B., Daigger, G. T. (2004). Regulations for biosolids land application in U.S. and European Union. Review. *Journal of Residuals Science and Technology* 1(4), 209-222.
- García-Peréz, M. A., (2010). Accuracy and completeness of publication and citation records in the Web of Science, PsycINFO, and Google Scholar: a case study for the computation of h indices in Psychology. *Journal of the American Society for Information Science & Technology*. 61(10), 2070-2085. Accessed May, 2015. Available at: <http://onlinelibrary.wiley.com/doi/10.1002/asi.21372/full>

- Gaskin, J. W., Brobst, R. B., Miller, W. P., Tollner, E. W. (2003). Long-term biosolids application effects on metal concentration in soil and bermudagrass forage. *Journal of Environmental Quality* 32(1), 146-152.
- Girovich, M. J. Biosolids treatment and management: Processes for beneficial use. Environmental Science & Pollution. 1996, ISBN-13: 978-0824797065.
- Giudice, B. D., & Young, T. M. (2011). Mobilization of endocrine disrupting chemicals and estrogenic activities in simulated rainfall runoff from land-applied biosolids. *Environ. Toxicol. Chem.* 30(10), 2220-2228.
- Gottschall, N., Topp, E., Edwards, M., Payne, M., Kleywegt, S., Russell, P., Lapen, D. R. (2013). Hormones, sterols, and fecal indicator bacteria in groundwater, soil, and subsurface drainage following a high single application of municipal biosolids to a field. *Chemosphere* 91, 275-286.
- Gottschall, N., Topp, E., Metcalfe, C., Edwards, M., Payne, M., Kleywegt, S., Russell, P., Lapen, D. R. (2012). Pharmaceutical and personal care products in groundwater, subsurface drainage, soil, and wheat grain, following a high single application of municipal biosolids to a field. *Chemosphere* 87, 194-203.
- Hall, J. E. (1995). Sewage sludge production, treatment and disposal in the European Union. *Water and Environment Journal* 9(4), 335-343.
- Hall, S. (2000). Environmental sound technologies in wastewater treatment for the implementation of the UNEP Global Programme of Action (GPA). Guidance on municipal wastewater. Available at:
http://www.sswm.info/sites/default/files/reference_attachments/UNEP%202004%20ENVIRONMENTALLY%20SOUND%20TECHNOLOGIES%20in%20wastewater%20treatment.pdf. Accessed November, 2013.

- Harrison, E. Z., & Oakes, S. R. (2002). Features: Investigation of alleged health incidents associated with land application of sewage sludges. *Journal of Environmental and Occupational Health Policy* 12(4), 387-408.
- Harrison, E. Z., Oakes, S. R., Hysell, M., Hay, A. (2006). Organic chemicals in sewage sludges. *Science of the Total Environment* 367, 481-497.
- Harrison, E. Z., McBride, M. B., Boudin, D. R. (1999). Land application of sewage sludges: an appraisal of the U.S. regulations. *Int. J. Environmental and Pollution* 11(1), 1-36.
- Hazard, C., Boots, B., Keith, A. M., Mitchell, D. T., Schmidt, O., Doohan, F. M., Bending, G. D. (2014). Temporal variation outweighs effects of biosolids application in shaping arbuscular mycorrhizal fungi communities on plants grown in pasture and arable soils. *Applied Soil Ecology* 82, 52-60.
- Higgins, C. P., Paesani, Z. J., Chalew, T. E. A., Halden, R. U., Hundal, L. S. (2011). Persistence triclocarban and triclosan in soils after land application of biosolids and bioaccumulation in *Eisenia foetida*. *Environ. Toxicol. Chem.* 30(3), 556-563.
- Hill, J. (2005). Recycling biosolids to pasture-based animal production systems in Australia: A review of evidence on the control of potentially toxic metals and persistent organic compounds recycled to agricultural land. *Australian Journal of Agricultural Research* 56(8), 753-773.
- Hombach-Klonisch, S., Danescu, A., Begum, F., Amezaga, M. R., Rhind, S. M., Sharpe, R. M., Evans, N. P., Bellingham, M., Cotinot, C., Mandon-Pepin, B., Fowler, P. A., Klonisch, T. (2013). Peri-conceptual changes in maternal exposure to sewage sludge chemicals disturb fetal thyroid gland development in sheep. *Molecular and Cellular Endocrinology* 367, 98-108.
- Hope, J. (1986). Sewage sludge disposal and utilization study. Washington State for Public Policy. Available at:

