The Feasibility of Converting Sewage Sludges into Biosolids as a Fertilizer for Use on Agricultural Land in China

LWS 548 Major Project
By
Shirley (Huiyuan) Liu

Master of Land and Water Systems
Faculty of Land and Food Sciences
University of British Columbia

Vancouver, British Columbia

August 2022

Table of Contents

Acknowledgement

I would like to express my deep and sincere gratitude to my academic supervisor, Dr. Les Lavkulich, Program Director, Master of Land and Water Systems, Faculty of Land and Food Systems, University of British Columbia, for his invaluable guidance throughout my project. I am extending my heartfelt thanks to Ms. Julie Wilson for all her assistance, suggestions, and support to this project and Megan Bingham for her support and encouragement throughout the program. Furthermore, I would like to express my gratitude to the Master of Land and Water Systems faculty for this amazing year. I would also love to acknowledge my classmates and friends in this program, Haoyue Wang and Qiaobo Yang, for their support and encouragement throughout my course of study.

Finally, I am extremely grateful to my parents, my family, and my boyfriend, for their love, caring, suggestions, and continuous support that encouraged me to complete this project successfully. Thank you so much.

EXECUTIIVE SUMMARY

The result of the increase of sewage production, the treatment of sewage sludge has become an important topic. The predominant sewage sludge treatment methods in China are land application (29.3%), incineration (26.7%), and landfilling (20.1%). Both incineration and landfilling are accompanied by large greenhouse gas (GHG) emissions, so land application is becoming a major concern for sewage sludge treatment. This study focused on the feasibility of using sewage sludge to produce biosolids for application as fertilizer on agricultural land in China.

This paper provided an integral analysis of the application of biosolids as fertilizer through an extensive literature review. The paper outlined the conditions for the application of biosolids as fertilizer, the factors limiting the use of biosolids as fertilizer, the treatment schemes for sewage sludge, and the methods for detecting contaminants in biosolids. Finally, based on the information collected, this paper provides solutions for the implementation of biosolids as fertilizer in China.

The use of biosolids as fertilizer on agricultural land in China is feasible and has the potential for greater development in the future as technical difficulties are addressed. Biosolids are subject to strict environmental standards to control the presence of contaminants such as pathogens, heavy metals, and microorganic pollutants. The selection and dosage of biosolids are adjusted in time considering the influence of factors such as, climate and soil properties. In addition, government subsidies and improved legislation can ensure the quantity and quality of biosolids and promote public acceptance.

This study provided a method of testing for contaminants that are currently present, however, as new chemicals are researched and discovered, more and more microorganic pollutants will be present in biosolids in the future, and therefore quality testing of biosolids is an ongoing life cycle assessment. This requires continued research in this direction by other scholars and researchers.

INTRODUCTION

China is experiencing a rapid increase in the production of wastewater and sewage sludge due to urbanization and industrialization (Chen et al., 2012). Sewage sludge is the solid product collected from wastewater treatment, which usually contains high concentrations of plant nutrients (e.g., nitrogen, phosphorous, potassium), organic and inorganic chemicals (e.g., triclocarban, mercury), and pathogens (Stehouwer, 2010). According to statistics from the China Statistical Yearbook 2019 (MOHURD, 2019) and Wei et al. (2020), the total annual production of wastewater and sewage sludge in China reached 700 million tons and 39 million tons (80% water content), respectively. And this production volume will grow at an average rate of 7% annually. Therefore, the disposal of sewage sludge has become a challenging task for China.

At the end of 2019, China's dominant disposal methods for sewage sludge included land application (29.3%), incineration (26.7%), and sanitary landfills (20.1%). The following table shows the comparison of incineration and landfills in terms of technical, economic, and environmental issues (Wang, 1997). As can be seen from the table, neither of the two conventional sewage sludge treatment methods is environmentally friendly. Therefore, for the sake of resource and environmental protection, there should implement more beneficial treatment methods, such as land application. Land application has a much shorter history of use in China than landfills and incineration, with only about five decades of use, and has only become widely available in the early 21st century.

Table 1: Comparison of two conventional sewage sludge disposal methods from the aspects of technical, economic, and environmental issues.

Sewage Sludge Disposal Method	Technical Aspect	Economic Aspect	Environmental Aspect
Incineration	Equipment needed; no high technologies needed	High cost of operations	Toxic chemicals and Green House Gas (GHG) emissions

Landfill	No technology needed	Low cost	GHG emission; waste of useful plant nutrients in sewage sludge

Land application of sewage sludge can provide significant benefits, including enhanced soil fertility, improved soil properties, as well as reduced GHG emissions (Chen et al., 2012). Since sewage sludge comes predominantly from municipal and industrial wastewater, it is rich in organic matter and plant nutrients and can be broadly used on agricultural land. In contrast to using conventional manure as fertilizer, sewage sludge has 5 times more organic matter, 3 times more Nitrogen, and 3 times more Phosphorus than manure (Wang, 1997). Hence, sewage sludge can increase soil fertility and is more beneficial for crop growth. Also, sewage sludge-derived soil conditioners can improve soil properties, such as aggregate stability and water retention and movement. These properties can enhance the sequestration of carbon in the soil, thus also reducing the effects of GHG emissions. The CO_2-equivalent emissions per ton of sludge for incineration, landfill, and land application are 2341kg, 1587kg, and 731kg.

