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Emergy Analysis for the Sustainable Utilization of Biosolids Generated in a Municipal Wastewater Treatment Plant

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Abstract

This contribution describes the application of an emergy-based methodology for comparing two management alternatives of biosolids produced in a wastewater treatment plant. The current management practice of using biosolids as soil fertilizers was evaluated and compared to another alternative, the recovery of energy from the biosolid gasification process. This emergy assessment and comparison approach identifies more sustainable processes which achieve economic and social benefits with a minimal environmental impact. In addition, emergy-based sustainability indicators and the GREENSCOPE methodology were used to compare the two biosolid management alternatives. According to the sustainability assessment results, the energy production from biosolid gasification is energetically profitable, economically viable, and environmentally suitable. Furthermore, it was found that the current use of biosolids as soil fertilizer does not generate any considerable environmental stress, has the potential to achieve more economic benefits, and a post-processing of biosolids prior to its use as soil fertilizer improves its sustainability performance. In conclusion, this emergy analysis provides a sustainability assessment of both alternatives of biosolid management and helps decision-makers to identify opportunities for improvement during the current process of biosolid management.

Keywords

Emergy; sustainability; indicator; biosolid; gasification; fertilizer

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1. Introduction

In some countries, such as Colombia, domestic wastewater treatment is mostly performed by the use of aerobic processes (Arias & Brown, 2009). Then, the process is complemented by an anaerobic stabilization and biosolids are generated. These biosolids contain a high caloric energy value and polluted organic load (Cherubini et al., 2009). When the biosolids are not properly managed, the wastewater treatment process is inadequate or incomplete (US EPA, 2016). Therefore, sustainable solutions to this problem for achieving greater social and economic benefits with a minimum or zero environmental burden are needed.

To address this solid management problem, there have been implemented various alternatives for the use of these biosolids. Conventionally, alternative solutions such as energy production, building and filling material, agricultural feedstock, etc. (US EPA, 2006; Wang et al., 2008; Fytli & Zabaniotou, 2008) are considered “feasible” if these are “technically correct” and “economically viable” without considering environmental or social constraints. In addition, these solutions are only analyzed in terms of economic, social, or environmental benefits by separate, instead of holistic, sustainability analysis (simultaneous evaluation of the three sustainability pillars).

Therefore, a new evaluation approach based on the concept of sustainability as “the compatibility between the energy, economic (maximum performance), and environmental aspects” should be implemented for the analysis and comparison of different biosolid management alternatives.

Moreover, the city of Medellín (including its metropolitan area), the second biggest city in Colombia in terms of population, 3,317,100 inhabitants and annual population growth rate of 1.58% (DANE, 2005), produces biosolids at a current rate of approximately 663,433,200 L/y (Velez, 2007). The production of biosolids in the municipal wastewater treatment plant (WWTP) system is rapidly growing, induced by the increase in the percentage of households connected to central wastewater treatment system, as well as by an increased content of organic matter in the industrial waste effluents (Werther & Ogada, 1999). Finding a more sustainable management solution to the biosolids and its (uncontrolled) increment rate and accumulation is not feasible to the decision-makers and stakeholders without a proper way to evaluate potential solutions through the entire life cycle. Smith, et al; (2009) emphasizes the needs of allocating some economic value to the biosolids, in order to provide a rational management by considering energy, economic, and environment benefits.

This current situation raises the need for assessing the current management of biosolids produced in cities like Medellín-Colombia in terms of a sustainability based evaluation method that is able to integrate social, economic, environment, and energy aspects simultaneously.

For several years, the possibility of quantifying the sustainability of a system by using emergy accounting methods has been studied (Brown; 2003). Emergy analysis is a methodological tool for assessing the sustainability of a system or process for environmental decision-making, proposed by H.T. Odum (1996). Studies like Buenfil (2001) employed emergy analysis to decide the most appropriate use and distribution of water resources for

human well-being and the environment. In addition, emergy analysis has been employed to evaluate the sustainability performance of urban zones (Yu, et al., 2016; Zhang et al., 2016) and their metabolism (Yang et al., 2014; Lei et al., 2016). So far, the application of emergy analysis to wastewater treatment systems has been evaluated in some previous contributions (Björklund et al., 2001; Syracuse & La Rosa, 2006; Vassallo & Fabiano, 2009). These approaches allowed identifying sustainable (or unsustainable) characteristics from the elements involved in the processes that originate the biosolids but not how sustainable the management (or end of use) of them is, which is the main subject of this contribution. A sustainable analysis of biosolids utilization is a forward step in developing a more sustainable process of wastewater treatment that has not yet been created.

On the other hand, scientists from the US Environmental Protection Agency (EPA) have developed the GREENSCOPE tool (Ruiz-Mercado et al 2012a; 2012b; 2013) in efforts to advance the development of tools for the sustainable evaluation of chemical processes. The GREENSCOPE tool performs sustainability evaluations to ensure sustainability during the design, production, and use of existing and new products. These advances are made by employing indicators that represent environmental, social, and economic stakeholder concerns with nearly 140 indicators in four relevant categories: environment, economics, energy, and mass-efficiency. GREENSCOPE provides a complete list of process indicators, defines absolute limits for best and worst case process scenarios, and allows for calculation of relative indicator scores (0–100%) between those limits. This percentage score approach facilitates the analysis of the sustainability evaluation results when comparing multiple process routes for the manufacturing of the same valuable product or when process modifications are implemented toward a more sustainable performance. Therefore, indicator results can illustrate the current state of sustainability for the biosolid management alternatives and identify possible process improvement opportunities and potential sustainability increase.

This work aims to identify a more sustainable option for the management of biosolids generated in a WWTP. The biosolids generated from the WWTP of the city of Medellín-Colombia will be used as a case study. The best solid management alternative will be defined as one that is economically profitable, energetically viable, and minimizes or eliminates any negative environmental impact. The current process of biosolid management, biosolids as a fertilizer or soil amendment, will be evaluated and compared to another alternative referenced as the most appropriate for biosolids incineration with electricity generation, fluidized bed gasification, by using emergy-based sustainability indicators. In addition, the GREENSCOPE methodology and evaluation tool will be employed for calculating the sustainability indicators as relative indicator percentage scores (0–100%) between well-defined limits for best and worst case process scenarios. This will allow a clear visualization and comparison between alternatives. This work explores emergy evaluation as a tool that not only allows one to assess the sustainability of a process, but also to improve it.

2. Material and Methods

2.1. Emergy accounting method

The emergy analysis is a method of environmental accounting based on embodied energy, which expresses all the process inputs (e.g., energy, natural resources, environmental goods and services) and outputs (products or services) in solar equivalents. Thus, emergy is defined as the amount of solar energy used directly or indirectly to generate a valuable product or service (Odum & Odum, 2003; Vassallo & Fabiano, 2009). In other words, emergy is the amount of total solar energy that is invested or is required to produce a valuable good or product. The units of emergy are solar equivalent joules (sej). Thus, the solar power unit is a measure that unifies the consumption of materials, energy, and social resources that are invested to obtain a product or service. For example, emergy translates mass and energy values in terms of embodied energy for quantifying how much solar energy was spent to obtain one unit of valuable product.

Emergy of a process is the sum of all renewable, non-renewable, and imported resources multiplied by their respective unit emergy value (UEV). Values of UEV (transformity, specific emergy, emergy per unit money, etc.) represent the ratio of solar energy embodied in a product or process per amount of that product or process in terms of sej per joule (sej/J), per kilogram (sej/kg), or per money earned (sej/\$) (Odum, 1996; Rugani B., 2010). Therefore, emergy allows equivalencies and compatibility in order to aggregate and combine economic, social, and environmental aspects in similar units of sej.

