Chapter

Comparative Life Cycle Assessment of Sewage Sludge (Biosolid) Management Options

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Abstract

Sludge formation during wastewater treatment is inevitable even with proper management and treatment. However, the proper treatment and disposal of sludge are still difficult in terms of cost of treatment, the presence of new pollutants, health problems, and public acceptance. Conventional disposal methods (e.g., storage, incineration) have raised concerns about legislative constraints and community perception that encourage the assessment of substitute sludge management options. Sludge management requires a systematic solution that combines environmental effectiveness, social acceptability, and economic affordability. Life cycle assessment is one of the most important tools to identify and compare the environmental impact of sludge treatment technologies to ensure sustainable sludge management. Increased production of sludge (biosolids) increases worldwide due to population growth, urban planning, and industrial developments. The sludge needs to be properly treated and environmentally managed to reduce the negative effects of its application or disposal. This chapter deals with the application of biosolids or sewage sludge, together with possible resources for sustainable development. In this section, the life cycle assessments of sludge treatment methods were also investigated and found that sludge treatment techniques lead to major environmental impact categories such as global warming potential, human toxicity, acidification potential, and resource consumption.

Keywords: life cycle assessment, sludge management, biosolid management, sustainability, sludge treatment

1. Introduction

Wastewater treatment plants (WWTP) are aimed to decrease the environmental impacts of discharging untreated wastewater into receiving bodies, but considering the need for long-term ecological sustainability, the objectives of wastewater treatment systems should include energy and resource savings and waste reduction [1].

Sewage sludge management is a management system that makes sludge recovery a central component of a wastewater treatment plant that strives to integrate it with improving the sustainability of wastewater plants. Currently, wastewater sludge production, treatment, and disposal methods vary from country to country, and the continued growth of sludge production is becoming a global problem. The sludge production rate is increasing due to the stricter legislation which is constantly solidifying for the sustainable disposal of wastewater. Nowadays, however, due to the increasing environmental awareness of the public and increasing pressure from environmental organizations, sludge management has become necessary with economic and environmentally friendly methods.

Conventional disposal methods (e.g., landfill, incineration, stabilization) have raised concerns about legislative constraints and community perception that encourage the assessment of substitute sludge management options. Sludge management requires a systematic solution combining environmental effectiveness, social acceptability, and economic affordability based on a life cycle approach. Life cycle assessment is one of the most important tools to identify and compare the environmental impact of sludge treatment technologies to ensure sustainable sludge management.

Generally, the terms biosolids and sewage sludge are used interchangeably. Biosolid includes 20% content of fat, 50% carbohydrate content, 30–40% content of organic matter, 3% total nitrogen, 1.5% total phosphorus, 0.7% total potassium content, 10–20% C/N ratio, pH of 6.5–7.0, and a specific gravity of 1.00 as reported by [2]. It is a by-product of treatment plants in large quantities varying in characteristics, containing organic and inorganic chemicals, heavy metals (iron, chromium, manganese, zinc, mercury, lead, nickel, cadmium and copper), and pathogens. It is considered as a resource due to the widespread application in biogas production, soil filling, organic fertilizer, and soil amendment.

Life cycle assessment (LCA) is a standardized and recognized tool to measure the overall environmental impact of providing a product or service. It is increasingly used to support commercial claims of products' environmental performance. It is also used as the basis for European environmental legislation, including Integrated Pollution Prevention and Control (IPPC) and Integrated Product Policy [3].

ORWARE, SimaPro, MARTES, UMBERTO, Ecobilan, LCAiT, SiSOSTAQUA, BioWin*, STAN*, GaBi 6, WWEST, BEAM, GEMIS, and Quantis Suite are the best known commercial sludge treatment and management LCA software. Among them SimaPro is the most widely used model. Global warming, acidification, eutrophication, photochemical smog, human toxicity, ecotoxicity, depletion of abiotic resource, and terrestrial ecotoxicity are the fundamental impact categories of sludge management [4–12]. Life cycle assessment methodology is generally implemented for the main sludge management like dewatering, thickening, and anaerobic digestion [12–18].

This chapter deals with the application of biosolids or sewage sludge, together with possible resources for sustainable development. Moreover, the life cycle assessments of sludge treatment methods were also investigated and found that sludge treatment techniques lead to major environmental impact categories such as global warming potential, human toxicity, acidification potential, and resource consumption.