- https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0CC8QFjAA&url=http%3A%2F%2Fwww.wsipp.wa.gov%2Frpfiles%2Fsewage.pdf&ei=248tVJOPDYeiyQSCI4GICw&usq=AFQjCNE7tj-iChYnMLf85JVICdYTCd_sbQ&bvm=bv.76477589,d.aWw. Accessed November, 2013.
- Jjemba, P. K., (2002). The potential impact of veterinary and human therapeutic agents in manure and biosolids on plants grown on arable land: A review. *Agriculture, Ecosystems and Environment* 93, 267-278.
- Jenkins, S. R., Armstrong, C. W., Monti, M. M., (2007). Health effects of biosolids applied to land: Available scientific evidence. Available at: <http://www.vdh.state.va.us/epidemiology/DEE/documents/Biosolidsfinal.pdf>. Accessed September, 2014.
- Jewell, W. J., & Seabrook, B. L. (1979). A history of land application as a treatment alternative: Technical Report. USEPA 430/9-79-012 U. S. Environmental Protection Agency, Office of Water Program Operation, Washington, D.C.
- Jin, V. L., Johnson, M-V. V., Haney, R. L., Arnold, J. G. (2011). Potential carbon and nitrogen mineralization in soils from a perennial forage production system amended with Class B biosolids. *Agriculture, Ecosystem and Environment* 141, 461-465.
- Johnson, D.E., Camann, D. E., Register, J. W., Prevost, R. J., Tillery, J. B., Thomas, R. E., Taylor, J. M., Hosenfeld, J. M., (1980). Health effects from wastewater aerosols at a new activated sludge plant: John Egan plant, Schaumburg, Illinois. pp. 136-159 in wastewater aerosols and disease proceedings of a symposium, September 19-21, 1979, H.R. Pahren, and W. Jakubowski, eds. USEPA-600/9-80-028. NTIS PB81-169864. Health effects research laboratory, office of research and development, U.S. Environmental Protection Agency, Cincinnati, OH.

- Jones, V., Gardner, M., Ellor, B. (2014). Concentrations of trace substances in sewage sludge from 28 wastewater treatment works in the U.K. *Chemosphere* 111, 478-484.
- Joshua, W. D., Michalk, D. L., Curtis, I. H., Salt, M., Osborne, J. G. (1998). The potential for contamination of soil and surface water from sewage sludge (biosolids) in a sheep grazing study, Australia. *Geoderma* 84(1-3), 135-156.
- Judy, J. D., Unrine, J. M., Bertsch, P. M. (2011). Evidence for biomagnification of gold nanoparticles within a terrestrial food chain. *Environ. Sci. Technol.* 45, 776-781.
- Katanda, Y., Mushonga, C., Banganayi, F., Nyamangara, J. (2007). Effects of heavy metals contained in soil irrigated with mixture of sewage sludge ad effluent for thirty years on soil microbial biomass and plant growth. *Physics and Chemistry of the Earth* 32, 1185-1194.
- Khuder, S., Milz, S. A., Bisesi, M., Vincent, R., McNulty, W., Czajkowski, K., (2007). Health survey of residents living near farm fields permitted to receive biosolids. *Archives of Environmental and Occupational Health* 62(1), 5-11.
- King, F. H., (1911.) *Farmers of Forty Centuries, or Permanent Agriculture in China, Korea and Japan.* Wisconsin, USA.
- Kinney, C. A., Campbell, B. R., Thompson, R., Furlong, E. T., Kolpin, D. W., Burkhardt, M. R., Zaugg, S. D., Werner, S. L., Hay, A. G. (2012). Earthworm bioassays and seedling emergence for monitoring toxicity, aging and bioaccumulation of anthropogenic waste indicator compounds in biosolids-amended soil. *Science of the Total Environment* 433, 507-515
- Kinney, C. A., Furlong, E. T., Kolpin, D. W., Burkhardt, M. R., Zaugg, S. D., Werner, S. L., (2008). Bioaccumulation of pharmaceuticals and other anthropogenic waste indicators in earthworms from agricultural soil amended with biosolids or swine manure. *Environ. Sci. Technol.*, 42, 1863-1870.