The total emergy from a process is calculated once the renewable, non-renewable, and imported resources entering a process have been defined and quantified. Then, the emergy-based sustainability indicators are calculated and analyzed by stakeholders who perform decision-making. This would allow one to identify more sustainable process alternatives with lower total emergy, normally from products and processes based on renewable resources. In a long run timeline, only systems with a high percentage of captured renewable emergy are more sustainable (Brown & Ulgiati, 2004; Lefroy & Rydberg, 2003; Cao & Feng, 2007).

Therefore, the emergy accounting approach can be considered a method for evaluation and environmental management. In addition, this method allows one to estimate and compare the emergy values of the different system components (energy, mass, social, economic, etc.), and it will define conditions or sustainability index indicators for sustainability decision-making as discussed in Cano et al. 2014.

Since this contribution aims to implement an emergy analysis approach to the management of biosolids generated in a WWTP as shown in Figure 1, applying emergy to assess the sustainability of a complete WWTP is not within the scope of this contribution. However, it is important to characterize and collect quantitative information regarding the type of WWTP and the wastewater for being treated. In addition, a wastewater characterization (total suspended solids, volatile solids, biological and chemical oxygen demands, ammonium, heavy metals, organic nitrogen, etc.) will determine the quality of the generated biosolids and their appropriate management or disposal.

After selecting the WWTP, the next task is to identify renewable, non-renewable and imported resources that are required at every stage of the process. The current case study process for obtaining the biosolids from the WWTP was based on previous contributions describing the implementation of emergy analysis for evaluating the sustainability of WWTPs (Geber & Björklund, 2001; Vassallo & Fabiano, 2009; Zhang et al, 2010). Therefore, the emergy analysis data from these previous studies are collected and used for the current work since the WWTP described in the literature is similar to the WWTP that was selected for this study evaluating the sustainability of the biosolid management.

2.2. Choice of the alternative use of biosolids

Two alternatives for the use of biosolids generated in a WWTP in the city of Medellín-Colombia were chosen to perform this emergy analysis comparison. The first process is the current management approach of using biosolids as soil fertilizers (farming system), which is employed in the selected WWTP. The other alternative is the energy production from biosolids by gasification. As mentioned previously, this energy recovery alternative is referenced in the literature as the most feasible under environmental and economic constraints when is compared with other technologies of energy recovery from biosolids incineration (e.g., pyrolysis, multiple hearth furnaces, etc.) (Stillwell et al., 2010; Wang et al., 2008; Petersen & Werther, 2005).

2.2.1. Current Alternative: Use of biosolids as fertilizers for silvopasture soils.—

The first alternative to be evaluated is currently implemented in the selected WWTP, the use of biosolids as fertilizer for silvopasture soils. The data and the conditions required for this application were collected from Zapata et al. (2011), where they reported the use of WWTP biosolids to fertilize silvopasture soils. The technique consists of adding biosolids with 10% (w/w) water content to the soil. This application occurs during dry periods and approximately every 45 days. This ensures good physicochemical soil conditions and surrounding ecosystems as shown in Figure 2. The emergy content of product is evaluated in terms of the nutrient content (quality) of the produced Kikuyu grass and the amount produced per hectare (quantity).

Biosolids or sewage sludge are defined as an organic byproduct generated from wastewater treatment facilities (EPA, 2000). Most of the biosolids are rich in nutrients and organic and inorganic pollutants (Adame, 2001). The main nutrients include nitrogen, calcium, magnesium, sulfur, boron, copper, iron, manganese, molybdenum, and zinc, which are considered essential for plant growing (Zapata et al., 2011). Inorganic pollutants are constituted by heavy metals, which some of them essential or having a negative effect in the plant vital processes (Adame, 2001). This depends on their physicochemical characteristics and concentration in the soil. Some studies found that biosolids yielded best result (in terms of fertilizer index; increasing of nutrients into the soil) when compared to other conventional fertilizers (Zapata et al., 2011). However, the use of biosolids as soil fertilizer is still controversial because of their heavy metal content, nevertheless, it was found that the amount of metals transferred to the cultivated crops is less than 0.05% of the sludge metal content that is applied annually (Velez, 2012). In addition, the use of biosolids in agriculture should be evaluated for each particular crop since the level of tolerance of plants to some

metals (mainly copper and aluminum) is variable and any excess can cause a rapid phytotoxicity (Zapata et al., 2011).

2.2.2 Alternative 2: Use of biosolids for energy recovery by a fluidized bed gasification process.—Fluidized bed gasification process has the advantage of turning stabilized sludges into high quality energy (Wang et al., 2008). This reduces the volume of biosolids, emits of toxic organic compounds and places heavy metals in a solid matrix, producing a clean fuel gas. Gasification is the thermochemical conversion of carbonaceous substrates (biosolids) into clean fuel gas by using steam and air/oxygen as gasifying agents. This process is shown in Figure 3. First, the biosolids (Str. 1) enter to the fluidized bed dryer to remove any remaining water (Str. 2) and to make or form into pellets (average diameter value, 2 – 5 mm). Then, the fluidized material (Str. 3) passed into a silo, where it is mixed with 10% coal (Str. 4) in order to promote fluidization, improve its calorific value, and promote the occurrence of some beneficial thermal reactions in the fluidized bed (Muniesa & Velo, 2005; Almeida, 2010). The biosolids (Str. 5) are fed to the gasification reactor in conjunction with water (Str. 35) and air (Str. 6). The produced ash during the gasification is collected from the middle of the reactor (Str. 10). In addition, the generated hot gas (Str. 7) is passed through a ceramic filter and a system of cyclones for removing some fly-ash content (Str. 15). Then, the gas (Str. 8) goes through a heat exchanger to supply the energy demand from the fluidized bed dryer.

The clean gas (Str. 9) contains some tars that are removed using a cleaning fluid column whose fluid is a thermal oil (Str. 23). The tars composed of ash, metals, and other carbonaceous compounds are removed from the cleaning oil by using a filtering unit (Str. 18). A formed cake in the filter (Str. 25) is then recirculated to the gasifier and is removed and treated as solid waste for management twice a year. Finally, as described in Figure 3 the synthesis gas (Str. 22) is combusted in a gas turbine to generate electricity (Str. 26) and some of the post-combustion gas heat content (Str. 27) is employed to meet the energy demand for air pre-heating (gasifier input stream) and part of the dryer heating needs (Str. 33). Thus, the product to be energetically evaluated in this application is the generation of electricity (Str. 28). In addition, in Appendix D is described the stream mass flows and energy balances of the fluidized bed gasification process. Table D1 illustrates the mass flow, composition values, and specifications for the process input and output streams according to Figure 3 (Figure D1). In addition, Table D2 describes the energy balances for major process equipment units, dryer, heat exchangers, turbine, and gasifier. Process energy and material balance data were established from experimental values and simulation models of a gasification pilot plant located in the National University of Colombia (Rodriguez & Olmos, 2014).

2.3. Implementation of the emergy evaluation methodology on the selected alternatives

For both biosolid management alternatives, the process starts from the same good: stabilized and dewatered sludge supplied by the WWTP. However, the two options end with two different final products, Kikuyu grass for the first alternative and electricity for the second one. Emergy flow diagrams for each of the described alternatives were obtained by following the methodology of emergy analysis described in Cano et al. 2014. In addition,

some emergy based sustainability indicator results will be employed to perform a practical comparison between alternatives. These sustainability indicators are: environmental loading ratio (ELR), emergy yield ratio (EYR), emergy sustainability index (ESI), emergy input ratio (EIR), renewability index (RI), soil emergy cost (SEC), and emergy exchange ratio (EER).

