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Çamur Arıtımının Yaşam Döngüsü Değerlendirmesi- Genel Bakış

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Özet

Arıtma çamurları, atıksu arıtma proseslerinin son ürünü olarak oluşur ve çamur yönetimi, arıtma tesislerinin işletiminde hem ekonomik hem de çevresel açıdan öneme sahiptir. Arıtma çamurlarının yönetimi çevreye olumsuz etkileri olan başlıca proseslerden birisidir. Atıksuların arıtılması sonucu oluşan arıtma çamurları, patojenler, ağır metaller, iz ve kalıcı organik kirleticiler içerebilir. Buna karşın; stabilize edilmiş çamur ise nütrient içeriği sebebiyle gübre olarak kullanılabilir. Bununla birlikte, ısıl değeri uygun olursa ek yakıt olarak da kullanılabilir. Arıtma çamurları bu sebeplerle aynı zamanda yenilenebilir enerji ve ham madde kaynağıdır. Susuzlaştırma, yoğunlaştırma, stabilizasyon, çürütme, kompostlama, piroliz, insinerasyon, kurutma, ıslak oksidasyon, süper kritik ıslak oksidasyon, düzenli depolama ve fosfor geri kazanımı uygulanan çamur arıtım metotlarıdır. Sürdürülebilir çamur yönetimini sağlamak için yaşam döngüsü değerlendirmesi, çamur arıtım teknolojilerinin çevresel etkilerinin belirlenmesi ve karşılaştırılmasına olanak sağlayan en önemli araçlardan biridir. Yaşam döngüsü değerlendirme (YDD), bir ürün ya da hizmetin yaşam döngüsü boyunca beşikten mezara kadar, girdilerinin, çıktılarının ve potansiyel çevresel etkilerinin gözden geçirilip değerlendirilmesini sağlayan bütünsel bir çevresel etki değerlendirme aracıdır. Yaşam Döngüsü Değerlendirme, bir ürün ya da hizmetin beşikten mezara yaklaşımıyla çevresel etkilerin analizini öngörür. Yaşam döngüsü değerlendirme, çevresel tehlikeleri tanımlamada kullanılan genişletilmiş bir çevresel etki değerlendirme metodolojisidir. Bu çalışmada, çamur arıtım metotlarının yaşam döngüsü değerlendirmeleri incelenmiştir. Yapılan çalışmalar, çamur arıtımının yaşam döngüsü değerlendirmesinde, ORWARE, SimaPro, MARTES, TEAM by, Ecobilan, UMBERTO, LCAiT, SiSOSTAQUA, BioWin*, STAN*, WWEST, BEAM, GaBi 6 ve GEMIS modellerinin sıklıkla tercih edildiğini göstermektedir. İncelenen 40 çalışma sonucunda, çamur arıtım tekniklerinin küresel ısınma potansiyeli, insan toksisitesi, asidifikasyon potansiyeli ve abiyotik kaynak tüketimi gibi majör çevresel etki kategorilerine yol açtığı bulunmuştur. IPCC, Ecoinvent, CML 2002 ve IMPACT 2002+ çamur arıtımı için kullanılan temel yaşam döngüsü etki değerlendirme metotlarıdır. Sürdürülebilir çamur yönetimini sağlamak için yaşam döngüsü değerlendirmesi, çamur arıtım teknolojilerinin çevresel etkilerinin belirlenmesi ve karşılaştırılmasına olanak sağlayan en önemli araçlardan biridir.

Anahtar kelimeler: Yaşam Döngüsü Değerlendirme; Arıtma Çamuru; Sürdürülebilirlik; Çevresel Etki

Life Cycle Assessment of Sewage Sludge Treatment - An Overview

Abstract

Sewage sludge occurs as an end-product of wastewater treatment processes, and its management holds importance in the operation of wastewater treatment plants from both an economic and an environmental point of view. Sewage sludge management is one of the main processes that have several unfavorable impacts to environment. Sewage sludge resulting from wastewater treatment can contain pathogens, heavy metals and trace and recalcitrant organic pollutants however stabilized sludge can be used as fertilizer because of its nutrient content. Besides, sludge can be used as additional fuel if its calorific value is available. So sludge is also renewable energy and raw material source. Dewatering, thickening, stabilization, digestion, composting, incineration, drying, wet oxidation, supercritical wet oxidation, landfilling and phosphorus recovery are implemented methods for sludge treatment. Life Cycle Assessment (LCA) is an integrated environmental assessment tool that ensures the review and evaluation of the inputs, outputs, and potential environmental impacts of a product or service during its life cycle, from cradle to grave. Life cycle assessment (LCA) envisages a cradle-to-grave approach for analyzing the environmental impacts of a product or system. Life cycle assessment is an extended environmental impact evaluation methodology that can be used to identify environmental hazards. In this study, conducted life cycle assessments of sludge treatment methods have been investigated. These studies demonstrate ORWARE, SimaPro, MARTES, TEAM by, Ecobilan, UMBERTO, LCAiT, SiSOSTAQUA, BioWin*, STAN*, WWEST, BEAM, GaBi 6 and GEMIS models that are frequently preferred for life cycle assessment of sludge treatment. As a result of researched 40 studies, it was found that sludge treatment techniques cause major environmental impacts categories such as global warming potential, human toxicity, acidification potential and abiotic resource depletion. IPCC, Ecoinvent, CML 2002 and IMPACT 2002+ are the main life cycle impact assessment methods for sludge treatment. To ensure sustainable sludge management; life cycle assessment is one of the significant tools that enable to detect and compare environmental impacts of sludge treatment technologiesi.