- Korboulewsky, N., Dupouyet, S., Bonin, G. (2002). Environmental risks of applying sewage sludge compost to vineyards. *Journal of Environmental Quality* 31(5), 1522-1527.
- Krause, R. (1985). Physical properties of soil improved by organic sludge.
- La Guardia, M. J., Hale, R. C., Harvey, H., Mainor, T. M. (2001). Alkylphenol ethoxylate degradation products in land-applied sewage sludge (biosolids). *Environ. Sci. Technol.* 35, 4798-4804
- Land, L. S. (2012). Chesapeake Bay nutrient pollution: Contribution from the land application of sewage sludge in Virginia. *Marine Pollution Bulletin* 64, 2305-2308.
- Langdon, K. A., Warne, M. St. J., Smernik, R. J., Shareef, A., Kookana, R. S. (2012). Field dissipation of 4-nonylphenol, 4-t-octylphenol, triclosan and bisphenol A following land application of biosolids. *Chemosphere* 86, 1050-1058
- Latare, A. M., Kumar, O., Singh, S. K., Gupta, A. (2014). Direct and residual effect of sewage sludge on yield, heavy metals content and soil fertility under rice-wheat system. *Ecological Engineering* 69, 17-24.
- Levine-Clark, M., and Kraus, J., (2007). Finding chemistry information using Google Scholar: a comparison with Chemical Abstracts Service. *Science & Technology Libraries.* 27(4), 3-17. Accessed May, 2015. Available at: http://www.tandfonline.com/doi/abs/10.1300/J122v27n04_02.
- Lewis, D. L., Gattie, D. K., Novak, M. E., Sanchez, S., Pumphrey, C. (2002). Interactions of pathogens and irritant chemicals in land-applied sewage sludge (biosolids). *BMC Public Health* 2(11), 1471-2458.
- Li, H., Helm, P. A., Metcalfe, C. D. (2010). Sampling in the Great Lakes for pharmaceuticals, personal care products, and endocrine-disrupting substances using the passive polar organic chemical integrative sampler. *Environ. Toxicol. Chem.* 29, 751-762.

- Li, H., Sumarah, M. W., Topp, E. (2013). Persistence and dissipation pathways of the antidepressant sertraline in agricultural soils. *Science of the Total Environment* 452-453, 296-301.
- Lichtenstein, A. H., Yetley, E. A., Lau, J., (2009). Application of Systematic Review methodology to the field of nutrition: National research series, Vol. 1. Agency for Healthcare Research and Quality (US). Technical Reviews, No. 17.1. Accessed May, 2015. Available at: <http://www.ncbi.nlm.nih.gov/books/NBK44075/#A29759>.
- Lind, P. M., Oberg, D., Larson, S., Eyle, C. E., Orberg, J., Rhind, S. M. (2010). Pregnant ewes exposed to multiple endocrine disrupting pollutants through sewage sludge-fertilizer pasture show an anti-estrogenic effect in their trabecular bone. *Science of the Total Environment* 408, 2340-2346.
- Lindsay, B. J., & Logan, T. J. (1998). Field response of soil physical properties to sewage sludge. *Journal of Environmental Quality* 27(3), 534-542.
- Lindstrom, A. B., Strynar, M. J., Delinsky, A. D., Nakayama, S. F., McMillan, L., Libelo, E. L., Neill, M., Thomas, L. (2011). Application of WWTP biosolids and resulting perfluorinated compound contamination of surface and well water in Decatur, Alabama, U.S.A. *Environ. Sci. Technol.* 45, 8015-8021.
- Lowman, A., McDonald, M. A., Wing, S., Muhammad, N. (2013). Land application of treated sewage sludge: Community health and environmental justice. *Eviron. Health Perspect* 121, 537-542.
- Maguire, R. O., Sims, J. T., Coale, F. J. (2000). Phosphorus solubility in biosolids-amended farm soil in the Mid-Atlantic Region of the U.S.A. *Journal of Environmental Quality* 29(4), 1225-1233.
- Mantovi, P., Baldoni, G., Toderi, G. (2005). Reuse of liquid, dewatered, and composted sewage sludge on agricultural land: Effects of long-term application on soil and crop. *Water Research* 39, 289-296.