Environmental loading ratio, ELR: As defined by eq. (1), ELR refers to the relationship between the inputs of non-renewable and imported resources to the system's use of renewable resources (Cao & Feng, 2007). Where F represents the total inputs of imported resources (e.g., machinery, human labor), R is the total inputs of renewable resources (e.g., oxygen consumption), and NR is the total inputs of nonrenewable resources (e.g., chemical substances).

$$ELR = \frac{NR + F}{R} \quad (1)$$

Low values of ELR ($ELR < 2$), indicate processes having a low environmental impact or a very large area to dissipate any negative environmental impact. When $ELR > 10$ there is a high environmental load and when $2 < ELR < 10$ the impact is considered moderate (Cao & Feng, 2007).

Emergy yield ratio, EYR: This indicates the relationship or dependency between the total system emergy on imported resources.

$$EYR = \frac{R + NR + F}{F} \quad (2)$$

This indicator defined by eq. (2) is used to estimate the dependence of the process on imported or purchased resources, and shows the contribution of local natural capital in the economy of the region or the process. Low values of EYR indicate low economic benefits and a weak market competition. On the contrary, high values of EYR denote strong competition ability and high economic benefits (Zhang et al. 2010). For example, an $EYR < 5$ indicates that a large number of secondary energy resources were used in the process; raw materials such as cement, steel and others. An $EYR > 5$ indicates the use of primary energy resources and when $EYR < 2$ indicates no significant contribution of local resources and this is associated to processes which are almost entirely manufactured externally (Brown et al. 2012).

Emergy Sustainability Index, ESI: The ESI encompasses the relationship between the emergy yield ratio and the environmental load ratio. Eq. (3) describes the calculation of this indicator.

$$ESI = \frac{EYR}{ELR} \quad (3)$$

This index reflects the ability of a system to provide products or services with minimal environmental stress and a maximum economic benefit (Zhang et al. 2010). When $ESI < 1$, process and products are not sustainable in the long term and high-consumption economic systems (Zhang et al. 2014). When $1 < ESI < 5$ a sustainable contribution to the economy for mid-term periods. For processes with $ESI > 5$ can be considered sustainable in the long term (Cao & Feng, 2007). However, when $ESI > 10$ the process is considered underdeveloped (Zhang et al. 2014).

Emergy Inversion Ratio, EIR: This indicator described by eq. (4) is the relationship between the input of imported resources into the system over the total amount of renewable and non-renewable resources.

$$EIR = \frac{F}{R + NR} \quad (4)$$

When comparing different process alternatives using this indicator, the process alternative scoring the lower value tends to be the most competitive and to thrive in the market. Generally, a higher value means a higher level of economic development of the system (Zhang et al. 2007).

Renewability Index, RI: This indicator comprises a relationship between the inputs of renewable sources to the system over the total input of emergy sources. Eq. (5) describes the calculation of this indicator.

$$RI = \frac{R}{(R + NR + F)} \quad (5)$$

Systems with a high percentage of renewable emergy are more likely to be more sustainable and prevail having abilities to survive under economic stress than those using more nonrenewable emergy inputs (Cohen et al. 2006; Rydberg & Haden, 2006).

Soil Emergy Cost, SEC: The SEC indicator as defined in eq. (6) is the ratio between non-renewable inputs to an agricultural system and the total emergy inputs.

$$SEC = \frac{NR}{(R + NR + F)} \quad (6)$$

This indicator provides a cost-benefit (soil-agriculture) relationship for farming practices. Thus, SEC compares agricultural yields to the loss of emergy associated with eroded soil and represents the amount of degraded soil per emergy unit. The value of this index should be less than one (Zhang et al. 2007). The range of values for this indicator can be defined according to the GREENSCOPE methodology. Therefore, an SEC = 0 is the best case and an SEC = 1 is the worst-case scenario.

Emergy Exchange Ratio, EER: This indicator as described by eq. (7) is calculated by dividing the total emergy of the product by the emergy received from the sale.

$$EER = \frac{NR + R + F}{(\text{Product revenue} \times \text{Emergy money ratio})} \quad (7)$$

The “emergy money ratio” known as emergy-money or emergy exchange, is the amount of emergy that can be purchased in one country by a unit of money (one dollar) in a specific year. In addition, EER provides a measure of who won or lost during trading between consumers and producers (Cohen et al. 2006). An EER > 1 indicates that more emergy was supplied to consumers than received in exchange. In other words, the producer received less emergy (sales revenue as emergy equivalents) than the amount of emergy used to produce the good. An EER < 1 indicates the manufacturer made a profit and received more emergy than the used for producing the good. When EER = 1 the same amount of employed emergy for the product manufacturing was obtained from sales revenue (Agostinho et al. 2008). According to the GREENSCOPE tool, an EER = 0 is the best case and when EER = 1 is considered a worst case scenario.

The above mentioned emergy-based indicators will allow decision-makers to account sustainability and choose more environmentally friendly solutions. In addition, calculation of all of the emergy indicators using the GREENSCOPE methodology after completion of all sustainability boundary value requirements will help decision makers to visualize the results of each indicator in a practical sustainability scale.

3. Results and Discussion

3.1. Emergy-based comparison of the two alternative uses

In Figure 1 is shown an illustrative process flow diagram of the WWTP that generates the biosolids for which finding a more sustainable management alternative is the main goal of this study. The WWTP processes $39.4 \times 10^6 \text{ m}^3$ of wastewater per year, whose removal yield of biochemical oxygen demand (BOD₅) and total suspended solids (TSS) is 83% and 88% respectively, leading to an annual output of 36.3×10^3 wet tons of biosolids (Empresas Públicas de Medellín (EPM), 2006; 2012). These and other relevant characteristic values of the WWTP selected for this study are shown in Table 1.

Before the produced biosolids are transported to suitable places for its upcoming usage or disposal, mechanical dewatering is employed to remove most of the water content (61–68% w/w).

According to some previous contributions representing some of the state-of-the-art on the application of emergy analysis to wastewater treatment systems (Björklund et al. 2001; Siracusa & La Rosa, 2006; Vassallo et al. 2009), it was found that most WWTPs require the same type of inputs from renewable, non-renewable, and imported sources for their operation. Therefore, the differences in the number of inputs to the process, regardless of the type of treatment would be negligible.

Moreover, the percentage ratios of F , R , and N from an activated sludge WWTP can be collected from previous contributions. For this work, reported values from a study performed by Zhang et al. (2010) were taken. These values expressed as percentage of the total emergy entering the system corresponded to 62.5% of imported resources (F , provided mainly by machinery and human labor), 34.4% of renewable resources (R , provided only by oxygen consumption), and 3% of nonrenewable resources (NR , provided only by the chemical inputs). These values show that (in terms of emergy) wastewater treatment is very costly because requires large amounts of imported resources. However, this value is low compared to the high energy cost and negative environmental and human health impacts, if untreated water is released to the environment.

The emergy evaluation will be performed by assuming that Kikuyu grass is the main valuable product for the biosolid land application process and electricity is the main product for the biosolid gasification process. In addition, the biosolids are considered renewable feedstocks for both systems. Though, it is necessary to mention that different assumptions such as products, inputs, outputs, etc. can be implemented and different results will be obtained when performing this emergy assessment. The assumptions and problem delimitations implemented in the current work were applied after consultation and agreement with the stakeholders interested in this research contribution. Moreover, the quantities of some renewable inputs (sun, rain, and wind) are the same for both alternatives as is assumed that both systems occupy one hectare of land localized in the same region. These shall be accounted for the assessment regardless of whether they are used in the system. For example, the hectare of land occupied by the gasification plant is getting all these renewable inputs without use them and simultaneously depriving the nature of receiving these inputs.