Keywords: Life Cycle Assessment; Sludge; Sustainability; Environmental Impact

1. Introduction

Wastewater treatment (WWT) plants should pay attention to the management of the sludge produced, because of its huge volume and its environmental impacts recently. The majority of pollutants that affect wastewater are concentrated by treatment processes in sludge; it is therefore critical having a suitable assessment methodology of sludge management options to analyse if pollution is redirected from water to other media, such as air and soil [1]. Sludge is a semi-solid residue generated resulting from wastewater treatment processes. Sewage sludge that is generated in various wastewater treatment methods such as primary settling, biological settling and tertiary treatment and chemical settling can include pathogens, heavy metals and recalcitrant organic and inorganic pollutant substances. Due to its content, sludge handling processess that have serious environmental impacts have been gained importance lately. For electing effective and less hazardous sludge handling process for environment, it should be known which one has less environmental impacts [3].

Life cycle assessment (LCA) methodology can be implemented to detect the environmental impacts of sludge treatment techniques and to decide which is applied and to collate with each other. The management of sewage sludge is often multi-focused and requires considering both economic and environmental consequences [7]. Life cycle assessment is a widespread and integrated environmental impact evaluation methodology over the past decade and one of the most widely known and internationally accepted procedures to compare environmental impacts of processes and systems and to evaluate their sustainability in the entire life cycle [1]. Life Cycle Assessment (LCA) can be a suitable tool of the sustainability assessment giving the quantitative and overall information on resources consumption and environmental emissions of the systems investigated [2]. Several researchers adopted this methodology to assess the environmental burdens of alternative sludge management scenarios [3-4] or treatment technologies [5-6].

Life cycle assessment gets easier this case. The studies that are related to LCA of sludge treatment methods demonstrate that life cycle assessment is the effective determination tool to detect which method is implemented. In several studies, by using different softwares, LCA evaluation of sludge treatment process such as dewatering, stabilization, thickening and other disposal methods have been realized.

This study aims to analyze life cycle assessment surveys in sludge treatment presented in the literature and to gather them under one roof.

2. Sludge Treatment

A wastewater treatment plant (WWTP) is a facility in which a combination of various processes (e.g., physical, chemical and biological) are used to treat industrial and domestic wastewater and remove pollutants [8]. Until recently, sludge disposal has attracted little attention compared with considerable emphasis on discharges of treated wastewater. Sludge management in wastewater treatment plants is a significant environmental issue all over the world. Each of these management options has its own merits and disadvantages [9].

Sewage sludges contain sediments in raw wastewater and solid substances formed during wastewater treatment [10]. Dewatering, thickening, stabilization, digestion, composting, pyrolysis, incineration, drying, wet oxidation, super critical wet oxidation, landfilling, conditioning, thermal treatment, elutriation are the mainly sludge treatment and disposal methods. It should be known the specific features of raw sludge to determine which method will be implemented. Main sludge resources of a biological wastewater treatment plant are primary settling tank and secondary settling tank [11].

2.1. Sludge Resources of WWTPs

Sludge treatment systems show differences according to sludge sources, process type and operating method. [11]. Sludge resources of wastewater treatment plants are given in Table 1 [12].

Table 1. Sludge resources of WWTP's [18]

Process	Sludge Type
Screenning	Rough Solid Waste
Grit Chamber	Sand and Scum
Pre-aeration	Sand and Scum
Primary Sedimentation	Primary Sludge and Scum
Biological Treatment	Suspended Solids
Secondary Sedimantation	Biological Sludge and Scum
Sludge Disposal	Sludge, compost and ash

In a wastewater treatment plant, main types of sludge are:

Primary sludge: generated by settleable solids removed from raw wastewater in primary settling. This sludge has high putrescibility and good dewaterability when compared to biological sludge. Dried solids (DS) content in primary sludge vary between 2 % and 7% [16];

-**Secondary sludge** (or *biological* sludge) : produced by biological processes such as activated sludge consisting of microorganisms, biodegradable matter (either soluble or particulate), endogenous residue, and inert solids. DS content in secondary sludge changes between 0,5 % and 1,5%[16];

Chemical sludge: produced by precipitation of specific matters using some chemical like ferric salt or alum (i.e. phosphorus) or suspended solids [17].