- Mata-Alvarez, J. (2003). Biomethanization of the organic fraction of municipal solids wastes. Department of Chemical Engineering, University of Barcelona, Barcelona, Spain. Published by IWA, London, U.K. pp. 1-323.
- McBride, M. B. (2003). Toxic metals in sewage sludge-amended soils: Has promotion of beneficial use discounted the risk? *Advances in Environmental Research* 8, 5-19.
- McClellan, K., & Halden, R. U. (2010). Pharmaceuticals and personal care products in archived U.S. biosolids from the 2001 USEPA national sewage sludge survey. *Water Research* 44, 658-668.
- McFarland, M. J., Kumarsamy, K., Brobst, R. B., Hais, A., Schmitz, M. D. (2012). Groundwater quality protection at biosolids land application sites. *Water Research* 46, 5963-5969.
- Meozzi, P., Bresters, A. R., Coulomb, I., Deak, B., Saabye, A., Spinosa, L., Utivik, A. Ø., Uhre. (2007). Sludge treatment and disposal. Management approaches and experiences. ISWA's working group on sewage and waterworks sludge. European Union Agency. Available: [file:///C:/Users/owner/Downloads/sludge%20\(1\).pdf](file:///C:/Users/owner/Downloads/sludge%20(1).pdf). Accessed March 2, 2014. p. 10.
- Metcalf, & Eddy, (2003). Wastewater engineering: Treatment and reuse. 4th ed. Published by TMH. p. 1-1820.
- Mikki, S., (2010). Comparing Google Scholar and ISI Web of Science for earth sciences. *Scientometrics*. 82(2), 321-331. Accessed May, 2015. Available at: <http://www.springerlink.com/content/u86v2042qu654130/>
- Milieu, WRc, RPA, (2010). Environmental, economic and social impacts of the use of sewage sludge on land. Final report, part III: Project interim reports. Available at:

- http://ec.europa.eu/environment/waste/sludge/pdf/part_iii_report.pdf. Accessed March 16, 2014. p. 1-16.
- Monteiro, S. C. and Boxall, A. B. A. (2010). Occurrence and fate of human pharmaceuticals in the environment. *Rev. Environ. Toxicol.*, 202, 53-154.
- Morais, S. A., Delerue-Matos, C., Gabarrell, X., Blanquez, P. (2013). Multimedia fate modeling and comparative impact on freshwater ecosystems of pharmaceuticals from biosolids-amended soils. *Chemosphere* 93, 252-262.
- Moss, L. H., Epstein, E., Logan, T, L. (2002). Evaluating risks and benefits of soil amendments used in agriculture. Final Report Project 99-PUM-1. Alexandria, VA: Water Environment Research Foundation.
- Muchuweti, M., Birkett, J. W., Chinyanga, E., Zvauya, R., Scrimshaw, M. D., Lester, J. N. (2006). Heavy metal content of vegetables irrigated with mixtures of wastewater and sewage sludge in Zimbabwe: Implications for human health. *Agriculture, Ecosystems and the Environment* 112, 41-48.
- NEBRA (North East Biosolids and Residuals Association). (2007). A national Biosolids regulation, quality, end use and disposal survey. Final Report. Available at: <http://www.nebiosolids.org/uploads/pdf/NtlBiosolidsReport-20July07.pdf>. Accessed November, 2013.
- NRC (National Research Council), (1996). Use of reclaimed water and sludge in food crop production. Committee on the use of treated municipal wastewater effluents and sludge in the production of crops for human consumption. Water Science and Technology Board. Available at: <http://www.casaweb.org/documents/2014/use-of-reclaimed-water-sludge-in-food-production.pdf>. Accessed November, 2013.
- NRC (National Research Council), (2000). Biosolids applied to land: Advancing standards and practices. *Prepublication copy*. Available at:

- <http://water.epa.gov/scitech/wastetech/biosolids/upload/complete.pdf>. Accessed October 7, 2013. p. 1-266.
- OEEB (Occupational and Environmental Epidemiology Branch), (2005). Human health risk evaluation of land application of sewage sludge/biosolids. NC Department of Health and Human Services. Available at: http://www.sludgevictims.com/pdf_files/HumanHealthRiskSludgeNC.doc. Accessed November, 2013. p. 1-22.
- Oleszczuk, P., & Hollert, H. (2011). Comparison of sewage sludge toxicity to plants and invertebrates in three different soils. *Chemosphere* 83, 502-509.
- Pepper, I. L., Zerzghi, H., Brooks, J. P., Gerba, C. P. (2008). Sustainability of land application of Class B biosolids. *Journal of Environmental Quality* 37(5), s-58-s-67.
- Perez-Elvira, S. I., Diez, N. D., Fdz-Polanco, F. (2006). Sludge minimization technologies. Reviews in *Environmental Science and Bio/Technology* 5(4), 375-398.
- Qasim, S. R. (1999). Wastewater treatment plants: Planning, design, and operation. Previously published by Technomic Publishing Co., PA.
- Qi, Y., Thapa, K. B., Hoadley, A. F. A. (2011). Application of filtration aids for improving sludge dewatering-A review. *Chemical Engineering Journal* 171(2), 373-384.
- Qiong, L., Ju-mei, L., Xi-long, C., Dong-pu, W., Yi-bing, M. (2012). On-farm assessment of biosolids effects on nitrogen and phosphorus accumulation in soils. *Journal of Integrative Agriculture* 11(9), 1545-1554.
- Rhind, S. M., Kyle, C. E., Kerr, C., Osprey, M., Zhang, Z. L. (2011). Effect of duration of exposure to sewage sludge-treated pastures on liver tissue accumulation of persistent endocrine disrupting compounds (EDCs) in sheep. *Science of the Total Environment* 409, 3850-3856.