In other words, all UEVs in this work refer to an emergy baseline value of 9.44×10^{24} sej/y (Odum, 1996). The emergy per unit of labor was based on emergy consumed per person ratio, and the emergy money ratio scores on a baseline of 8.70×10^{12} sej/\$, which was reported for the country of Ecuador for the year 1996 (Odum, 1996). In addition, any transformity value employed in this work contains labor and services required to produce economic goods.

3.2. Calculations and emergy diagram: Use of biosolids as soil fertilizers.

The emergy analysis methodology described by Odum (Odum, 1996; 2003) and Cano et al. (2014) was used for evaluating the application of biosolids to soil as fertilizer. The inventory of renewable resources (R) includes the sun, rain, and air since these ecological goods directly affect the hectare of soil to be analyzed. On the other hand, a list nonrenewable resources (NR) in the emergy analysis comprises of soil productivity loss by erodible

processes and desertification, or in this case, because of the loss of productivity due to accumulation of heavy metals present in the biosolids. Although, it has been shown that there is no significant accumulation of heavy metals in the soil due to the use of biosolids (Zapata et al. 2011). Finally, the set of imported resources (F) consists of the electricity associated to the electric power consumed by pumps for applying the biosolids, the fuel spent on transportation, the machinery related to the irrigation pumps, the transport truck, and workmanship. Also categorized as imported resources are the costs associated with phytoremediation treatment for the soil when it completes its life productivity and/or reaches limit concentrations of heavy metals established by US EPA and the soil will be no suitable for agronomic or farming purposes (US EPA, 1986, 2003).

Figure 4 shows more details on the emergy inputs and outputs occurring during the application of biosolids on agricultural land for soil fertilization. The yield of the process is the silvopasture grass production, to which the total emergy input to the system is transferred. The different emergy sources were aggregated as renewable, nonrenewable, and purchased inputs. In addition, the biosolids are constituted by biomass (organic material), heavy metals, and nutrients. As mentioned before, some water (10% w/w) is added to the biosolids in order to improve their fluidization and transporting when it is applied to the land as a fertilizer. This amount of water is not accounted for the analysis since it is assumed that this is rainwater stored in a tank inside the same hectare of land. This amount of water is negligible (Zapata et al. 2011) compared to the high precipitation occurring on the location where the biosolids are applied, which has a multi-year average rainfall between 1,562 mm and 2,680 mm (Government of Antioquia, 2007). However, water usage should be accounted in regions where water scarcity is a big issue. It is noteworthy that biosolids are not receiving any type of pretreatment before being applied to the soil. More details regarding qualitative and quantitative aspects of these inputs for the farming system, using renewable sources such as biosolids can be found in Cano et al. (2012).

Table 2 describes all emergy flow values of renewable, non-renewable, and imported inputs for the usage of biosolids as soil fertilizers for grass production. Since the flows to a local area of renewable inputs (sun, rain, wind) are co-products from the same source, to avoid double counting it is utilized only the highest one (rain). Calculation methods of these values are explained in Cano et al. (2014). For more information regarding specific calculations, assumptions, baseline, and transformity values see Appendix A, Table A1. The emergy flows are represented as the fraction that each contributes to the total emergy of the agricultural process as follows: $NR=0.288$, $R=0.610$, and $F=0.101$.

Furthermore, in Appendix B is described the effect of loss of soil productivity due to the accumulation of heavy metals by multiple applications of biosolids into the soil. Although there is not a significant accumulation of the heavy metals after few applications, it is necessary to consider that after many times of application, metal accumulation becomes evident and significant, causing toxicity and the soil turns unproductive.

3.3. Calculations and emergy diagram: Use of biosolids for power generation by a gasification process.

For the gasification system, as described in one of the previous sections, among renewable resources (R) there are the sunlight, rain, and air. These goods shall be accounted for, regardless of the fact these directly affect the process. This is due to the fact the land occupied by the gasification plant is getting all these inputs, and depriving the nature of receiving them. Furthermore, nonrenewable resources (NR) are associated with coal and oil ignition. Finally, imported resources (F) are related to the fuel used for transportation, the electricity required to meet the power consumption of the pump, the power consumption of the (air) compressor, and the resistance to heat the water (vapor entering as gasifying agent), machinery related to two worm gears, compressor, pump, turbine, gasifier, and other worthless elements (silos and cyclones, cleaner, fluidized bed dryer). Finally, the cost of labor, water used as gasifying agent, and the cost of the waste disposal (ash, tars, oils and heavy metals) are categorized as imported resources. Based on the energy circuit symbols proposed by Odum (1996), an aggregated diagram of material and energy flows for the power generation from biosolids process is presented in Figure 5. This diagram illustrates the material and energy flows and the structure of major process units that consume these renewable (sun, wind, potash, etc.), nonrenewable (carbon oil, etc.), and imported (fuel, machinery, labor, etc.) emergy resources.

In addition, Table 3 describes all emergy values for each of the renewable, nonrenewable, and imported inputs for the usage of biosolids for power generation by a gasification process. Calculation methods of these values are explained in Cano et al. 2014. For more information regarding specific calculations, assumptions, baseline, and transformity values see Appendix C, Table C1. In addition, the emergy flows are represented as the fraction that each of them contributes to the total emergy from the gasification process as follows: the fraction of nonrenewable (NR) 0.011, renewable (R) 0.48, and imported resources (F) 0.509.

The percentage of the resources (NR , R , F) entering each of the systems and the overall emergy of the process are summarized in Table 4. In this Table is described the amount of total solar energy invested in each of the two process alternatives, being higher for the power generation alternative. Furthermore, it is shown the balance between renewable and imported resources entering the process when biosolids are used as fertilizers to agricultural soils. This case seems as a best tradeoff, a balance between imported and renewable resources indicating a more sustainable process. In addition, as observed from Tables 2 and 3, both biosolid management options are energy intensive systems and similar R input values. Therefore, the renewability or non-renewability nature of the fuel and local electric grid (purchased inputs) can be accounted on the sustainability evaluation results. This will make the emergy evaluation and comparison more comprehensive. However, the renewable (nonrenewable) percent component data of the fuel and electricity in Colombia at local level distribution are not yet available (US Energy Information Administration (EIA), 2015).

3.4. Sustainability emergy-based indicator results and analysis.

As discussed previously, the emergy analysis differentiates and separates the inputs from renewable, nonrenewable, and imported sources. These distinctions make it possible to

define emergy indicators, which provide valuable information for making sustainability decisions, especially when different alternatives are treated (Brown et al. 2012; Cohen et al. 2006, Smith and Ruiz-Mercado, 2014). All these indicators previously defined in section 2.3 will be calculated based on data provided in Table 4. In addition, the GREENSCOPE methodology will be applied by employing a general scale for measuring sustainability according to the identification and use of best possible target (100% of sustainability) and a worst-case scenario (0% of sustainability) as reference states for each indicator. In other words, as the upper and lower bounds of a normalized sustainability measurement scale. This sustainability scale allows the transformation of the emergy-based indicator scores to a dimensionless form using the worst and best scenarios as is described by eq. (8).

$$\text{Percent Score} = \frac{\text{Actual} - \text{Worst}}{\text{Best} - \text{Worst}} \times 100\% \quad (8)$$

This equation helps to visualize and compare the sustainability assessment results of each indicator during the emergy analysis. Table 5 compiles the best and worst case scenario scores for each emergy indicator. These reference scores for each indicator were selected from the value domains described in section 2.3. More details regarding the selection criteria of these boundary values and their definitions can be found elsewhere (Ruiz-Mercado et al 2012a; 2013). The goal is to assess which alternative is more sustainable by using emergy as a criterion for decision-making. Therefore, the emergy indicator scores will be calculated and discussed by employing the indicator equations in section 2.3 and data collected from Tables 2 and 3.