2.2. Sludge Properties and Amounts

In determining the sludge treatment and final sludge disposal and removal methods, it is very important to know the properties and content of the sludge and solid waste. At the same time, the source of solid waste is closely related to the sludge age and process type in the system [11]. Some physical properties of treatment sludge have been given in Table 2 [11].

It should not be forgotten that the amount of sludge produced varies greatly according to implemented processess [13]. Sludge volume comprises of huge water content and minor solid matter content. The volume of sludge mainly depends on its water content and slightly on the character of the solid substance [12]. Sewage sludge contains approximately 0,25 % - 12 % dry matter [11].

Table 2. Physical Properties of Sewage Sludge [11]

Sludge/Solid Waste	Definition
Primary Sludge	It is revealed from primary settling tank. It is grey and has bad odor. It can be digested easily.
Chemical Settling Sludge	It is occured in the result of settling with metal salts. It has high iron content and dark red color. In the case of leaving the tank, as primary sludge its digestion is slow. A significant amount of gas escapes and If it stays in the tank for a long time, the density of the sludge increases.
Activated Biological Sludge	It is brown and flocked form. If dark color is observed, then septic conditions have occurred. If its color is light, the settleability is low. Sludge tends to be easily septicidal.
Compost	Its colors are dark brown and black. It is odorless. It can be used as garden mold.
Anaerobic Digested Sludge	It is dark brown-black and contains a lot of gas. If it is digested well, it does not smell bad.
Aerobic Digested Sludge	It is dark Brown. It has flocculant features It is not bad smell but mostly moldy smell. If it is disintegrated, it can be dewatered. easily in sludge drying beds.

Major chemical composition of untreated sludge and activated sludge are total dry solids, volatile solids, grease and fats, nitrogen, phosphorus, potassium such as nutrients, ph, alkalinity, organic acids, and energy content. Nutrient content is important to decide ultimate disposition of the processed sludge. Furthermore, the fertilizer value of sludge depends on its nutrient contents. Alkalinity, pH and organic acid composition have significancy in process control of anaerobic digestion. Heavy metal, pesticide and hydrocarbon contents should be considered in order to decide whether implement of incineration and land application. Calorific value should be known if thermal process is implemented [12].

The microbial activity is based on the amount of sludge applied [14]. Since sewage sludge is formed from many different sources, there are different nutrients for the growth of different organisms in each source. It is also possible to purify disease-causing microorganisms (pathogens) in sludge. The classification of organisms in an environment is called "taxonomy" and it is very difficult to determine their species and amounts. Depending on the type of wastewater to be treated, in particular, the raw primary settling sludge contains a large number of different organisms. There are also many organisms in the activated sludge. Even if fixed nutrients are given, the amount and variety of organisms are constantly changing. Particularly important is the content of pathogenic organisms and organic matter contained in the sludge when sewage sludges are used for agricultural purposes. Organic matter and pathogen removal should be done by applying stabilization procedures for agricultural implementation[11].

2.3. Sludge Treatment Methods

Sludge is produced from either industrial, domestic, or wastewater treatment plants during the process of wastewater treatment and is the solid residue that remains following the wastewater treatment [15]. The sludge treatment network is given in Figure 3 [17,18].

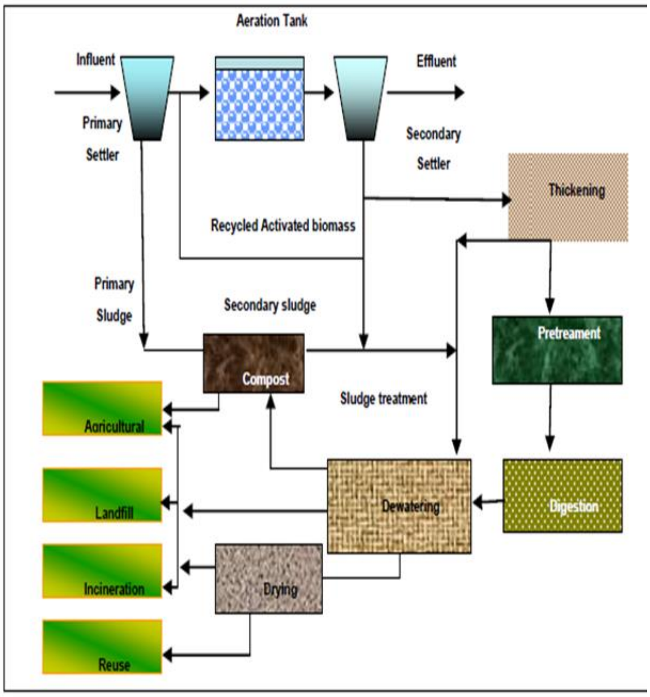

Figure 3. Sludge Treatment Network [17,18]