However, land application is restricted due to contaminants present in the sewage sludge, such as heavy metals and pathogens, the result of deregulated standards for sludge. To ensure that the treated sludge does not poison the environment and human health, the government and environmental ministries must establish strict standards for sludge disposal. Although there are policies that set standards for treated sewage discharge, the actual regulations are very loose. As a result, the management of sewage sludge has also been neglected. Moreover, the investments in sewage treatment have been reduced in China's 12th Five-Year Plan period, further exacerbating the difficulty of land application of sewage sludge (Soh, 2018).

Treatment alternatives for sewage sludge for land application are aerobic digestion, anaerobic digestion, drying, and composting (Chen et al., 2012). Anaerobic digestion is widely used in developed countries in North America and Europe and has minimal GHG emissions. However, this technology faces challenges in its implementation in China because of scale and economic and technical difficulties (Wang, 1997). For small and medium-sized wastewater treatment plants (WWTPs), anaerobic digestion technology is highly expensive to operate. Whereas for large-scale WWTPs, technical and economic difficulties reduce the efficiency of operation.

Although much of the literature has reported on the methods for monitoring contaminants in sewage sludge for quality assurance, there is a lack of comprehensive monitoring techniques applicable to most practical situations. For example, Chen et al. (2012) assessed the concentrations of perfluorooctane sulfonate (PFOS) and perfluorooctanoate (PFOA) in sludges using a PP centrifuge tube with the addition of chemicals (i.e., Na_2CO_3 & TBAHS solutions). However, this method is not effective to investigate heavy metals. If each kind of pollutant measurement uses a different method, the whole testing process is costly, which is not conducive to the implementation of the project.

Therefore, to fill in the knowledge gap identified above, this paper conducted research to study the feasibility of converting sewage sludge into biosolids as a fertilizer for use on agricultural land and build an integrated framework to promote the use of biosolids in China.

OBJECTIVES

The specific objectives of this paper were to:

- Conduct an integral analysis of the feasibility of converting sewage sludge into biosolids as a fertilizer on agricultural land in China, and identify the barriers and potential risks of applying biosolids on China's agricultural land from environmental, social, and economic aspects,
- Analyze different biosolid treatment schemes such as anaerobic digestion and composting and summarize the benefits and drawbacks of using these schemes for land application, as well as provide the best choice,
- Provide solutions for applying biosolids based on current national and geographical situations, and
- Provide recommendations and future research.

METHODS

To accomplish the study in accordance with the goals, this paper conducted a systematic literature review. The assessment focused on the following areas:

- Conditions for using biosolids as fertilizer

  Like other chemical fertilizers, biosolids as a product have their own conditions foruse, due to the different treatment methods and raw material content, and

- Current treatment schemes and monitoring methods of contaminants.

Current treatment schemes including composting and anaerobic digestion are two popular methods to produce biosolids. In order to ensure that the contaminants in biosolids do not exceeded, regulatory guideline it is necessary to choose the appropriate monitoring method and detection time to guarantee the health requirements and save money and energy.

- Obstacles to the implementation of biosolids in China

As discussed in the introduction, obstacles to converting sewage sludge into biosolids include the lack of financial support from the government and advanced technical issues. There are other reasons that affect the use of biosolids in China, such as geographical restrictions and public acceptance.

- Current regulations and guidelines used in other regions

United States Environmental Protection Agency (US EPA) provides a guide that can be used in many regions. Many countries in Europe also have legislation and pollutant limits for the use of biosolids on agricultural land.

North America has countries with relatively large territories, like Canada and the United States, national management and zoning are essential and worth learning for China.

LITERATURE REVIEW

Conditions of Using Biosolids as Fertilizer

Biosolids are treated sewage sludges obtained after the first and second filtration of municipal wastewater (Sullivan et al., 2022). Treated biosolids have small amounts of harmful pollutants, such as heavy metals, organic micropollutants, and pathogens, and can therefore be disposed of by incineration, landfill, land application, brick manufacture, etc. According to the introduction section, land application is the most potential one and has the least environmental impact compared to other treatment methods. Thus the use of biosolids as fertilizer is one of the popular options for land application.

The use of biosolids as fertilizer in crop systems requires higher quality conditions to avoid the harmful effects of biosolids on human health and ecosystem health. Therefore, the use of biosolids should meet the following conditions.

High Standards for Pollutant Control in Biosolids

Crops and plants cannot selectively obtain only nutrients from biosolids. Heavy metals and organic micropollutants can also be absorbed by plants, while pathogens can spread by various means, contaminate soil, air and water, and endanger human and animal health through skin contact, respiration and food chain, and also accelerate the spread of plant diseases. Therefore, biosolids must meet strict standards to ensure that these contaminant levels are not threatening to humans and ecosystems.

Many countries have explicit legislative standards for contaminant content in biosolids. For example, the United States Environmental Protection Agency (US EPA) categorizes biosolids as Class A and Class B based on treatment methods, which contain over 700 pollutant content limits. And both types of biosolids can be applied on agricultural lands, where the treatment process of Class B biosolids is the minimum standard for the use of biosolids as a land application in the U.S. European countries also set limited concentrations of contaminants in biosolids. Table 2 highlights a few contaminant ranges according to the study done by Collinignarelli et al. (2019)

Table 2: Summary of heavy metals, organic compounds, and pathogens in biosolids from European countries

Pollutants	Limit Values
Zn (ppm)	2500 – 4000
Cu (ppm)	1000 – 1750
Cd (ppm)	20 – 40
Hg (ppm)	16 – 25
PCB (Polychlorinated Biphenyls) (ppm)	< 0.8
E. Coli (CFU g_{DM}^{-1})	100 – 1000
Salmonella (CFU g_{DM}^{-1})	100 – 1000

Crop Type

The crop type is also one of the important measures for biosolids selection. Because of the variation in nutrient content of different wastewater sources and differences in treatment schemes, the ratio of nutrients to contaminants within the generated biosolids is relatively fixed. The nitrogen (N) and phosphorus (P) concentration of the biosolids should also be higher for crops that require large amounts of N and P (Sullivan et al., 2022). The United States Department of Agriculture (USDA) (2022) has reported that China's main crop types include rice, wheat, cotton, and corn. The rest of this paper focuses on the feasibility of growing wheat on Chinese agricultural land as an example of biosolids as fertilizer. Figure 1 shows the total wheat production on the map of China. As can be seen, the main production region of wheat is in the central east of China.