2. Life cycle assessment (LCA)

Life cycle analysis (LCA) is a method of assessing the environmental impact of products and processes throughout their lives, including raw material procurement, production, use, final disposal, and all transport phases between these stages.

With this analysis, the comprehensive inventory of all energy, water, and substance inputs together with the emitted waste is evaluated together, and the possible environmental effects of the products are calculated. Unlike other narrow-scale environmental impact analyses, the LCA examines environmental issues with its "cradle-to-grave" approach [19].

Depending on the stage of the life cycle, LCA studies can be grouped as "cradle to grave," "cradle to door," "cradle to cradle," and "door to door." It is a definition used for studies examining the whole life cycles of a product or process from cradle to grave and includes all the processes to be passed from the raw material production (cradle) to the disposal of the waste (grave).

A product or process from the cradle to the door partially covers the processes from the production of the raw material (cradle) to the stage (door) to which it is delivered to the factory. This is a life cycle study which partially covers processes.

The recycling of waste during the waste disposal phase is referred to as the cradle-to-cradle approach.

"Door to door" is an approach that deals with the life cycle of a single stage of a product or a process [20].

LCA is a rapidly evolving tool designed to help environmental management in sustainable products and services in the longer term, also called "life cycle analysis," "life cycle approach," "cradle-to-grave analysis," or "ecological balance."

The standard LCA method consists of four main steps:

First step: aim and scope definition: At this stage, the objective of LCA study, target groups, basic variables, necessary data, constraints, and assumptions used are defined. Systematic and functional units are the two most important elements defining the scope and knowledge of the study, and while determining the system boundaries, the life cycle of the product is included in the analysis [21]. The functional unit refers to the unit function of the system under consideration and should be expressed clearly and in detail and should reflect the basic function of the product or system [22].

Second step: life cycle inventory analysis: At this stage, energy, water, raw material inputs, and released solid waste, wastewater, and air emissions are determined within the boundaries. In the meantime, inventory information about all unit processes in the product's life cycle is compiled through data collection forms, and deficiencies are completed by using literature review and sectoral reports.

All collected data is rearranged according to the functional unit. It is made available for the calculation of environmental impacts. At this stage, data quality and accuracy are vital at every step.

As a result of the literature research, it was determined that UMBERTO, GEMIS, SimaPro, GLOSSARY BEAM, MARTES, Ecobilan, LCAiT, SiSOSTAQUA, BioWin, STAN, GaBi 6, and WWEST are the most preferred sludge treatment and management LCA software [4–12]. Among them SimaPro is the most widely used model. Global warming, acidification, eutrophication, photochemical smog, human toxicity, ecotoxicity, depletion of abiotic resource, and terrestrial ecotoxicity are the fundamental impact categories of sludge management. Life cycle assessment methodology is generally implemented for main sludge management like dewatering, thickening, and anaerobic digestion [12–18].

Third step: life cycle impact analysis: At this stage, environmental impact potentials are calculated using inventory data collected and compiled in the previous stage. Mandatory (classification and characterization) and voluntary (normalization and weighting) substages of the impact analysis stage are defined in [23, 24]:

a. At the classification stage, the individual inventory items are assigned according to the relevant environmental impact categories. For example, CO_2 emissions are categorized as "global warming." The most commonly used environmental impact categories in LCA studies are acidification, eutrophication, global warming, photochemical ozone formation, ozone depletion, ecotoxicity, and resource consumption (see **Figure 1**).