Main sludge treatment methodologies are dewatering, thickening, conditioning and stabilization [11]. For all that, fundamental final disposal options of sludge are landfilling, agricultural use, composting and incineration [19]. Among the processes, thickening, conditioning, dewatering and drying are the primary methods utilized to seperate water from sludge. Digestion, composting, and incineration are the methods used for stabilization for reduction of the organic matters and pathogenic microorganisms in sewage sludge [12].

Major sludge processing, disposal and treatment methods aim weight, mass and volume reduction and stabilization in general [12]. The waste activated sludge, major by-product of municipal wastewater treatment has been increasing worldwide as a result of an increase in the amount of wastewater being treated [24]. Anaerobic digestion is the most well–known and common process for stabilization of treatment sludge. Anaerobic digestion is a slow process, which results in a long residence time and the requirement of a large tank volume. In order to improve hydrolysis and anaerobic digestion performance disintegration was developed as the pre-treatment process of sludge to accelerate the anaerobic digestion and to increase degree of stabilization [31].

Sludge minimization is very important for decreasing operatio costs of wastewater treatment plants. So, sludge reduction should be ensured for limitation of costs.

about reduction of sludge production and minimization of excess sludge [19]. The current approach to sludge minimization is the reduction of volume of wet sludge and the reduction of dry mass of sludge [20]. Aerobic biological treatment processes, such as the widely used activated sludge process generate a large amount of sludge causing a serious problem for water pollution control. Sludge treatment and disposal should be considered for design, operation, and cost [21]. Treatment and disposal of excess sludge can account for 25%–65% of total plant operation costs [22]. For many authorities and engineers, the effective sludge management is still a significant challenge since the investment and operational costs [12]. Treatment and disposal of excess sludge in a biological wastewater treatment system needs enormously high cost, which has been predicted to be 50–60% of the total expense of wastewater treatment plant [23,24].

Sludge disintegration can be defined as the destruction of sludge via external forces. These forces can be physical, chemical or biological [24].Nowadays, for the aim of waste activated sludge (WAS) minimization and more biogas production than classical anaerobic digestion, several disintegration methods have been researched. The methods can be classified as below: [26];

• Chemical disintegration (Fenton process, Ozone treatment, alkaline treatment etc.)

• Mechanical disintegration (Ultrasonic treatment, Stirred ball-mill, Highpressure homogenizer, Lysat centrifuge, Jet Smash Technique, The High Performance Pulse Technique etc.)

• Thermal disintegration

• Biological disintegration (High temperature sludge stabilization with thermophilic bacteria, Enzymatic lysis)

Ultrasonic treatment [27, 28, 29], ozone oxidation [24, 25, 30, 31], mechanical disintegration [32], alkaline treatment [33], thermal treatment [34], Fenton Process [35], and biological hydrolysis with enzymes [36] were investigated for sludge disintegration objective by several researchers in half-scale and lab-scale plants [21].

OSA, wet oxidation, super critical wet oxidation and phosphorus recovery are the other advanced sludge management methods [37].

All sludge treatment and management methods have various significant and negligible environmental impacts. In this study, the previous studies that LCA methodology were implemented for detecting environmental impacts of sludge management, have been reviewed and investigated.

3. Life Cycle Asssessment

3.1. Life Cycle Assessment (LCA) Definition

Life cycle assessment means a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle [38].

Life Cycle Assessment (LCA) is a technique for evaluating the potential environmental and potential impacts associated with a product or service by:

-Compiling an inventory of relevant inputs and outputs,

-Evaluating the potential environmental impacts associated with those inputs and outputs,

-Interpreting the results of the inventory and impact phases in relation to the objectives of the study [38].

Life cycle evaluations involve cradle-to-grave analyses of production or service systems and ensure comprehensive asessments of all upstream and downstream energy inputs and environmental emissions.

There are four main phases of the LCA process:

Scope and Goal: The scoping step determines which processes will be included, which environmental concerns will be included, what economic or social good is provided by the goods or services in question, resolves any technical issues and defines the audience for the LCA [39].