- *Environmental loading ratio.* ELR values of 0.64 and 1.08 were obtained for the grass production and for the gasification system, respectively. According to the definition of ELR, both alternatives describe good environmental performance. However, the use of biosolids as fertilizer represents a better option.
- *Emergy yield ratio.* The evaluation of EYR shows values of 9.86 and 1.96 for the agricultural and gasification system, respectively. In economic terms, the higher the EYR, more energy is being provided to the process compared to the amount being removed, which is the case of the agricultural system. However, the gasification process indicates a low economic performance. This may be because this process is mainly based on the use of imported and nonrenewable resources. 50% of the total emergy of the process comes from purchased sources, even though the biosolids are taken as a renewable resource, which compensates in 45% the system imported resources.
- *Emergy sustainability index.* Current results show that in the gasification process, an acceptable contribution to the economy in the mid-term is presented with an ESI equal to 1.81. This score is at the lower limit of the value domain ($1 < \text{ESI} < 5$) denoting a low environmental stress. This suggests low economic feasibility (although it may not generate losses) and minimum or non-utilization of local resources. In contrast, the agricultural system gives a result of 15.44 which is considered a score from underdeveloped processes. This is a process that can be

more exploited since it has more potential or ability to deliver a higher economic performance without causing significant environmental impacts. In addition, the environment would have the ability to absorb more impact due to the process without degrading its quality.

- *Emergy inversion ratio.* Table 5 shows EIR values of 0.11 and 1.04 for the farming and gasification systems respectively. For this indicator, a lower value means a lower economic cost of the process with high benefits. Therefore, a competitive and prosperous market scenario can occur when biosolids are used as renewable fertilizers. Another good characteristic is the fact that emergy attributed to the imported resources (F) with regard to total emergy is very low (10%).
- *Renewability index.* As shown in Table 5, the agricultural system represents the highest value, 61.02%. Therefore, this is the scenario, which is most likely to be sustainable and prevail over time. In addition, biosolids provide a large percentage of emergy to the thermal and agricultural processes (44 and 52%, respectively, compared to the total emergy inputs of each process). The RI for the thermal system is 47.98%.
- *Soil emergy cost.* The SEC was only applied to the agricultural process application since it measures the loss of soil productivity by the presence of heavy metals. The value of 0.29 is considered very low (compared to the unit), indicating the loss of soil is minimum compared to the total yield and benefits.
- *Emergy exchange ratio.* According to Table 5, the EER results of both systems indicate that producers receive less emergy as payment compared to the amount spent to yield a valuable good ($EER > 1$). Currently, this represents a minor loss to the grass producer than for the electricity generation scenario. This may reflect that no economic benefits would be obtained by selling the generated products since their emergy content are not accounted in their economic price. This might be happening to the economic market price for electricity, which is not reflecting its high emergy content.

In Table 5 is summarized all calculated emergy indicator scores. Based on the indicator values and the GREENSCOPE percentage scores, the results from the agriculture option are more favorable. However, the agricultural process is an underdeveloped process since its ESI is more than 10. In addition, this indicates some missing opportunities to obtain better economic and energy benefits from the agriculture option. In contrast, the ESI for the gasification process is just 18.1% of the optimum value. This seems a low score, but it is a good starting for taking advantages of more potential benefits that can be obtained from the utilization of biosolids for energy production. Another interesting aspect to analyze is the good ELR performance values from both options when comparing their GREENSCOPE scores. This can provide some opportunities to trade better economic benefits with small environmental costs.

3.5. Graphical comparison and analysis of the alternative uses.

Finally, by making emergy-based ternary diagrams as developed by Giannetti et al. (2006), we would be able to suggest which option is more sustainable for the management of biosolids. Figure 6 describes a ternary diagram comparing the two alternatives of biosolid management, (1) farming system and (2) thermal system. Note that the points labeled R , N , and F in the equilateral triangle diagram refer to 100% R , 100% N , and 100% F , respectively and each side a binary system. In addition, the lines parallel to, e.g., segment $\bar{R}F$ represent the points for which % N is constant. The composition of any system in a ternary diagram can be determined by the zero reading along the frontal baseline of the diagram until 100% of the other corner of the triangle. The size of a point plotted in the diagram is proportional to the amount of used emergy.

According to the emergy diagram, the agricultural system shows less amount of used emergy to perform the process than the thermal processing system (size of the solid dots). For the agricultural system, the total renewable inputs is 60%, in contrast to 47% for the thermal system.

Since the agricultural system alternative contains a high percentage of renewable resources and is underdeveloped ($ESI > 10$), this cannot be located in the best area of sustainability range ($1 < ESI < 5$). At the same time, there is a small percentage of imported resources (F) indicating that the process can be more developed without paying a high environmental cost. In contrast, the thermal system shows a more sustainable score (it is located in the optimal area ($1 < ESI < 5$)). However, this score is quite close to the lower limit. That means, the thermal process is sustainable in the medium time frame but, it is not long-term guaranteed.

Thus, under an emergy-economic framework, energy recovery from biosolids by fluidized bed gasification is the best alternative (but not optimal) for the use of biosolids generated in a WWTP in the city of Medellin, Colombia. This does not mean the current provision of biosolids is economically or environmentally unsuitable. On the contrary, it does not generate environmental stress since its maximum economic yield that can be reached has not been achieved. As for the current alternative of management, the use of biosolids as soil fertilizers can be improved so that a sustainable balance between imported and renewable sources can be achieved.

A possible alternative is to bring stabilized biosolids to a post-treatment before being applied to soil. In this post-treatment, concentrations of heavy metals and pathogens decrease, taking biosolids from class B to class A. By this post-treatment there will be an increment of imported resources, offsetting entries of renewable resources. In addition, more biosolid soil applications can be performed without restrictions if concentrations of heavy metals and pathogens decreased. This is recommended by Fytili & Zabaniotou (2008), that before the use of biosolids as fertilizers, they must be pretreated for the removal of these hazardous compounds. However, this will lead to the increase of capital and manufacturing costs.

4. Conclusions

This work aimed to evaluate the sustainability of biosolids processing alternatives by employing an emergy based sustainability assessment and indicators. The biosolids generated from the WWTP of the city of Medellín-Colombia were used as case of study. The current process of solid management, biosolids as silvopastoral soil fertilizer, was evaluated and compared to another alternative, biosolids for energy recovery by gasification process. According to the emergy indicator results and their corresponding analysis, the energy production from biosolid gasification is energetically profitable, economically viable, and environmentally suitable.

According to the emergy indicators, the agricultural system management shows less amount of used emergy to perform the process than the thermal processing system. In addition, the agricultural system describes a total renewable input value of 60% compared to a 47% value for the thermal system. In other words, the agricultural system encompasses a high contribution (%) of renewable resources and is underdeveloped ($ESI > 10$). Moreover, the thermal system displays a more beneficial score in a short time frame, which is located in the lower ESI domain ($1 < ESI < 5$). However, since this score is quite close to the lower limit, the thermal process is not sustainable in a long-term time frame. Therefore, some trade-off alternatives for combining both solutions instead of a unique biosolid management method should be explored by the stakeholders. A combined solution can benefit the utilization of one specific alternative when some sustainability aspects are the priority or when time events can influence the process inputs, as a consequence shifting the process performance results. In addition, more technical studies for the optimization of both processing activities should be developed. This would help the improvement of current results.