- Rhind, S. M., Kyle, C. E., Ruffie, H., Calmettes, E., Osprey, M., Zhang, Z. L., Hamilton, D., Mckenzie, C. (2013). Short- and long-term temporal changes in soil concentrations of selected endocrine disrupting compounds (EDCs) following single or multiple applications of sewage sludge to pastures. *Environmental Pollution* 181, 262-270.
- Robinson, K. Gg, Robinson, C. H., Raup, L. A., Markum, T. R. (2012). Public attitudes and risk perception toward land application of biosolids within the south-eastern United States. *Journal of Environmental Management* 98, 29-36.
- Roig, N., Sierra, J., Marti, E., Nadal, M., Schuhmacher, M., Domingo, J. L. (2012). Long-term amendment of Spanish soils with sewage sludge: Effects on soil functioning. *Agriculture, Ecosystem and Environment* 158, 41-48.
- Rusin, P. A., Maxwell, S., Brooks, J. P., Gerba, C. P., Pepper, I. L. (2003). Evidence for the absence of staphylococcus aureus in land applied biosolids. *Environ. Sci. Technol.* 37, 4027-4030.
- Rylander, R., (1999). Health effects among workers in sewage treatment plants. *Occupational and Environmental Medicine*, 56(5), 354-357.
- Sablayrolles, C., Gabrielle, B., Motrejaud-Vignoles, M. (2010). Life cycle assessment of biosolids land application and evaluation of the factors impacting human toxicity through plant uptake. *Journal of Industrial Ecology* 14(2), 231-241.
- Sabourin, L., Beck, A., Duenk, P. W., Kleywegt, S., Lapen, D. R., Li, H., Metcalfe, C. D., Payne, M., Topp, E. (2009). Runoff of pharmaceuticals and personal care products following application of dewatered municipal biosolids to an agricultural field. *Science of the Total Environment* 407, 4596-4604.
- Sanchez-Monedero, M. A., Mondini, C., del Nobili, M., Leita, L., Roig, A. (2004). Land application of biosolids. Soil response to different stabilization degree of the treated organic matter. *Waste Management* 24(4), 325-332.

- Schlosser, O., Grall, D., Laurenceau, M. N., (1999). Intestinal parasite carriage in workers exposed to sewage. *Eur. J. Epidemiol.* 15(3), 261-265.
- Schowanek, D., David, H., Francaviglia, R., Hall, J., Kirchmann, H., Krogh, P. H., Schraepen, N., Smith, S., Wildemann, T. (2007). Probabilistic risk assessment for linear alkylbenzene sulfonate (LAS) in sewage sludge used on agricultural soil. *Regulatory Toxicology and Pharmacology* 49, 245-259.
- Schroder, J. L., Zhang, H., Zhou, D., Basta, N., Payton, M. E., Zazulak, A. (2008). The effect of long-term annual application of biosolids on soil properties, phosphorus, and metals. *Soil Science Society of America Journal* 72(1), 73-82.
- Schwarz, K. R., Sidhu, J. P. S., Pritchard, D. L., Li, Y., Toze, S. (2014). Decay of enteric microorganisms in biosolids-amended soil under wheat (*Triticum aestivum*) cultivation. *Water Research* 59, 185-197.
- Sepulvado, J. G., Blaine, A. C., Hundal, L. S., Higgins, C. P. (2011). Occurrence and fate of Perfluorochemicals in soil following the land application of municipal biosolids. *Environ. Sci. Technol.* 45, 8106-8112.
- Shah, V., Jones, J., Dickman, J., Greenman, S. (2014). Response of soil bacterial community to metal nanoparticles in biosolids. *Journal of Hazardous Materials* 274, 399-403.
- Sidhu, J. P. S., & Toze, S. G. (2009). Human pathogens and their indicators in biosolids: A literature review. *Environment International* 35, 187-201.
- Singh, R. P., & Agrawal, M. (2009). Potential benefits and risks of land application of sewage sludge. *Waste Management* 28(2), 347-358.
- Shober, A. L., Stehouwer, R. C., Macneal, K. E. (2003). On-farm assessment of biosolids effects on soil and crop tissue quality. *Journal of Environmental Quality* 32(5), 1873-1880.