Figure 1: Map of total wheat production in China.

Biosolid Dosage

Another essential condition is the dosage of biosolids. This is a variable condition and influenced by several factors. This paper summarized two main factors that affect biosolids dosage on agricultural land in China, which are climate and soil properties.

Climate

Precipitation may affect the dosage of biosolids due to soluble N and P. Soluble salts in biosolids are lost with the movement of water in regions with high precipitation, leaving fewer nutrients available for crops use, and resulting in increased biosolids use (Sullivan et al., 2022). And according to the study done by Luo, et al. (2000), heavy metals and soluble salts are mobilizable in the soil and can move to deeper soil layers. An increase in precipitation can also promote the rate of movement of heavy metals and soluble salts, which can lead to an increase in the use of biosolids. In addition, the accumulation of heavy metals can cause crop and soil pollution due to their mobility.

Soil Properties

Since one of the methods of treating sewage sludge is to add lime to the process, some biosolids will have a high pH (pH > 12) (Luo, et al. 2000). And there are many acidic soils in the south of China, so high pH biosolids are more suitable to be applied on agricultural land for the purpose of soil pH adjustment.

The degree of soil compaction can also affect the dosage of biosolids. Less compacted soils have better aeration and higher water content, so the amount of biosolids applied can be more than in high-compacted soils.

Challenges of Implementing Biosolids as Fertilizer

Terrain Limitation

The construction of the municipal wastewater treatment plant is located on the Plains and biosolids production is a process in wastewater treatment plants. Figure 2 shows the topographic distribution of China (Zhao et al., 2017), and most of the densely populated areas in the Figure are in the green zone, or Plains, in eastern China. Hence, siting a biosolids-producing wastewater treatment plant in a densely populated and highly developed Plain area is a major challenge. Of particular interest is the location of No. 51 (Sichuan) in Figure 2. Chengdu, the capital of Sichuan, has an elevation ranging from 500m to 5364m, with an urban area of 12,390 km^2, and a population of 1,163.28 million (“Chengdu”, 2022). The wastewater treatment capacity of Chengdu City is close to 171,000m^3/d (Wang, 2018). As an example, the Joint Abbotsford Mission Environmental Systems Wastewater Treatment Plant (JAMES Plant), located on the US-Canada border, with a wastewater treatment capacity of 48,000m^3/d (City of Abbotsford, 2022), requires a large site area to meet the wastewater treatment demand. Therefore, the terrain requirement becomes one of the reasons that affect the production of biosolids, thereby hindering their use as fertilizer.

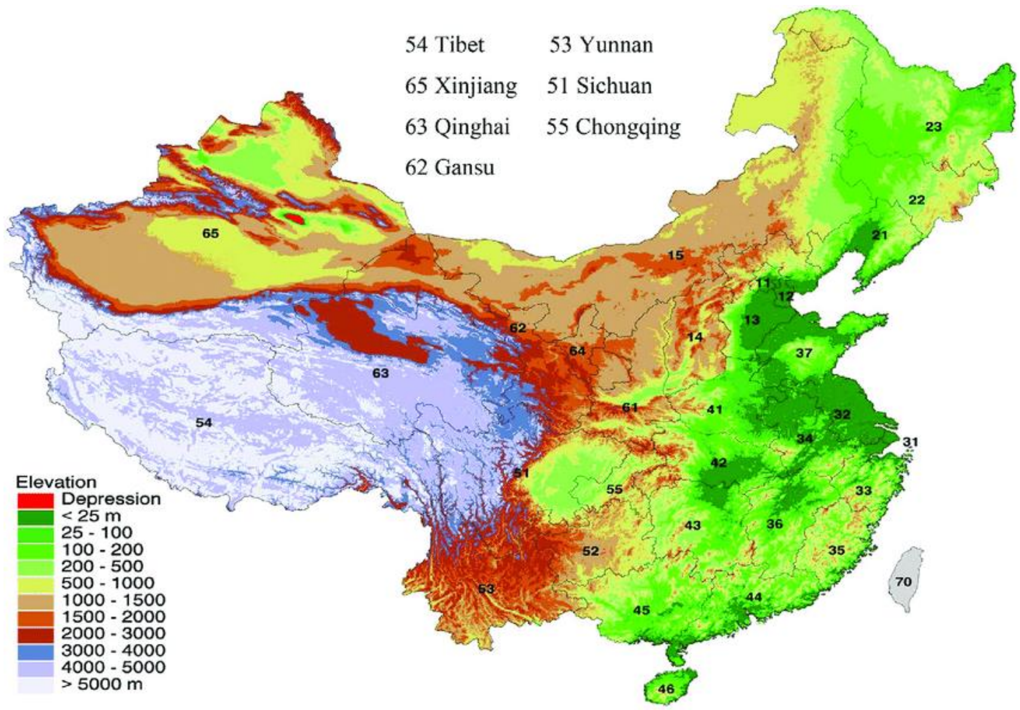

Figure 2: Topography map of China

Technology Limitation

The immaturity of the treatment industry technology for sewage sludge can lead to incomplete removal of pollutants and is a major impediment to the application of biosolids as fertilizer. The municipal sewage sludge treatment industry in China has been developed for a relatively short period of time, and the process is still largely at the research and trial stage, with few engineering examples and fully successful and stable operations.