It is concluded that the current biosolid management alternative is underdeveloped and has not been exploited to its maximum limit (higher economic performance at lower environmental impact) raising the possibility of getting better economic results. In addition, some results showed that modifying the ratios between renewable and imported resources can improve the current solid management solution and achieve a better economic performance. This suggests that emergy analysis allows a holistic sustainability assessment and aids to identify and modify unsustainable practices.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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7. References

- ADAME (Agence de l'environnement et de la maîtrise de l'Énergie) (2001). On the municipal sewage sludge. http://www.mddelcc.gouv.qc.ca/matieres/articles/caract_boues1.pdf (in French).
- Agostinho F, Diniz G, Siche R, Ortega E (2008). The use of emergy assessment and the Geographical Information System in the diagnosis of small family farms in Brazil. *Ecological Modelling*, 210(1–2), 37–57.
- Almeida JM (2010). Gasification of sludges from urban waste water treatment plants (WWTP). Polytechnic University of Madrid [PhD thesis] (in Spanish).
- Álvarez O, Vélez I & Poveda G (2008). Uncertainty associated with the in the long term water balance. <http://www.fagro.edu.uy/~agromet/curso/1-2/TeoRadiacion.pdf> (accessed December 2014) (in Spanish).
- Arias ME, & Brown MT (2009). Feasibility of using constructed treatment wetlands for municipal wastewater treatment in the Bogotá Savannah, Colombia. *Ecological Engineering*, 35(7), 1070–1078.
- Bargigli S, Raugei M, Ulgiati S (2004). Comparison of thermodynamic and environmental indexes of natural gas, syngas and hydrogen production processes. *Energy*, 29(12–15), 2145–2159.
- Bastianoni S, Campbell DE, Ridolfi R, Pulselli FM (2009). The solar transformity of petroleum fuels, *Ecological Modelling*, 220(1), 40–50.
- Björklund J, Geber U, Rydberg T (2001). Emergy analysis of municipal wastewater treatment and generation of electricity by digestion of sewage sludge. *Resources Conservation and Recycling*, (31), 293–316.
- Brown MT, 2003 Resource Imperialism. Emergy Perspectives on Sustainability, International Trade and Balancing the Welfare of Nations. In: Book of Proceedings of the International Workshop “Advances in Emergy Studies. Reconsidering the Importance of Emergy” Porto Venere, Italy, 24–28 September 2002.
- Ulgiati S, Brown MT, Giampietro M, Herendeen RA, and Mayumi K, Editors. SGE Publisher Padova, Italy, Pg. 142.
- Brown MT, & Ulgiati S (2004). Emergy analysis and environmental accounting. *Encyclopedia Energy*, 2, 329–354.
- Brown MT, Raugei M, Ulgiati S (2012). On boundaries and “investments” in Emergy Synthesis and LCA: A case study on thermal vs. photovoltaic electricity. *Ecological Indicators*, 15(1), 227–235.
- Buenfil AA (2001). Emergy evaluation of water. University Of Florida [Ph.D. Thesis]
- Cano NA (2012). Emergy analysis of the disposal of sludge produced in a wastewater treatment plant. (Application to a WWTP in the Metropolitan Area of the Aburrá Valley). National University of Colombia [Ms.C Thesis] (in Spanish).
- Cano NA, Gallego D, Velásquez H (2014). Emergy Evaluation: A Tool for the Assessment of Sustainability in Project Development. *Int. Journal of Engineering Research and Applications*: 2248–9622, Vol. 4, Issue 2.
- Cao K, & Feng X (2007). The Emergy Analysis of Multi-Product Systems. *Process Safety and Environmental Protection*, 85(5), 494–500.
- Cherubini F, Bargigli S, Ulgiati S (2009). Life cycle assessment (LCA) of waste management strategies: Landfilling, sorting plant and incineration. *Energy*, 34(12), 2116–2123.
- Cohen MJ, Brown MT, & Shepherd KD (2006). Estimating the environmental costs of soil erosion at multiple scales in Kenya using emergy synthesis. *Agriculture, Ecosystems & Environment*, 114(2–4), 249–269.
- Compressors and Networks Co. (2012). Compressors and HAVC at Medellín–Colombia. <http://compresoresyredes.com/productos.php> (accessed December 2014) (in Spanish).
- DANE (2005). General Census 2005 - Results from the Medellín metropolitan area - DANE, The Metropolitan Area of the Aburrá Valley. http://www.dane.gov.co/files/censo2005/resultados_am_municipios.pdf (in Spanish).
- El Tiempo Weather News (2012). Medellín-Colombia Weather. <http://www.eltiempo.net/colombia/medellin.html> (accessed December 2014) (in Spanish).

- Empresas Públicas de Medellín (2006). Environmental Report 2006. https://www.epm.com.co/site/Portals/0/centro_de_documentos/inversionistas/Informe_ambiental_hist06_000.pdf (in Spanish).
- Empresas Públicas de Medellín (2012). A Physico-chemical Analysis Report, San Fernando Biosolid Wastewater Treatment Plant. Water Quality Control Team - Empresas Públicas de Medellín E.S.P (in Spanish).
- Engineering Manual Co. (2012). Screw Conveyor Catalog & Engineering Manual. http://www.screwconveyor.com/SCC%20EngCat10_LR.pdf (accessed December 2014).
- Fluck R, Baird D, Panesar B (1992). The energy required in the production of vegetables in Florida. Proceeding Florida State Horticultural Society, 105, 330–333.
- Fytli D, & Zabaniotou A (2008). Utilization of sewage sludge in EU: application of old and new methods—A review. Renewable and Sustainable Energy Reviews, 12(1), 116–140.
- Geber U, & Björklund J (2001). The relationship between ecosystem services and purchased input in Swedish wastewater treatment systems — a case study. Ecological Engineering, 18, 39–59.
- Giannetti BF, Barrella F. a., & Almeida CMVB (2006). A combined tool for environmental scientists and decision makers: ternary diagrams and emergy accounting. Journal of Cleaner Production, 14(2), 201–210.
- Gobernación de Antioquia (2007). Planning department, SUB-PROFILE, NORTH ANTIOQUIA (in Spanish).
- Turbine Green (2012). <http://www.greenturbine.eu> (accessed December 2014).
- Gross B, Eder C, Grziwa P, Horst J, & Kimmerle K (2008). Energy recovery from sewage sludge by means of fluidised bed gasification. Waste management, 28(10), 1819–26. [PubMed: 17919896]
- Kawasaki Co. (2012). Kawasaki Precision Machinery Network. http://www.khi.co.jp/kpm/pdf/all_pdb.pdf (accessed December 2014).
- Lefroy E & Rydberg T (2003). Emergy evaluation of three cropping systems in southwester Australia. Ecol. Model. 161,195–211.
- Midilli A, Dogru M, Howarth CR, & Ling MJ (2001). Combustible gas production from sewage sludge with a downdraft gasifier. Energy Conversion & Management, 42, 157–172
- Lei K, Liu L, Hu D, Lou I (2016). Mass, energy, and emergy analysis of the metabolism of Macao. Journal of Cleaner Production, 114(15), 160–170.
- McGhee T (1991). Water supply and sewerage. McGraw-Hill, Ed. New York.
- Muniesa Bastida, B., & Velo García, E. (2005). Basic engineering of a gasification plant for sewage sludge for treatment of 14,000 Mg / year of dry sludge. Polytechnic University of Catalonia [Ms.C Thesis] (in Spanish). Retrieved from <http://upcommons.upc.edu/pfc/browse?type=author&value=Muniesa+Bastida+%2C+Blanca>.
- National Aeronautics and Space Administration, NASA (2012). NASA surface Meteorology and solar Energy-Location. [Http://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?uid=3030](http://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?uid=3030) (accessed July 2012).
- Odum HT, & Odum B (2003). Concepts and methods of ecological engineering. Ecological Engineering, 20(5), 339–361.
- Odum H, Brown M, & Brandt-Williams S (2000). Handbook of emergy evaluation. Center for Environmental Policy Environmental Engineering Sciences. (U. of Florida, Gainesville, Ed.). Florida <http://www.ees.ufl.edu/cep/emergydownloads.asp> (accessed December 2014).
- Odum HT (1996). Environmental accounting: Emergy and Environmental Decision Making. (J. W. and Sons, Ed.). New York.
- Petersen I, & Werther J (2005). Experimental investigation and modeling of gasificationof sewage sludge in the circulating fluidized bed. Chemical Engineering and Processing: Process Intensification, 44(7), 717–736. doi:10.1016/j.cep.2004.09.001
- Poveda G, Mesa OJ, Vélez JI, Mantilla R, Ramírez JM, Hernández OO, Borja AF, Urzola JA (2007). HidroSIG: an interactive digital atlas of Colombia's hydro-climatology. Journal of Hydroinformatics, 9 (2), 145–156.
- Quick Transport Solutions Inc. (2012). California transport company. <http://www.quicktransportsolutions.com/truckingcompany/california/paul-j-franco-usdot-2775220.php> (accessed December 2014).