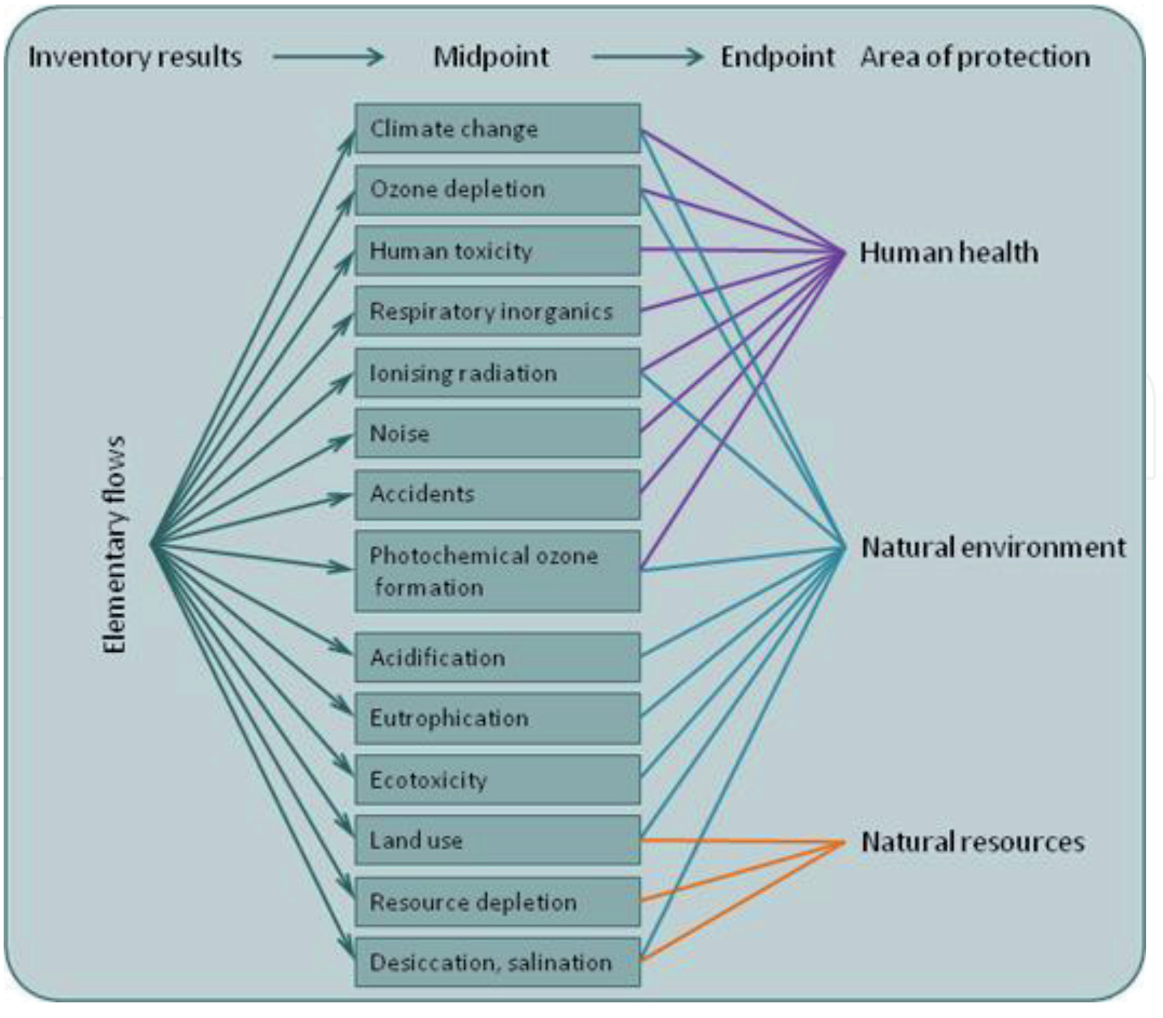

Figure 1.
LCA impact assessment mechanism [19].

b. In the characterization stage, inventory items contributing to the same environmental problem are multiplied by the relevant coefficients and expressed over the common unit, and the aggregated impact is calculated for each environmental impact category. For example, CO_2, CH_4, and N_2O emissions leading to global warming are expressed by an equivalent of kg CO_2.

c. In the normalization phase, different environmental impact potentials are compared according to the common reference system using accepted normalization methods. Normalization indicates which environmental impact potential is higher.

d. In the weighting phase, the normalization results are multiplied by coefficients using one of the weighted methods that are accepted and based on the reduction targets for each environmental impact category. Weighting reveals which environmental impact potential is more important. LCA has a wide range of applications in the private, public, and academy sector for a wide range of products, services, and systems. LCA develops strategic planning, public policies, and performance indicators; identifies priority products and processes in production; identifies improvement opportunities; provides important inputs in product development or redesign stages, various sustainability declarations, and eco-label programs; and support and compare different production alternatives. Among these, environmental declarations and carbon and water footprint calculations are important in sustainable consumption and production.