Incomplete Removal of Contaminants

Heavy metals such as Zinc (Zn), Copper (Cu), Cadmium (Cd), Chromium (Cr), Mercury (Hg), are common products of industrial wastewater. The composition of heavy metals in sewage sludge may vary depending on the source of the industrial effluent, but the dominant heavy metals in sewage sludge are Zn and Cu in China (Luo, et al.2000). While the leather industry contains a higher level of Cr, and the plastic industry contains more Hg content, these heavy metals have low solubility and are relative stable in sludge, therefore, they cannot be removed easily using degradation. Although heavy metals can be filtered out of the sludge system by biological methods using bacterial cyclic reduction-oxidation of Sulfur (S), which converts insoluble sulfides into soluble sulfates, there are still minor residues of heavy metals present in the biosolids.

China has detected 35 organic contaminants in sewage sludge over the past three decades, including Polychlorinated Biphenyls (PCBs), Polycyclic Aromatic Hydrocarbons (PAHs), and pharmaceuticals, hormones, and antibiotics (Meng et al., 2016). Although some pollutants are degraded to some extent during sewage sludge treatment, it is still difficult to remove them completely (Luo, et al., 2000). As stated in the Conditions section, organic micropollutants can be absorbed by crops and pose a threat to humans and ecosystems.

In addition, pathogen removal is also affected by the differences in treatment methods, so pathogen cannot be completely removed. The treatments will be presented specifically in the Schemes section. According to the study done by Luo, et al. (2000), composting is more effective in removing pathogen concentrations than anaerobic digestion.

Financial Limitation

The economic constraints are summarized in two main aspects, one is the cost of expensive instrumentation and operation, and the other is the cost of expensive biosolids fertilizer. For example, anaerobic digestion, which is widely used in other countries, such as the United States, to treat sewage sludge, requires a large economic investment in technical equipment and operation, which can be an unaffordable cost for small and medium-sized wastewater treatment plants in China (Wang, 1997). Therefore, not many wastewater treatment plants have sufficient funds to produce biosolids. On the other hand, because of the high price of biosolids as fertilizer, many low-income farmer households cannot afford the fertilizer cost. Even though biosolids can provide economic benefits at crop harvest time by helping to increase food production, farmers still choose to use untreated sludge, such as human and livestock manure to reduce costs.

Legislation Limitation

At present, the laws and regulations on the production of sewage sludge and biosolids in China are inadequate. Although the Chinese government has set a comprehensive catalog of national food safety standards (The State Council the People’s Republic of China, 2022) that strictly regulate the levels of heavy metals and organic matter in food, there are no relevant laws governing the content of contaminants in biosolids. Moreover, the government-set standards for sewage effluent discharge are not strictly controlled in remote areas. This further hinders the implementation of biosolids fertilizers on agricultural land.

However, it is worth mentioning that China now also classifies sewage sludge for the application on agricultural land as Class A and Class B (Meng et al., 2016), which is used in agriculture soils and used in agriculture soils but not for vegetable and cereal production. According to the Chinese sludge standard, the maximum tolerable concentration (MTC) of PAHs in sludge of Class B and above is 6000 ng/g, which is consistent with the US and European standards (de Sena et al., 2009).

Public Acceptance

The last reason that impedes the use of biosolids as fertilizer on agricultural land is public acceptance. Because of the presence of contaminants in biosolids, many people have doubts about the health effects of biosolids and are hesitant to accept biosolids as a fertilizer for their crops. The topic of biosolids has only become popular in China in recent two decades, so many people are not aware of the effects and conditions of using biosolids. Even though biosolids products meet health standards, the public are still reluctant to accept biosolids fertilizers because of the "water over mud" mentality (Wang, 2018). In addition, the amount of biosolids used on agricultural land needs to be carefully calculated and controlled. Over-application can have negative effects, which may decrease public acceptance of biosolids fertilizers.

Biosolids Treatment Schemes and Monitoring Methods

Treatment Schemes

Murray, et al. (2008) has analyzed treatment schemes of sewage sludge in China and summarized 9 different schemes based on different destination uses (e.g., landfill, agricultural use, cement manufacture, etc.) from environmental and economic aspects. This paper only focussed on using biosolids as fertilizer on agricultural land, Table 3 summarizes sewage sludge treatment schemes related to land application.

Table 3: Summary of treatment schemes with environmental and economic analysis for land application

Treatment Scheme	Total Economic Cost (Million$)	Environmental Assessment			
		SO_2 (kg)	GWE (kg CO_2)	Electricity (kWh)	Fuel (MJ)
Lime Stabilization	35	8.7×10^3	1.5×10^7	-5.9×10^8	5.8×10^7
Anaerobic Digestion (no lime)	31	-1.9×10^5	-1.1×10^7	-6.2×10^8	-4.6×10^7
Anaerobic Digestion (lime)	35	-1.9×10^5	-4.2×10^6	-6.2×10^8	-2.9×10^6
Heat Drying + Composting	80	1.2×10^4	5.6×10^6	-5.9×10^8	8.3×10^7

According to the results shown in Table 3, anaerobic digestion without lime is the best choice in terms from both economic and environmental aspects. The total cost of anaerobic digestion, including capital costs, operation costs, transportation costs, and direct costs, is $31,000,000. The environmental assessment takes into account four aspects: sulfur dioxide (SO_2) emissions, global warming effect (GWE), electricity use, and fuel. The natural gas generated from anaerobic digestion can be used as fuel to offset CO_2 emissions and to generate electricity, so the numbers in the Table are negative.