- Smith, S. R., (2009). Organic contaminants in sewage sludge (biosolids) and their significance for agricultural recycling. *Phil. Trans. R. Soc. A* 367, 4005-4041.
- Snyder, E. H., & O'Connor, G. A. (2013). Risk assessment of land-applied biosolids-borne triclocarban (TCC). *Science of the Total Environment* 442, 437-444.
- Soh, I., Lang, G. Decision making for biosolids management. Available at: http://www.ewmce.com/Resources/Documents/Ida_Soh_and_Graham_Lang_-_Decision_Making_for_Biosolids_Management.pdf. Accessed November, 2013.
- Spinosa, L., Veslind, P. A. (2001). Sludge into Biosolids. Processing, disposal, utilization. London, U.K.: IWA Publisher.
- Sterritt, R. M., & Lester, J. N. (1980). The value of sewage sludge to agriculture and effects of the agricultural use of sludges contaminated with toxic elements: A review. *Sci. Total Environ.* 16(1), 55-90.
- Stewart J. M., Bhattacharya, S. K., Madura, R. L., Mason, S. H., Schonberg, J. C. (1995). Anaerobic treatability of selected organic toxicants in petrochemical wastes. *Water Resources* 29, 2730-2738.
- Tanner, B. D., Brooks, J. P., Gerba, C. P., Haas, C. N., Josephson, K. L., Pepper, I. L. (2008). Estimated occupational risk from biosolids generated during land application of Class B Biosolids. *Journal of Environmental Quality* 37(6), 2311-2321.
- Tanner, B. D., Brooks, J. P., Haas, C. N., Gerba, C. P., Pepper, I. L. (2005). Bioaerosol emission rate and plume characteristics during land application of liquid B biosolids. *Environ. Sci. Technol.* 39, 1584-1590
- Tian, G., Franzluebbbers, A. J., Granato, T. C., Cox, A. E., O'Connor, C. (2013). Stability of soil organic matter under long-term biosolids application. *Applied Soil Ecology* 64, 223-227.

- Tian, G., Granato, T. C., Carlson, C. R., Abedin, Z. (2006). Effect of long-term application of biosolids for land reclamation on surface water chemistry. *Journal of Environmental Quality* 35(1), 101-113.
- Tisdall, J. M., & Oades, J. M. (1982). Organic matter and water-stable aggregates in soils. *Journal of Soil Science* 33(2), 141-163.
- Topp, E., Monteiro, S. C., Beck, A., Coelho, B. B., Boxall, A. B. A., Duenk, P. W., Kleywegt, S., Lapen, D. R., Payne, M., Sabourin, L., Li, H., Metcalfe, C. D. (2008). Runoff of pharmaceuticals and personal care products following application of biosolids to an agricultural field. *Science of the Total Environment* 396, 52-59.
- Toze, S., Sidhu, J. (2012). Biosolids: Human health impacts. *Encyclopedia Environmental Health*, 394-402.
- USEPA (United States Environmental Protection Agency), (1993). 40 CFR Part 257 et al. Standards for the use or disposal of sewage sludge; Final rules. Available at: <http://water.epa.gov/scitech/wastetech/biosolids/upload/fr2-19-93.pdf>. Accessed October, 2013. p. 1-29.
- USEPA (United States Environmental Protection Agency), (1999). Biosolids generation, use and disposal in the United States. USEPA 530-R-99-009. p. 1-81.
- USEPA (United States Environmental Protection Agency), Biosolids: Targeted national sewage sludge survey report –Overview. Available at: <http://water.epa.gov/scitech/wastetech/biosolids/tnsss-overview.cfm#production>. Accessed November, 2013. p. 1-10.
- USEPA (United States Environmental Protection Agency), (2000). Biosolids technology fact sheet. Alkaline stabilization of biosolids. USEPA 832-F-00-052. Available at: http://water.epa.gov/scitech/wastetech/upload/2002_06_28_mtb_alkaline_stabilization.pdf. Accessed November, 2013. p. 1-9.