Fourth step: interpretation of results: It is the purpose of this stage to interpret the results of the inventory and environmental impact analysis stages according to the purpose and scope of the study and to present important results and recommendations for the system or product under consideration [23, 24].

The carbon footprint is an environmental indicator that measures the global climate change caused by greenhouse gases (GHG) from the life cycle of products and services. Greenhouse gases emitted at each stage are expressed in terms of the total CO_2 equivalent units multiplied by the relevant coefficients. Basically carbon footprint calculation is also a life cycle approach; however, unlike LCA, it does not cover all emissions but only inputs that contribute to global warming. Principles and procedures for product carbon footprint calculation and declaration are defined in [24], ISO 14067: 2013. Here, ISO 14040 and ISO 14044 LCA standards are used for footprint calculations, and ISO 14020, ISO 14024, and ISO 14025 standards are used for declarations [24].

Water footprint calculations are likewise based on life cycle principles, and the basic rules and principles for footprint calculations of products, processes, and institutions are included in the ISO 14046: 2014 standard. With this method, in addition to direct and hence water input-outputs, air and soil emissions affecting water quality are also addressed [25].

The main uses of LCA can be summarized as follows:

a. Analyzing problems related to a specific product

b. Determining the important parameters that affect a study for product development

c. New product design

d. Choosing between similar products, processes, and services

One of the areas where LCA is used in particular is green purchasing applications. Eco-labels (where environmentally friendly products are documented) are preferred by consumers; Blue Angel is used in Germany, but in Scandinavian countries Green Swan is used.

Below are examples of other uses:

a. Compliance of the various packaging alternatives with the European Union's packaging directive

b. Evaluating the different waste management approaches of the municipalities

c. Comparing different types of biomass for a particular use (e.g., obtaining electricity) to determine environmental advantages and disadvantages

d. Strategic comparison between alternatives in order to make a decision on a public investment, for example, evaluation of transport methods (road, rail, sea) for certain regions or a particular sector

e. Harmonization of the construction sector with the environment

f. Improving the raw material production stage by switching to sustainable raw materials in production

g. Reducing the carbon footprint by increasing the energy efficiency of the electronic goods produced through R&D studies

h. Making product shipments more efficient and reducing air emissions by making changes in product packaging

i. Reducing the environmental impact of the final disposal phase by designing more recyclable products

As a summary the LCA study, which covers all stages of the product value chain, evaluates the total environmental impact such as global warming, acidification, eutrophication, photochemical smog, human toxicity, ecotoxicity, depletion of abiotic resource, and terrestrial ecotoxicity which are the fundamental impact categories of sludge management [26].

3. Life cycle assessment of sewage management

A sludge management that yields the best results requires a systematic solution that combines environmental effectiveness, social acceptability, and economic affordability based on a life cycle approach. For example, it is reported in the literature that total sludge production in China increased by an average of 13% per annum from 2007 to 2013, producing 6.25 million tons of dry solids in 2013 and reaching 39.78 million tons in 2020. In the same study, more than 80% of the sludge was disposed without any process, the organic content of the sludge was around 37%, and because of this low organic matter content, anaerobic digestion was not an efficient method, and therefore storage and incineration after dewatering was the most common method [27]. With the increase in population, the urban settlement areas expanded, and many of the wastewater treatment plants in the rural areas are now located within the settlements, and the gradual improvement in socioeconomic development and living standards has led the residents to pay more attention to the quality of the living environment [1]. In addition, since the environmental awareness of the public has increased, the odors caused by treatment plants have become a new and troublesome social problem. Another study suggests that municipal waste management in China tends to incinerate instead of landfill, but it causes social conflicts as it impedes the construction of treatment plants near public land or habitats [28].

Another study reached a more striking conclusion, stating that the inhabitants of 12 Chinese cities protested the incineration projects due to environmental concerns and only three incineration projects were allowed from 2009 to 2015, while others were canceled and the disposal of sludge into the long-term storage or incineration facilities was increasingly difficult [29].