Monitoring Methods

Biosolids are required to be of high quality so that they have low impacts on humans and ecosystems. Therefore, sample testing of biosolids must also be ensured to be rigorous and effective. Based on the classification of hazardous substances in biosolids, the testing is divided into the following parts: odors, pathogens, heavy metals, microorganic pollutants, and soil. Finally, the frequency of biosolids testing is also enumerated.

Odors

The main sources of odor in biosolids are organic and inorganic forms of sulfur, mercaptans, ammonia, amines and organic fatty acids (USEPA, 2000). Differences in the treatment of biosolids can affect the composition of these odors. For example, the main products in anaerobic digestion are hydrogen sulfide and other sulfur-containing gases, while the main products in composting are ammonia, amines, sulfur-based compounds, fatty acids, aromatic hydrocarbons, and hydrocarbons. The higher the concentration of these substances in the biosolids, the more the olfactory impact they produce that will hinder the degree of public acceptance, as the public may perceive this unpleasant smell as being due to an incomplete treatment process. However, a study by Byliński et al. (2019) found that real-time monitoring of volatile odor compounds using Flux Hood Chamber and Proton Transfer Reaction Time Of Flight Mass Spectrometer (PTR-TOF-MS) technique was relatively efficient, to identify the odor origins. This method is featured by simple operation, short single detection time and no sample preparation. Moreover, this method takes into account the dynamic property of the gas, so it is a holistic measurement and accurate.

Pathogens

Unlike odors, pathogens in biosolids can cause nonpoint source pollution through receiving water bodies, thus threatening ecological and human health. The study by Pepper, et al. (2006) lists significant pathogens in biosolids, such as Salmonella sp. (bacteria), Cryptosporidium (protozoa), Hepatitis A virus (enteric viruses), Ascaris lumbricoides (helminth worms), and others. Although polymerase chain reaction (PCR) can detect the presence of pathogens in biosolids by finding their DNA or RNA (MedlinePlus, 2022), this method cannot determine the effectiveness of treatment of the biosolids (Pepper, et al. 2006). Therefore, according to Sidhu & Toze (2009), indicators are more suitable as a measure of the treatment process. And their study points out several optimal indicators to measure different types of pathogens for example that enterococci is the indicator of bacterial pathogens and adenovirus is the indicator of enteric viruses. However, metrics for protozoa and helminth worms still need further study.

Heavy Metals

Heavy metals are chemical substances and are therefore simpler to detect in biosolids than in pathogens. Common heavy metals in biosolids include cadmium (Cd), cobalt (Co), copper (Cu), nickel (Ni), lead (Pb), zinc (Zn), iron (Fe), and manganese (Mn). Tessier, et al. (1979) provided a validated method for metal detection and this method was also applied in the study of Bai et al. (2011; 2012). This method performs a sequential five-step extraction of the metals by means of fractionation. The collected biosolids samples are stored at 4°C and then dried in a forced air oven at 105°C. The advantage of this method is that the extraction is performed on the sample solids themselves and not on the suspended matter, thus making the operation simpler and more accurate. The following is a specific description of the five steps and environmental conditions that affected the fractions.

- Fraction 1 – Exchangeable

  Fraction 1 may be affected by changes in the ionic composition of the water and by sorption-desorption processes. This step involves taking 1 g of biosolid sample and 8 ml of magnesium chloride ($MgCl_2$) at a concentration of 1 M for 1 hour at room temperature for extraction.
- Fraction 2 – Bound to carbonates

  This fraction is susceptible to pH changes. Therefore, the sodium acetate (NaOAc) solution is first adjusted to pH 5.0 and concentration 1 M with acetic acid (HOAc). Then 8 ml of 1 M NaOAc and the residue of the Fraction 1 is leached out at room temperature for a sufficient time (e.g., 5 hours (Bai et al., 2011; 2012)).
- Fraction 3 – Bound to iron and manganese oxides

  Iron and manganese oxides, as superior metal scavengers, are unstable under anoxic conditions. This step is to select 20 ml of 0.04 M hydroxylammonium chloride (NH_2OH-HCl) in 25% (volume per volume(v/v)) HOAc solution and the residue from Fraction 2 to be extracted at a temperature of 96°C for 5 hours.

- Fraction 4 – Bound to organic matter

  Organic matter and metals can combine and release soluble metals under oxidizing conditions. The operation of this fraction is divided into two steps. The first step is to add 3 ml of 0.02 M nitric acid (HNO_3) and 8 ml of 30% hydrogen peroxide (H_2O_2) that adjusted pH to 2.0 with HNO_3 to the residue of Fraction 3 at a temperature of 85°C for 5 hours with continuous heating. This reactant is then mixed with 20 ml of ammonium acetate (NH_4OAc), which is obtained by dilution of 5 ml 3.2 M NH_4OAc and 20% (v/v) HNO_3, for 30 min at room temperature.
- Fraction 5 – Residual

  After the first four processes of metal removal, the remaining solids, containing predominantly primary and secondary minerals, are extracted by reacting a mixture of hydrogen fluoride (HF) and perchloric acid ($HClO_4$) with the residue of Fraction 4.