Life Cycle Inventory (LCI): The inventory ensures information about all environmental inputs and outputs from all parts of the product system involved in the life cycle assessment. This involves modeling of the product system, data collection and verification of data for inputs and outputs for all parts of the product system. Inputs contain materials, energy and chemicals. Outputs include air emissions, water and wastewater emissions and solid waste [39].

Life Cycle Impact Assessment: The assessment takes inventory data and converts it to indicators for each impact category. A typical list of impact indicators includes [39] :

• Global Climate Change
• Stratospheric Ozone Depletion
• Smog
• Noise
• Acidification
• Eutrophication
• Natural Resources Consumption (habitat, water, fossil fuels, minerals, biological resources)
• Human Toxicity
• Ecotoxicity.

Data Interpretation: The last step is an analysis of the impact data that leads to the conclusion whether ambitions from the aim and scope can be met.

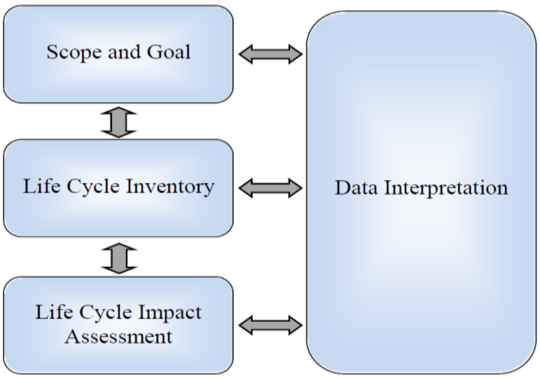

Figure 1. Phases of a Life Cycle Assessment [40]

3.2. Life Cycle Impact Asssessment Methodologies

Life cycle impact assessment (LCIA) is the third and the most significant phase of LCA. A typical LCA contain global climate change, ozone depletion, smog, acidification, eutropication, natural resources consumption, human toxicity, ecotoxicity as environmental impact categories. It has been realized by using different LCA approaches and softwares.

LCA, with its ambition to ensure insights into the potential environmental effects of the complete and detailed system associated with the provision of goods and services, has evolved into a powerful and fairly robust methodological framework. Such a comprehensive LCA approach can be described as a ‘‘detailed LCA’’ when compared to simplification approaches [42].

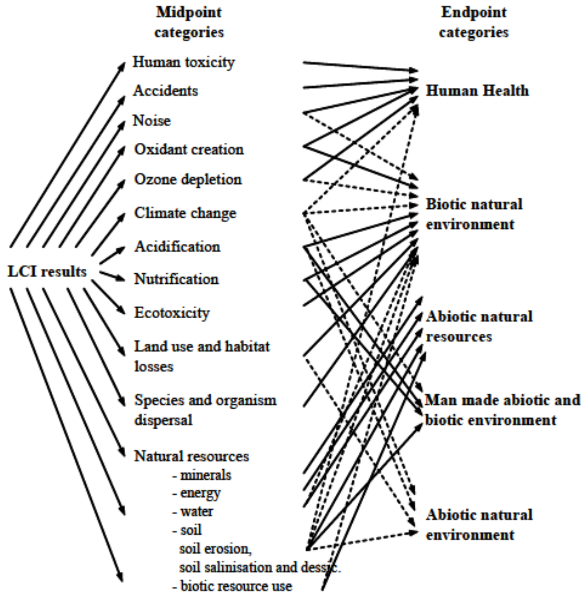

Figure 2. Mechanisms of LCIA [41]

For several practitioners of LCA, it is appropriate to use a dedicated models. A rough division into three classes of software can be made. Generic LCA software, typically intended for use by researchers, consultants and other LCA specialists. Specialized LCA-based software of various types for specific decision makers, typically intended for use by designers in engineering or construction, the purchasing department, or environmental and waste managers. Tailored LCA software systems are used for clearly defined applications in specific IT environments (as interfaces to business management software). These are usually firm-specific adaptations of generic software or software packages programmed directly for the needs of the firm [43]. ORWARE, SimaPro, MARTES, TEAM by, Ecobilan, UMBERTO, LCAiT, SiSOSTAQUA, BioWin*, STAN*, WWEST, BEAM, GEMIS, Quantis Suit [43] are the common commercial LCA softwares.

4. LCA Surveys for Sludge Treatment and Management

4.1. Assessment of the Conducted Studies

Sludge management is receiving increased attention worldwide for a variety of reasons, including the inability to directly discharge or recycle waste streams, and the need for high solid content for purposes of residuals treatment transport, landfilling, disposal, and agricultural usage [44]. For ensuring sludge management, first of all, it should be known how many environmental impact released to the ecosystems.

According to research studies, first of all the method and database have been decided for LCA. In lots of studies, models have been utilized such as Simapro, MARTES and Gabi 6 [49, 50,52, 53, 54,57, 61,62, 73,76, 82,83].