Since EU member states have to reduce the amount of biodegradable municipal waste to 35% of 1995 by 2016, they have to make the transition from a linear to circular economy where waste can be converted into resources. Therefore, like all biodegradable wastes, wastewater sludge is seen as a source of energy and material production. However, a sewage management should be considered, including the method of processing sludge, where and how the final products (e.g., fertilizer, biogas) are used, the amount of greenhouse gas (GHG) emissions, and the selection of the most sustainable wastewater sludge treatment technology. Composting, anaerobic digestion, incineration, chemical stabilization, and the use of fertilizer in agricultural land are the most commonly used sewage management methods. The change of sludge management methods from country to country was mentioned in the previous chapters. Portugal, Ireland, the United Kingdom, Luxembourg, and Spain use more than 75% of the sludge produced as fertilizer for agricultural land; 86% of the sludge produced in Lithuania, Finland, and Estonia is composted; the Netherlands, Belgium, Germany, Slovenia, Austria, and Switzerland prioritize incineration, while Malta, Romania, Italy, and Bosnia and Herzegovina mostly report the use of sludge for storage [30].

In a sludge life cycle assessment study in France, it was noted that the final combination of anaerobic digestion and land application caused the lowest emissions during operation [5]. Many researchers have indicated that, from an economic point of view only, a large-scale incineration plant or anaerobic digester may be the most effective way to treat sludge [30].

It was reported that land filling has the greatest impact (296.9 kg CO_2 eq./t sludge), followed by mono-incineration (232.2 kg CO_2 eq./t sludge) and carbonization (146.1 kg CO_2 eq./t sludge) in terms of the emission quantity of greenhouse gases. They also stated that co-incineration with municipal solid waste has the benefit of reducing greenhouse gas emission by −15.4 kg CO_2 eq./t sludge [31].

A calculator calculating the greenhouse gas (GHG) emissions (carbon dioxide including bio-based, methane, and nitrous oxide measured as carbon dioxide equivalents) from sewage sludge treatment methods found at the end of the comprehensive study showed that composting, anaerobic digestion, and incineration resulted in the lowest emissions of the GHG gases. If you need to elaborate further, anaerobic digestion generated the least carbon dioxide equivalent emissions among all the treatment methods studied. The second best option was incineration of sludge, while the third best was composting [31].

In another study a life cycle assessment (LCA) was performed on five common sewage sludge treatment practices, namely, dewatering of mixed sludge, lime stabilization of dewatered sludge, anaerobic digestion of mixed sludge, dewatering of anaerobically digested sludge, and incineration of dewatered anaerobically digested sludge. The sludge residues were applied on agricultural land, and it was found that the incineration of dewatered anaerobically digested sludge scenario performed better results [2].

Ten impact categories, namely, human toxicity carcinogenic effects, human toxicity non-carcinogenic effects, ecotoxicity, freshwater eutrophication, marine eutrophication, terrestrial eutrophication, terrestrial acidification, particulate matter formation, climate change, and photochemical oxidant formation, were also assessed in this study. It was concluded that in human toxicity and ecotoxicity categories, impacts were dominated by the application of zinc and copper to agricultural soil. For the freshwater eutrophication potential category, the fate of phosphorus was found to be (P) dominated, while the fate of N had a profound effect on all nontoxic impact categories other than freshwater eutrophication [2].

4. Conclusions

As a result of the literature blended in this section, it is concluded that biosolids have significant disadvantages for their use in agriculture and other applications and, therefore, sludge or biosolids should be sampled, controlled, and monitored regularly for pollutants (pathogens, heavy metals, etc.). However, it is also concluded that biosolids play an important role in energy production, and crop production. The most comprehensive sludge management studies have shown that land application is an important contribution to global warming, eutrophication, and acidification. More scientific research is needed on different aspects of biosolids or sewage sludge to be a more suitable resource for sustainable development. It is vital that the most efficient sludge management strategy should focus on economic, technological, and societal constraints.

The LCA study, which covers all stages of the product value chain, evaluates the total environmental impact such as global warming, acidification, eutrophication, photochemical smog, human toxicity, ecotoxicity, depletion of abiotic resource, and terrestrial ecotoxicity which are the fundamental impact categories of sludge management.

A literature blending in GHG showed that composting, anaerobic digestion, and incineration have the lowest emissions. Many researchers have indicated that, from an economic point of view only, a large-scale incineration plant or anaerobic digester may be the most effective way to treat sludge. A sludge management that yields the best results requires a systematic solution that combines environmental effectiveness, social acceptability, and economic affordability based on a life cycle approach.

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