Microorganic Pollutants

The results of Torri & Alberti (2012) showed that a 3:2 volume ratio of n-hexane (C_6H_{14}) to acetone ($(CH_3)_2CO$) as extraction solution for the detection of microorganic pollutants in biosolids yielded relatively effective results. The protocol is:

First, a 10 g of biosolids sample is heated at 40°C. Then 20 ml of C_6H_{14} and $(CH_3)_2CO$ mixture is added to the solid and processed for 20 minutes with the aid of an ultrasonic bath. Finally, the extract is put into a gas chromatography mass-spectrometry (GC-MS) system for analysis. This method allows the detection of most organic contaminants and is simple as there is no need for pre-concentration steps.

Soil Testing

When applying biosolids as fertilizer to agricultural land, it is necessary to consider the long-lasting effects of the biosolids on the land apart from the effects of the biosolids alone on the crops. For example, the accumulation of nutrients from biosolids in the soil can influence the amount of biosolids applied. If the accumulation in the soil is ignored, excessive application of biosolids can cause pressure on the ecological balance. Therefore, soil tests including soil pH, nutrients, and contaminants are particularly important.

Soil testing begins with a zoning process based on factors such as original soil fertility, soil texture, and crop type (Keith, 2016). A representative sample of 400 g is taken from each area and the depth of sampling is usually between 5cm and 30 cm below ground level. The samples must be stored in containers at room temperature and sent to the laboratory for testing on the same day.

Frequency of Biosolids Testing

The above monitoring methods are not valid if only conducted once, therefore, in order to ensure timely measurements while taking into account the limited budget, Table 4 (Iranpour et al., 2004) summarizes the testing frequency of each testing method.

Table 4: Summary of sampling frequency according to different monitoring methods

Monitoring Method	Sample Frequency	Sample Location
Pathogen	Depends on biosolids applied in metric tonnes per year: • Once per year (< 320) • 4 times per year (320 ~ 1650) • 6 times per year (1650 ~ 16500) • 12 times per year (>= 16500)	Biosolids
Heavy Metals	Depends on biosolids applied in metric tonnes per year: • Twice per year (< 250) • 4 times per year (250 ~ 1000) • 4 times per year (1000 ~ 2500) • 8 times per year (2500 ~ 4000) • 12 times per year (> 4000)	Biosolids
Microorganic Pollutants	Depends on biosolids applied in metric tonnes per year: • Twice per year (< 250) • 4 times per year (250 ~ 1000) • 8 times per year (1000 ~ 2500)	Biosolids

	• 12 times per year (2500 ~ 4000) • 12 times per year (> 4000)	
Soil Testing	One per three years	Agricultural Land

SOLUTIONS

Based on the information collected, the challenges currently faced must be addressed, if biosolids are to be applied as fertilizer on agricultural lands in China.

Territorial constrains that affect the scale of the construction of wastewater treatment plants and the production of biosolids can be solved using a site-specific approach. The flat regions in the eastern part of China are selected for the construction of wastewater treatment plants and biosolids production lines, while the rugged regions in the western part of China can take advantage of China's well-developed transportation system to complete the two-site transfer. For example, the primary product of a small local wastewater treatment plant can be transported to a large-scale treatment plant in a neighboring area, and conversely, the treated biosolids can be transported to different areas via transport lines. At the same time, this approach can boost the local economy and relieve some of the pressure on the operating costs of wastewater treatment plants.

Both economic and legislative constraints need to be addressed with government support. The government has played a critical role in promoting the use of biosolids as fertilizer on farmlands. The process of producing biosolids requires significant capital investments, so governments can allocate funds or appeal to individual investors to contribute funds. Since the price of produced biosolids is usually high for farmers, the government can provide subsidies that encourage farmers to choose biosolids as a fertilizer. In addition, legislation on the use of biosolids needs to be completed as soon as possible under the government's supervision, and the standards of other countries (e.g., US EPA) can be used to set standards for the use of biosolids in China.

Since biosolids is still a relatively new concept to the Chinese public, in order to increase public acceptance of biosolids as fertilizers, firstly, media such as social networking software can be used to promote the advantages of biosolids. Second, open houses can be set up at farms that use biosolids as fertilizer to attract the public to visit the crops and have volunteers to educate the public about the effects of biosolids. In addition, ensuring that the test results of biosolids are open and transparent can also increase public acceptance.

However, technical limitation is one of the most challenging problems to solve, which will take a period of exploration to achieve. The most common biosolids treatment method in China is composting, but according to the summary of treatment schemes, the most economical and environmentally advantageous method is anaerobic digestion without lime. Therefore, China needs to gradually realize the transition from composting to anaerobic digestion and to select pilot tests to examine the superiority of anaerobic digestion over composting in China.

CONCLUSIONS

The purposes of this paper were to conduct an integrated analysis of biosolids as fertilizers for agricultural land applications in China, to discover the current obstacles to the implementation of biosolids, to compare different biosolid treatment schemes, to discuss the feasibility of using biosolids on agricultural land, and to provide solutions to the obstacles.

The use of biosolids as fertilizers must take into account the necessary conditions, including high production standards, the type of crop, and the amount of biosolids used to reduce the impacts on human and ecosystems. Strict standards of biosolids can limit the concentration of contaminants (i.e., heavy metals, microorganic pollutants, pathogens) in biosolids, and only the biosolids that meet standards can be used as fertilizers. Crop type is also a factor to affect the choice of biosolids, as different crops have changes in N and P needs. However, biosolids as the product of wastewater, their N and P concentrations are relatively fixed from the same treatment plant, so the choice of biosolids can be changed with different crop types. Also,the biosolid dosage can be varied by climate and soil properties. High-volume precipitation can enhance the movement of materials in biosolids above and through the soil, so areas with high precipitation should have less biosolids usage to prevent from surface runoff carrying contaminants from biosolids. And acidic soils can be regulated by high pH biosolids, thus making them more suitable for most crops.