Yoshida et al., studied many studied about this subject [7, 43]. Hospido et al., has many research studies related to this topic [49, 52, 61,69]. Also Svanstrom and her team have several surveys in this manner [5,53].

LCA assessment of sludge management and treatment studies were listed in Table 5 in details [43]. In this table, study area, used LCA databases and LCIA methods, utilized models, assuming functional units, fulfilled sludge treatment techonologies and implemented sensitivity analysis related to the investigated studies have been defined.

According to the table, in several studies, sensity analysis have not been applied [6, 45,46, 49,50,52,53, 55, 56, 57, 58, 59, 61, 62, 63, 64, 65, 67, 68, 69, 70, 71, 72, 73, 75, 76, 77, 78, 79, 81,82, 83].

Life cycle assessment methodology is generally implemented for main sludge treatment such as dewatering, thickening and anaerobic digestion [45, 46, 47, 48, 49, 51, 52, 54, 56, 57, 58, 61, 63, 64, 66, 67, 69, 70, 71, 72, 73, 74, 76, 77, 78, 79, 80, 81, 82, 83].

According to the studies, IPCC, Ecoinvent, CML and IMPACT 2002+ are the commonly used life cycle impact assessment (LCIA) methods for sludge treatment and management [6, 48, 49, 52, 56, 57, 59, 62, 64, 66, 67, 68, 69, 72, 74, 76, 77, 78, 80, 81,83].

For detecting functional units of all LCA studies for sludge treatment, treated and/or disposed sludge amounts and volumes and treated wastewater amounts have been considered.

In this chapter, LCA metholody and LCIA methods for sludge treatment have been indicated with Table 5. In section 4.2. , the impacts results of LCA for sludge treatment have been given with details.

Reference Number	Search Area	LCI Database and LCIA Methods	Models Used	Sensitivity Analysis	Sludge Treatment Technologies Considered	Functional Unit
[45]	Sweden	EPS	ORWARE	-	Anaerobic Digestion, Composting, Drying, Using on land	1 individual equivalent for 1 year
[46]	Australia	-	-	-	Anaerobic Digestion, Phosphorus recovery, Lime Addition, Drying, Using on land	1 mg of thickened sludge
[47]	Sweden	-	-	Electricity substitution rate	Thickening, Dewatering, Phosphorus recovery, Lime Addition, Coincineration, Using on land, Aerobic stabilization	1 mg of sludge
[48]	France	CML and BUWAL	-	Weight and mass impact factor	Thickening, Dewatering, Anaerobic Digestion, Pyrolysis Lime Addition, Composting, Using on land, Landfilling, Monoincineration.	1 mg of mixed sludge
[49]	Spain	SimaPro databank, CML, USES LCA, IPCC, BUWAL	SimaPro	-	Thickening, Dewatering, Using on land	Daily wastewater flow under humid and dry condition
[50]	Göteborg, Sweden	EPS and ET-long	MARTES	-	Coincineration, Using on Land, Phosphorus recovery, Pasteurization	1 mg of mixed sludge
[51]	Ålborg, Denmark	SEA	-	Fourteen operational parameters	Composting, Anaerobic Digestion, Drying, Monoincineration, Using on land, Coincineration, Landfilling.	1 mg removed chemical oxygen demand from wastewater
[52]	Galicia, Spain	IDEMAT, BUWAL, CML, IPCC, USESLCA	SimaPro	-	Thickening, Dewatering, Anaerobic Digestion, Monoincineration, Using on Land.	1 mg of mixed thickened sludge
[53]	Göteborg, Sweden	EPS and ET-long	MARTES	-	Drying, Wet oxidation, ,Phosphorus recovery, Using on land, Pasteurization, . super critical wet oxidation	1 mg of digested sludge
[54]	Switzerland, France	-	SimaPro	Transport, Volatile solids substance, scale of the treatment plant, sludge dewatering efficiency rate	Wet oxidation, Landfilling, Thickening, super critical oxidation, Dewatering, , Lime Addition, Drying, Monoincineration, Coincineration, Pyrolysis, Using on land.	1 mg of sludge

Table 5. LCA surveys conducted [43] .