USEPA (United States Environmental Protection Agency), (1999). Environmental regulations and technology: Control of pathogens and vector attraction in sewage sludge. Chapter 6: processes to significantly reduce pathogens (PERPs). p. 43. Available at: <http://infohouse.p2ric.org/ref/09/08691.pdf>. Accessed April, 2015.

USEPA (United States Environmental Protection Agency), (2003). Environmental regulations and technology: Control of pathogens and vector attraction in sewage sludge. USEPA/625/R-92/013. Available at: <http://www2.epa.gov/sites/production/files/documents/625R92013ALL.pdf>. Accessed November, 2013. p. 1-186.

USEPA (United States Environmental Protection Agency), (2007). 2001 national sewage sludge survey report. Office of the water (4303T). USEPA-822-R-07-006

USEPA (United States Environmental Protection Agency), (2009). Persistent organic pollutants: A global issue, a global response. Available at: <http://www2.epa.gov/international-cooperation/persistent-organic-pollutants-global-issue-global-response>. Accessed August, 2014.

USPEPA (United States Environmental Protection Agency), (2012). Sewage sludge (Biosolids). Frequently asked questions. Available at: <http://poultryems.ag.vt.edu/assessment/biosolids.pdf>. Accessed April, 2014.

USEPA (United States Environmental Protection Agency), (2002). Land application of Biosolids. Office of the Inspector General Status Report 2002-000004. pp. 1-49.

USEPA (United States Environmental Protection Agency), (2012). A plain English guide to the USEPA Part 503 rule. Chapter 5. Pathogen and vector attraction reduction requirements. Available at: http://water.epa.gov/scitech/wastetech/biosolids/503pe_index.cfm. Accessed October, 2014.

- USGPO (United States Government Publishing Office), (2006). Title 40: Protection of the environment. General pretreatment regulations for existing and new sources of pollution. Available at:
<http://www.gpo.gov/fdsys/search/pagedetails.action?collectionCode=CFR&searchPath=Title+40%2FChapter+I%2FSubchapter+N%2FPart+403&granuleId=&packageId=CFR-2006-title40-vol1&oldPath=Title+40%2FChapter+I%2FSubchapter+N&fromPageDetails=true&collapse=true&ycord=544>. Accessed September, 2014.
- Vaxelaira, J., & Cezac, P. (2004). Moisture distribution in activated sludges: A review. *Water Resources* 38(, 2215-2230.
- Venkatesan, A. K., & Halden, R. U. (2014). Brominated flame retardants in U.S. biosolids from the USEPA national sewage sludge survey and chemical persistence in outdoor soil mesocosms. *Water Research* 55, 133-142.
- Verma, S. (2002). Anaerobic digestion of biodegradable organics in municipal solid waste. Unpublished thesis, Department of Earth & Environmental Engineering, Henry School of Mines, Fu Foundation School of Engineering & Applied Science, Columbia University. Available at: Verma, S., 2002: Anaerobic Digestion of Biodegradable Organics in Municipal Solid, Accessed August, 2014.
- Walters, E., McClellan, K., Halden, R. U. (2010). Occurrence and loss over three years of 72 pharmaceuticals and personal care products from biosolids-soil mixtures in outdoor mesocosms. *Water Research* 44, 6011-6020.
- Wang, H., Megesan, G. N., Kimberley, M. O., Payn, T. W., Wilks, P. J., Fisher, C. R. (2004). Environmental and nutritional responses of a Pinus radiata plantation to biosolids application. *Plant and Soil* 267, 255-262.
- Wang, X., Chen, T., Ge, Y., Jia, Y. (2008). Studies on land application of sewage sludge and its limiting factors. *Journal of Hazardous Materials* 160, 554-558.