The barriers influencing the use of biosolids as fertilizer in China are summarized as territorial constraints, technical constraints, financial constraints, legislative constraints, and public acceptance. Terrain, a natural factor affecting biosolids production, creates differences between the eastern plains and the western mountainous regions of China. Technological limitations are mainly due to the fact that China is still in the exploratory stage with a slightly late start on wastewater treatment. And economic considerations mainly come from the pressure of investment limiting the construction and operation of a portion of wastewater treatment plants. The lack of legislation on biosolids at the present stage is also a major factor affecting the application of biosolids as fertilizer, and despite the existence of food safety regulations and laws, there is a deficiency of laws related to the safety of raw materials (i.e., biosolids). Finally, public stereotypes and concerns about the safety of biosolids have hindered further development of biosolids.

Wastewater treatment to obtain biosolids can be done by lime stabilization, anaerobic digestion without lime, anaerobic digestion with lime, and composting. The economic analysis of capital investment, operation and maintenance costs, and the environmental analysis of SO_2 emissions, GWE, electricity use, and fuels results in the lime free anaerobic method being the best choice. On the contrary, composting is the most expensive and least environmentally friendly method.

The detection of hazardous compounds can be performed separately from biosolids and from soil. Odors, pathogens, heavy metals, and microorganic pollutants can be measured by taking samples from biosolids. While soil samples need to be taken from different soil areas and soil depth.

Effective solutions are compiled for the identified factors that limit the application of biosolids as fertilizers. The government plays an important role in promoting the application of biosolids throughout the process. Terrain differences allow for the widespread use of biosolids through rapid transportation. With government oversight and subsidies, the economic pressure on producers and farmers can be alleviated, while improved legislation can ensure the quality of biosolids, thus increasing public acceptance. Nevertheless, technical challenges still need extensive experimentation and exploration by researchers.

Based on the information gathered, the application of biosolids as fertilizer on Chinese agricultural land is feasible and this application has a great potential for future market development in China.

SUMMARY and RECOMMENDATIONS

This paper discussed the feasibility of using biosolids as fertilizer on growing wheat in China. However, other crops such as rice, corn and peanut could also be candidate crops but require detailed analysis due to their N and P requirements, major growing regions, and the impacts of pollutant contents. This paper provided a holistic approach to the analysis of crops so that future studies can be adapted to the crop type to obtain more credible results.

As more chemicals and organic compounds are developed and put on the market, more and more of these pollutants are likely to appear in biosolids. Therefore, the detection of organic compounds with a growing trend is a life-cycle assessment that requires timely detection and correction. Future research on biosolids should focus more on emerging organic micropollutants and explore effective methods to reduce their content in biosolids.

In addition, with the total agricultural land area in China on the decline (TrendingEconomics, 2022) and the increase in municipal sewage sludge production, the production of biosolids will outweigh the demand in the future. Apart from considering biosolids as fertilizers for land application, they can also be used as efficient soil remediation products. Therefore, future research direction can also be appropriately adjusted towards soil remediation. At the same time, it is a positive cycle, when more soils unsuitable for cultivation are rehabilitated, the area of agricultural land will increase, thus achieving a balance between biosolids supply and demand.

References

Anonymous. (2022). https://en.unesco.org/creative-cities/sites/default/files/OverviewofChengduEnglishversion.pdf

Bai, S., Srikantaswamy, S., Krishnanandan, V., & Naik, O. P. (2011; 2012). Speciation of heavy metals in biosolids of wastewater treatment plants at mysore, karnataka, india. *Environmental Monitoring and Assessment, 184*(1), 239-249. https://doi.org/10.1007/s10661-011-1964-3

Byliński, H., Barczak, R. J., Gębicki, J., & Namieśnik, J. (2019). Monitoring of odors emitted from stabilized dewatered sludge subjected to aging using proton transfer reaction–mass spectrometry. *Environmental Science and Pollution Research International, 26*(6), 5500-5513. https://doi.org/10.1007/s11356-018-4041-4

Chen, H., Yan, S., Ye, Z., Meng, H., & Zhu, Y. (2012). Utilization of urban sewage sludge: Chinese perspectives. *Environmental Science and Pollution Research International, 19*(5), 1454-1463. https://doi.org/10.1007/s11356-012-0760-0

Chen, H., Zhang, C., Han, J., Yu, Y., & Zhang, P. (2012). PFOS and PFOA in influents, effluents, and biosolids of chinese wastewater treatment plants and effluent-receiving marine environments. *Environmental Pollution (1987), 170*, 26-31. https://doi.org/10.1016/j.envpol.2012.06.016

City of Abbotsford. (2022). Biosolids Management. https://www.abbotsford.ca/city-services/water-wastewater/biosolids-management

Collivignarelli, M., Abbà, A., Frattarola, A., Carnevale Miino, M., Padovani, S., Katsoyiannis, I., & Torretta, V. (2019). Legislation for the reuse of biosolids on agricultural land in europe: Overview. *Sustainability (Basel, Switzerland), 11*(21), 6015. https://doi.org/10.3390/su11216015

de Sena, R. F., Tambosi, J. L., Floriani, S. L., Virmond, E., Schröder, H. F., Moreira, R. F. P. M., & José, H. J. (2009). Determination of inorganic and organic priority pollutants in biosolids from meat processing industry. *Waste Management (Elmsford), 29*(9), 2574-2581. https://doi.org/10.1016/j.wasman.2009.05.002