- Raskin I, & Ensley BD, (2000). *Phytoremediation of Toxic Metals: Using Plants to Clean Up the Environment* (Wiley-Interscience, Ed.), New York, USA, Pg. 304.
- Rodas E, Toro J (2005). Process specification of the San Fernando Wastewater Treatment Plant. National University of Colombia at Medellin, Colombia (in Spanish).
- Rodriguez EC, Olmos LC, (2014). "Technical and Economical Assessment of Power Generation Technologies Firing Syngas Obtained from Biosolid Gasification". *Producción Más Limpia Journal. Área Metropolitana Del Valle De Aburra* 9 (1) 31–43.
- Ruiz-Mercado GJ, Smith RL, Gonzalez MA (2012a). Sustainability Indicators for Chemical Processes: I. Taxonomy. *Ind. Eng. Chem. Res* 51, 2309–2328.
- Ruiz-Mercado GJ, Smith RL, Gonzalez MA (2012b). Sustainability Indicators for Chemical Processes: II. Data Needs. *Ind. Eng. Chem. Res* 51, 2329–2353.
- Ruiz-Mercado GJ, Gonzalez MA, Smith RL (2013). Sustainability Indicators for Chemical Processes: III. Biodiesel Case Study. *Ind. Eng. Chem. Res* 52, 6747–6760.
- Rugani B 2010 *Advances towards a comprehensive evaluation of Emergy in Life Cycle Assessment*; University of Siena: Siena, Italy.
- Rydberg T, & Haden A (2006). Emergy evaluations of Denmark and Danish agriculture: Assessing the influence of changing resource availability on the organization of agriculture and society. *Agriculture, Ecosystems & Environment*, 117(2–3), 145–158.
- Siracusa G, & La Rosa AD (2006). Design of a constructed wetland for wastewater treatment in a Sicilian town and environmental evaluation using the emergy analysis. *Ecological Modelling*, 197(3–4), 490–497.
- Smith KM, Fowler GD, Pullket S, & Graham NJD (2009). Sewage sludge-based adsorbents: a review of their production, properties and use in water treatment applications. *Water Research*, 43(10), 2569–94. [PubMed: 19375772]
- Smith RL, Ruiz-Mercado GJ (2014). A method for decision making using sustainability indicators. *Clean Technol. Environ. Policy* 16, 749–755.
- Stillwell AS; Hoppock DC; Webber ME (2010). Energy Recovery from Wastewater Treatment Plants in the United States: A Case Study of the Energy-Water Nexus. *Sustainability*, 2, 945–962.
- UNICAMP (2002). Table of transformities of natural resources, industrial inputs and ecosystem products. <http://www.unicamp.br/fea/ortega/curso/transformid.htm> (accessed January 2016).
- U.S. Energy Information Administration (2015). Colombia International energy data and analysis. <https://www.eia.gov/beta/international/analysis.cfm?iso=COL> (accessed January 2016).
- U.S. Environmental Protection Agency (2016). <http://www.epa.gov/biosolids> (accessed January 2016).
- U.S. Environmental Protection Agency (2006). *Emerging Technologies for Biosolids Management*; US EPA Office of Wastewater Management: Washington, DC; p 135.
- US Environmental Protection Agency (2003). *A citizen's guide to phytoremediation*. US EPA: Washington, DC.
- US Environmental Protection Agency (1986). *Commission of European Communities. Council Directive 86/278/EEC on the protection of the environment and in particular of the soil, when sewage sludge is used in agriculture*.
- Vassallo P & Fabiano M (2009). Emergy required for the complete treatment of municipal wastewater. *Ecological Engineering*, 35(5), 687–694.
- Velez J (2007). Biosolids: A problem or a solution? *Producción mas Limpia*, 2, 57–71.
- Wang H, Brown SL, Magesan GN, Slade AH, Quintern M, Clinton PW, Payn TW (2008). Technological options for the management of biosolids. *Environmental Science and Pollution Research - International* 15(4): 308–317. [PubMed: 18488261]
- Werther J, & Ogada T (1999). Sewage sludge combustion. *Progress in Energy and Combustion Science*, 25, 55–116.
- Yanga D, Kao WTM, Zhanga G, Zhang N (2014). Evaluating spatiotemporal differences and sustainability of Xiamen urban metabolism using emergy synthesis. *Ecological Modelling*, 272 (24), 40–48.

- Yu X, Geng Y, Dong H, Ulgiati S, Liu Z, Liu Z, Ma Z, Tian X, Sun L (2016). Sustainability assessment of one industrial region: A combined method of emergy analysis and IPAT (Human Impact Population Affluence Technology). *Energy* (107), 818–830.
- Zapata R, Osorio N, Berrio C, & Sotelo, (2011). Evaluation of the agronomic, environmental and health risks arising from the direct application of biosolids for growing pasture in dairy production agro-ecosystem at northern Antioquia. *EPM journal*, 4, 8–38 (in Spanish).
- Zhang LX, Song B, & Chen B (2012). Emergy-based analysis of four farming systems: insight into agricultural diversification in rural China. *Journal of Cleaner Production*, 28, 33–44.
- Zhang LX, Yang ZF, & Chen GQ (2007). Emergy analysis of cropping–grazing system in Inner Mongolia Autonomous Region, China. *Energy Policy*, 35(7), 3843–3855.
- Zhang X, Deng S, Wu J, & Jiang W (2010). A sustainability analysis of a municipal sewage treatment ecosystem based on emergy. *Ecological Engineering*, 36(5), 685–696.
- Zhang XH, Pang MY, Wang CB (2014). Emergy analysis of a small hydropower plant in southwestern China, *Ecological Indicators*, (38), 81–88.

Figure 1.
Illustrative process flow diagram of the WWTP producing the biosolids selected for this study (Adapted from Rodas E. & Toro J., 2005).

Figure 2.
Use of biosolids as fertilizer for silvopastoral soils.

Figure 3. Process flow diagram describing the biosolids gasification process by using a fluidized bed (adapted from Gros et al., 2008: Energy recovery from sewage sludge by means of fluidized bed gasification).

Figure 4.

An aggregated system diagram for describing the relationships between energy components and pathways for the biosolids used as soil fertilizer for grass production. These energy sources are discretized as renewable, nonrenewable, and imported inputs.

Figure 5.

An aggregated energy and material flow diagram for describing the relationships between energy components and pathways for the energy recovery process of biosolids by fluidized bed gasification. These energy sources are discretized as renewable, nonrenewable, and imported inputs.