Reference Number	Search Area	LCI Database and LCIA Methods	Models Used	Sensitivity Analysis	Sludge Treatment Technologies Considered	Functional Unit
[55]	Generic	-	-	-	Drying, Coincineration	1 kg of digested sludge
[56]	Italy	TEAM database, AQUASAVE, CML USES IPCC	TEAM by Ecobilan	-	Thickening, Dewatering, Anaerobic Digestion, Composting, Monoincineration, Using on land Landfilling.	20 mg of mixed sludge
[57]	Galicia, Spain	IDEMAT, Ecoinvent, CML 2000	SimaPro	-	Thickening, Using on Land, Dewatering	1 person equivalent of wastewater
[58]	Germany	IFU and IFEU database,	UMBERTO	-	Anaerobic Digestion, Using on land	Wastewater from 5000 residents
[59]	Chengdu, China	US EIO-LCA, IPCC	-	-	Coincineration, Using on land	84 mg produced sludge/ 1 day
[60]	Stockholm, Sweden	-	LCAiT	N_2O greenhouse gase emissions from using on land	Wet oxidation, Composting, super critical wet oxidation, Using on land, Phosphorus recovery.	1 mg digested sludge
[61]	Galicia, Spain	IDEMAT	SimaPro	-	Thickening, Dewatering, Anaerobic Digestion, Using on land	1 person equivalent of wastewater
[62]	France	Simapro databank, Eco Indicator, EDIP EPS, Ecopoints, CML	SimaPro	-	Lime Addition, Using on land	Treated Wastewater in the treatment plant for one year
[63]	Japan	Japanese interindustry relationship table, USES LCA.	-	-	Drying, Thickening, , Lime addition, Dewatering Composting, Monoincineration, sludge melting, Anaerobic Digestion	1 mg of sludge
[64]	Taragona, Spain	Ecoinvent, CML	SiSOSTAQUA	-	Anaerobic Digestion, Composting, Coincineration, Using on land, landfilling.	1 m^3 of wastewater
[65]	Rural Australia	USES	-	-	Lime addition, Composting, Drying, coincineration, using on land, landfilling.	2 mg of sludge
[66]	Generic	IFU IFEU databank, IMPACT 2002+ method	BioWin*	Eleven parameters of leakage greenhouse emissions and phosphorus and nitrogen removal	Thickening, Dewatering, Anaerobic Digestion, Using on land.	10 million liters domestic wastewater per day
[67]	EU15	Probas Databank, CML, IMPACT 2002+	STAN*	-	Thickening, Dewatering, Lime addition, Monoincineration, Using on land, Phosphorus recovery.	1 mg of sludge
[68]	France	USES and IPCC method	-	-	Composting, Drying, Using on land.	1 mg of sludge
[69]	Generic	Ecoinvent, CML2	-	-	Anaerobic Digestion, Using on land.	10 liters primary sludge and waste activated sludge

Table 5 continued [43]

Reference Number	Search Area	LCI Database and LCIA Methods	Models Used	Sensitivity Analysis	Sludge Treatment Technologies Considered	Functional Unit
[70]	California, USA	US EIO-LCA	WWEST	-	Thickening, Anaerobic Digestion, Dewatering, Using on land.	1 million liters of wastewater
[71]	Japan	-	-	-	Thickening, Anaerobic Digestion, Drying, Landfill, Sludge melting, Dewatering	12 000 m^3 / day sludge flux for 3 organic loading rates
[72]	Ontario, Canada	CML2	BEAM	-	Dewatering, Thickening, Anaerobic Digestion, Using on land, Landfilling.	100 mg of sludge
[73]	Seva, Spain	CML2	SimaPro	-	Thickening, Dewatering, , Lime addition, Monoincineration, Composting, Anaerobic Digestion	1 mg of sludge
[74]	China	IMPACT 2002+ Ecoinvent	-	Statistical variability analysis	Thickening, Dewatering, Drying, Coinicineration.	1 mg of cement (sludge reuse)
[75]	Shanghai, China	GEMIS, EDIP	GEMIS	-	Coincineration.	1 TJ of steam
[76]	Generic	Ecoinvent, CML 2	SimaPro	-	Anaerobic Digestion, Using on land, Landfilling, Pretreatment processes	10 liters of mixed sludge
[77]	Barcelona, Spain	CML 2	-	-	Anaerobic digestion	100 m^3 thickened sludge
[78]	Sweden	IPCC	-	-	Thickening, Dewatering, Monoincineration Using on Land**,** Struvite precipitation	11 kg of Phosphorus for agricultural purpose
[79]	Japan	JEMAI database	-	-	Anaerobic Digestion, Composting, Monoincineration, hydroapatite precipitation Pyrolysis, Using on Land, Struvire Precipitation, Alkali Extraction Thickening, Drying Dewatering	Treatment of wastewater related to 100 000 individuals
[80]	Saint Louis, Missouri, U.S.	ReCipe 2008,Eco-indicator 99,CML 2002.	-	Monte Carlo Simulation	Dewatering, multiple hearth incineration-ash to landfill	567.8×103 m^3/day wastewater, 105. 5 ton/day dry sludge.
[81]	Gaziantep, Turkey	Energy Market Regulatory Authorities (EMRA), IMPACT 2002 +, Ecoinvent	Simapro Software Version 7.3.3.	-	Dewatering, Thermal drying, Incineration, Landfilling.	Incineration of one kg of digested sewage sludge
[82]	Gothenburg, Sweden	Ecoinvent, ILCD Handbook	Gabi 6	-	Dewatering, Mesophilic digestion,	1 dry tonne of sludge
[83]	Ireland	CML 2001, EPA data	GaBi 6	-	Thickening, Dewatering, Anaerobic Digestion.	35 000 m^3 /day wastewater
[6]	Muret - France, Albi city -France.	Heijungs Guideliness, IPCC.	-	-	Thermal drying, Fry-drying, Conventional Drying.	1000 kg of sludge