- Waterhouse, B. R., Boyer, S., Adair, K. L., Wratten, S. D. (2014). Using municipal biosolids in ecological restoration: What is good for plants and soil may not be good for endemic earthworms. *Ecological Engineering* 70, 414-421.
- Wei, Y., Van Houten, R. T., Borger, A. R., Eikelboom, D. H., Fan, Y. (2003). Minimization of excess sludge production for biological wastewater treatment. *Water Research* 37, 4453-4467.
- WERF (Water Environment Research Foundation), (2004). Identifying and controlling odor in the municipal wastewater environment health effects of biosolids odors. Health effects of biosolids odor: A literature review and analysis and analysis. *Final Report*. Available at:
<http://www.werf.org/WERFDownload.aspx?ContentKey=0ebc1944-3cc2-4384-942b-4595a4d3e3f5&ContentItemKey=a3e6ea04-0d89-42e4-8e3c-c04cf4843680>. Accessed October, 2013.
- WtERT (Waste-to-Energy Research and Technology Council), (2014). Anaerobic digestion process. Available at:
<http://www.wtert.eu/default.asp?Menu=13&ShowDok=12>. Accessed September, 2014.
- Wu, C., Spongberg, A. L., Witter, J. D., Sridhar, B. B. M. (2012). Transfer of wastewater associated pharmaceuticals and personal care products to crop plants from biosolids treated soil. *Ecotoxicology and Environmental Safety* 85, 104-109.
- Xia, K., Bhandari, A., Das, K., Pillar, G. (2005). Occurrence and fate of pharmaceuticals and personal care products (PPCPs) in biosolids. *Journal of Environmental Quality* 34(1), 91-104.
- Xia, K., Hundal, L. S., Kumar, K., Armbrust, K., Cox, A. E., Granato, T. C. (2010). Triclocarban, triclosan, polybrominated diphenyl ethers, and 4-nonylphenol in

- biosolids and in soil receiving 33-year biosolids application. *Environment Toxicology and Chemistry* 29(3), 597-605.
- Xu, G. (2014). Analysis of sewage sludge recovery system in EU- in perspective of nutrients and energy recovery efficiency, and environmental impacts. Unpublished master degree thesis in industrial energy, Norwegian University of Science and Technology, Department of Energy and Processing Engineering. Available at: <http://ntnu.diva-portal.org/smash/get/diva2:706854/FULLTEXT01.pdf>. Accessed November, 2014.
- Yang, C., Meng, X-Z., Chen, L., Xia, S. (2011). Polybrominated diphenyl ethers in sewage sludge from Shanghai, China: Possible ecological risk applied to agricultural land. *Chemosphere* 85, 418-423.
- Ying, G-G., & Kookana, R. S., (2007). Triclosan in wastewaters and biosolids from Australian wastewater treatment plants. *Environment International* 33, 199-205.
- Zaleski, K. J., Josephson, K. L., Gerba, C. P., Pepper, I. L. (2005). Survival, growth, and regrowth of enteric indicator and pathogenic bacteria in biosolids, compost, soil and land applied biosolids. *Journal of Residuals Science & Technology* 2(1), 49-63.
- Zerzghi, H., Gerba, C. P., Brooks, J. P., Pepper, I. L. (2010). Long-term effects of land application of Class B biosolids on the soil microbial populations, pathogens, and activities. *Journal of Environmental Quality* 39(1), 402-408.
- Ziemba, C., Yang, W., Peccia, J. (2013). Modelling human off-site aerosol exposures to polybrominated flame retardants emitted during the land application of sewage sludge. *Environmental International* 60, 232-241.

VITA

Harris Gbomina, Jr., was born in Zwedru, Grand Gedeh County, Liberia. He completed his High School Diploma in a refugee camp in Nigeria in 1998 with a scholarship award from the United Nations High Commissioner for Refugees (UNHCR). He later attended the Federal College of Forestry, Ibadan, Nigeria and received a National Diploma (ND) in Forestry Technology in 2000. After graduation, the college employed him as an Agricultural Superintendent for two years.

In 2002, he was admitted to the University of Agriculture Abeokuta (UNAAB), Nigeria where he obtained his Bachelor of Forestry degree in 2006. He won the honor of receiving the best graduating student award in the department upon graduation. After graduation, he returned to his country, Liberia, and worked with Société Générale de Surveillance (SGS), the world leading inspection company in the development and implementation of the timber tracking system (Chain of Custody) for the Liberia Forest Sector. He left as Operations Manager after two years to the United States.

In the spring of 2012, he began his M.S degree program at the University of Missouri-Kansas City. While at the University, he served as the vice president of the students' chapter of the Association of Environmental and Engineering Geologists (AEG). He also volunteered his time at the Missouri Department of Conservation where he worked for 6 months.