Figure 6. Emergy comparison of the alternative for using the biosolids generated in a WWTP: (1) biosolids for soil fertilization and (2) biosolids for energy recovery by fluidized bed gasification.

Table 1.Process characteristics of the selected WWTP^a.

ACTIVITY		UNIT /y	VALUE
Removal of contaminants	BOD ₅	×10 ³ t	7.25
		% removal	82.5
	TSS	×10 ³ t	17.85
		% removal	87.7
Total volume of city's wastewater		×10 ⁶ m ³	179
Volume of treated wastewater		×10 ⁶ m ³	39.4
Wet mass of biosolids produced [†]		×10 ³ t	36.3
Biosolids composition ¹	Solids		0.366
	C		0.120
	H		0.056
	P		0.026
	N	mass fraction	0.016
	S		0.001
	Cl		0.001
	Heavy metals		0.003
	Ash		0.120

^aData provided by the studied WWTP (EPM, 2012).

Table 2.

Emergy calculations from using biosolids as soil fertilizers for grass production, discretizing renewable, nonrenewable, and imported resources.

Note	Item	Unit	Data, units/y	Unit solar emergy* (sej/unit)	Solar emergy ($\times 10^{13}$ sej/y)	Em\$ value (\$/y)	Emergy fraction
RENEWABLE RESOURCES							
a	Sun	J	5.72×10^{13}	1	5.7	6.6	
b	Rain, chemical energy	J	1.33×10^{11}	3.10×10^4	413	475	0.043
c	Wind, kinetic energy	J	3.63×10^8	2.45×10^3	0.09	0.10	0.000
d	Phosphate (from the sludge)	g	1.86×10^5	1.60×10^{10}	297	341	0.031
e	Nitrogen (from the sludge)	g	3.60×10^5	6.38×10^9	230	264	0.024
f	Potash (from the sludge)	g	6.00×10^4	1.74×10^9	10	12	0.001
g	Biomass (from the sludge)	g	2.00×10^7	2.70×10^9	4863	5590	0.510
NONRENEWABLE STORAGEES							
h	Net soil loss (heavy metals from the sludge)	J	2.2×10^{11}	1.24×10^5	2747	3157	0.288
PURCHASED INPUTS							
i	Fuel	J	5.48×10^{10}	1.11×10^5	607	698	0.064
j	Electricity	J	8.10×10^9	2.69×10^5	218	250	0.023
k	Machinery	g	5.54×10^4	1.79×10^{10}	99	114	0.010
l	Labor	J	9.42×10^7	4.45×10^6	42	48	0.004
m	Phytoremediation	\$	1.17×10^3	8.70×10^{12}	1015	1167	0.107
Total Emergy					9527	10950.18	1
PRODUCT TRANSFORMITY, Calculated							
n	Total Yield, Grass mass	ton	280				
	Transformity			3.40×10^8			
	Emergy Money Ratio		8.70×10^{12}				
	Grass sale Price (\$)		3111				
	Summary	NR	R	F	Y	Y (\$/y)	
	($\times 10^{13}$ sej/y)	2747	5813	966	9526	10950.18	
	Fraction	0.288	0.610	0.101	1		

* Unit solar emergy (sej/unit) references for respective row number: **a.** Odum, 1996; **b.** Agostinho et al., 2008; **c.** Agostinho et al., 2008; **d.** UNICAMP, 2002; **e.** Agostinho et al., 2008; **f.** Agostinho et al., 2008; **g.** Zhang et al., 2010; **h.** Agostinho et al., 2008; **i.** Odum, 1996; **j.** Agostinho et al., 2008; **k.** Odum et al., 2000; **l.** Odum et al., 2000; **m.** Odum, 1996; **n.** The “transformity, calculated” of a product is obtained by dividing the total emergy input by the energy content of the final product.

Table 3.

Emergy calculations: Use of biosolids for energy recovery by fluidized bed gasification, discretizing renewable, nonrenewable, and imported sources.

Note	Item	Unit	Data, units/y	Unit solar emergy* (sej/unit)	Solar emergy ($\times 10^{13}$ sej/y)	Em\$ value (\$/y)	Emergy fraction
RENEWABLE RESOURCES							
a	Sun	J	5.72×10^{13}	1	6	6.6	
b	Rain, chemical energy	J	1.33×10^{11}	3.10×10^4	413	475.3	0.034
c	Wind, kinetic energy	J	3.63×10^8	2.45×10^3	0.1	0.1	0.00001
d	Oxygen (in air)	g	1.30×10^7	5.16×10^7	67	77.0	0.005
e	Biomass (from the sludge)	g	2.00×10^7	2.70×10^9	5400	6206.9	0.441
NONRENEWABLE STORAGEES							
f	Coal	J	3.28×10^{10}	3.92×10^4	129	147.8	0.010
g	Washing oil	J	1.20×10^9	6.60×10^4	8	9.1	0.001
PURCHASED INPUTS							
h	Fuel	J	5.48×10^{10}	1.11×10^5	607	698.2	0.050
i	Electricity (mixing, drying, gasifying, Gas cleaning)	J	8.19×10^9	2.69×10^5	220	253.2	0.018
j	Machinery	g	2.80×10^6	1.79×10^{10}	5004	5751.5	0.408
k	Labor	J	5.32×10^8	4.45×10^6	237	272.2	0.019
l	Water	g	3.83×10^4	6.64×10^5	3	2.9	0.000
m	Disposal cost	\$	1.93×10^2	8.70×10^{12}	168	193.0	0.014
Total Emergy					12256	14087.1	1
n	PRODUCT TRANSFORMITY, Calculated						
	Total Yield, Electricity	kW	262336.59			72.87128	
	Transformity (sej/J)			4.67×10^8			
	Emergy Money Ratio		8.70×10^{12}				
	Electricity Sale price (\$/kWh)		14.5				
Summary							
	($\times 10^{13}$ sej/y)	NR	R	F	Y	Y (\$/y)	
		137	5880	6239	12256	14087.07	
	Fraction	0.011	0.480	0.509	1		

* Unit solar emergy (sej/unit) references for respective row number: **a.** Odum, 1996; **b.** Agostinho et al., 2008; **c.** Agostinho et al., 2008; **d.** Brown & Ulgiati, 2004; **e.** Zhang et al., 2010; **f.** Bastianoni et al., 2009; **g.** Odum, 1996; **h.** Odum, 1996; **i.** Odum et al., 2000; **j.** Odum et al., 2000; **k.** Odum et al., 2000; **l.** Bargigli et al., 2004; **m.** Odum, 1996; **n.** The “transformity, calculated” of a product is obtained by dividing the total emergy input by the energy content of the final product.

Table 4.

Emergy indexes of the two alternative uses of biosolids generated in a WWTP.

	NR (%)	R (%)	F (%)	Total Emergy (sej/y)
Alternative 1: Use of biosolids as soil fertilizers	28.8	61	10.1	9527×10^{13}
Alternative 2: Use of biosolids for energy recovery by fluidized bed gasification	1.1	48	50.9	12256×10^{13}

Table 5.

Emergetic indexes of the two alternative uses for each of the alternative uses of biosolids generated in a WWTP.

Energy indicator	Best target (100%)	Worst case (0%)	Agriculture: calculated value	Gasification: calculated value	GREENSCOPE sustainability %	
					Agr.	Gas.
ELR	0	10	0.64	1.08	93.6	89.2
EYR	5	1	9.86	1.96	100	24
ESI	10	0	15.44	1.81	100	18.1
EIR	0	1	0.11	1.04	89	0
RI	1	0	0.61	0.48	61.02	47.98
SEC	0	1	0.29	-	71	-
EER	0	10	3.52	970.21	64.8	0