Table 5 continued [43]

4.2. Results of the Conducted Studies

In this survey study, LCA for sludge management studies have been reviewed. According to the studies, the impact categories of LCA for sludge management have been given in Figure 4.

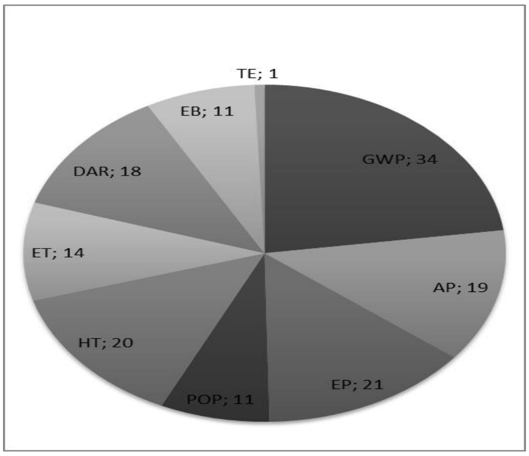

Figure 4. Impact Categories numbers of LCA studies for sludge treatment:

GWP, global warming potential; AP, acidification potential; EP, eutrophication potential; POP, photochemical oxidation potential; HT, human toxicity; ET, ecotoxicity; DAR, depletion of abiotic resource; EB, energy balance, TE, terrestrial ecotoxicity.

Models distribution in the studies that were implemented have been demonstrated in Figure 5.

According to the investigated studies, global warming potential is the most common impact category in LCA of sewage sludge treatment with 34 numbers. Eutrophication potential impact followed it with 21 numbers. Terrestrial ecotoxicity impact has the minimum effect among them**.**

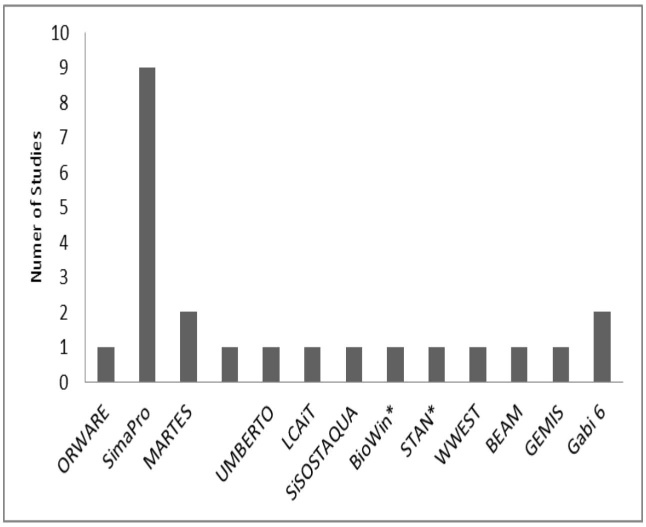

Figure 5. Models used in LCA assesment of sludge management

Simapro is the most commonly used model for LCA of sludge treatment according to the studies with 9 numbers. Gabi 6 and MARTES **ar**e the other popular models implemented in LCA of sludge treatment scenarios.

5. Conclusion

Life cycle assessment is one of the significant environmental impact detection methods of sludge treatment and management.

According to the literature, ORWARE, SimaPro, MARTES, TEAM by, Ecobilan, UMBERTO, LCAiT, SiSOSTAQUA, BioWin*, STAN*, WWEST, BEAM, GaBi 6 and GEMIS are the common models that are preferred for LCA of sludge treatment and management. Simapro is the most widely used model. IPCC, Ecoinvent, CML and its modifications and IMPACT 2002+ are the main life cycle impact assessment methods for sludge treatment. Among them, CML and its modifications are the most common life cycle impact asssesment tool.

Global warming potential, acidification potential, eutrophication potential, photochemical oxidation potential, human toxicity, ecotoxicity, depletion of abiotic resource, energy balance and terrestrial ecotoxicity are the fundamental impact categories of sludge treatment. Global warming potential within the impact categories is mostly observed.

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