Iranpour, R., Cox, H. H. J., Kearney, R. J., Clark, J. H., Pincince, A. B., & Daigger, G. T. (2004). Regulations for biosolids land application in U.S. and European Union. *Residuals Science & Technology, 1(4), 209-222.* https://d3pcsg2wjq9izr.cloudfront.net/files/9256/articles/5809/Regulations.pdf

Keith, R. (2016). Soil Sampling and Analysis for Managing Crop Nutrients. Ministry of agriculture, food, and rural affairs. http://omafra.gov.on.ca/english/engineer/facts/06-031.htm

Luo, Y., Qiao, X., & Wu, S. (2000). Land use of sludge and its environmental impact. *Tŭrăng (nánjīng), 32*(2), 79-85. https://doi.org/10.3321/j.issn:0253-9829.2000.02.006

MedlinePlus. (2022). *PCR Tests.* https://medlineplus.gov/lab-tests/pcr-tests/

Meng, X., Venkatesan, A. K., Ni, Y., Steele, J. C., Wu, L., Bignert, A., Bergman, Å., & Halden, R. U. (2016). Organic contaminants in chinese sewage sludge: A meta-analysis of the literature of the past 30 years. *Environmental Science & Technology, 50*(11), 5454-5466. https://doi.org/10.1021/acs.est.5b05583

MOHURD. (2019). *Chinese Statistical Yearbook of Urban and Rural construction.* http://www.stats.gov.cn/tjsj/ndsj/2019/indexeh.htm

Murray, A., Horvath, A., & Nelson, K. L. (2008). Hybrid life-cycle environmental and cost inventory of sewage sludge treatment and end-use scenarios: A case study from china. *Environmental Science & Technology, 42*(9), 3163-3169. https://doi.org/10.1021/es702256w

Pepper, I. L., Brooks, J. P., & Gerba, C. P. (2006). Pathogens in biosolids. *Advances in agronomy* (pp. 1-41). Elsevier Science & Technology. https://doi.org/10.1016/S0065-2113(06)90001-7

Sidhu, J. P. S., & Toze, S. G. (2009). Human pathogens and their indicators in biosolids: A literature review. *Environment International, 35*(1), 187-201. https://doi.org/10.1016/j.envint.2008.07.006

Soh, T. S. (2018). *China's 13th Five Year Plan: What Role Will Wastewater Play? WaterWorld*. https://www.waterworld.com/home/article/16201297/chinas-13th-five-year-plan-what-role-will-wastewater-play

Stehouwer, R. (2010). *What is sewage sludge and what can be done with it?* PennState Extension. https://extension.psu.edu/what-is-sewage-sludge-and-what-can-be-done-with-it

Sullivan, D.M., Tomasek, A., LaHue, D.G., Verhoeven, B., Moore, A., Brewer, L. J., Bary, A. I., Cogger, C. G., & Dari, B. (2022). Fertilizing with Biosolids. https://catalog.extension.oregonstate.edu/sites/catalog/files/project/pdf/pnw508.pdf

Tessier, A., Campbell, P. G. C., & Bisson, M. (1979). Sequential extraction procedure for the speciation of particulate trace metals. *Analytical Chemistry (Washington), 51*(7), 844-851. https://doi.org/10.1021/ac50043a017

Torri, S. I., & Alberti, C. (2012). Characterization of organic compounds from biosolids of buenos aires city. *Journal of Soil Science and Plant Nutrition, 12*(1), 143-152. https://doi.org/10.4067/S0718-95162012000100012

The State Council the People's Republic of China. (2022). *Food Safety Standards and Monitoring and Evaluation Division.* http://www.nhc.gov.cn/sps/spaqmu/202106/8fa91de44e204c27b12889083eba21e2.shtml

TrendingEconomics. (2022). *China: Agricultural land (% of land area).* https://tradingeconomics.com/china/agricultural-land-percent-of-land-area-wb-data.html

USDA. (2022). *China crop production maps.* https://ipad.fas.usda.gov/rssiws/al/che_cropprod.aspx

USEPA. (2000). *Biosolids and Residuals Management Fact Sheet.* https://www.epa.gov/sites/default/files/2018-11/documents/order-control-biosolids-management-factsheet.pdf

Wang, M. (1997). Land application of sewage sludge in china. *The Science of the Total Environment, 197*(1), 149-160. https://doi.org/10.1016/S0048-9697(97)05426-0

Wang, K. (2018). Status of municipal sewage sludge treatment in Chengdu and countermeasures for sustainable development[J]. *Environmental Health Engineering, 2018, 26(1): 23-25*. http://www.srhj.org.cn/CN/abstract/abstract43.shtml

Wei, L., Zhu, F., Li, Q., Xue, C., Xia, X., Yu, H., Zhao, Q., Jiang, J., & Bai, S. (2020). Development, current state and future trends of sludge management in china: Based on exploratory data and CO2-equivaient emissions analysis. *Environment International, 144*, 106093-106093. https://doi.org/10.1016/j.envint.2020.106093

Zhao, H., Yin, Z., Xiang, H., Liao, Z., & Wang, Z. (2017). Preliminary study on alterations of altitude road traffic in china from 2006 to 2013. *PloS One, 12*(2), e0171090-e0171090. https://doi.org/10.1371/journal.pone.0171090