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Original Research

# Environmental life cycle assessment of an integrated biosolids microsieving-drying-gasification pilot plant from WWTP

David Fernández-Gutiérrez 1, Anthoula Manali 2, Konstantinos Tsamoutsoglou 2, Petros Gikas 2, Andrés Lara Guillén 1,*

1 Centro Tecnológico de la Energía y el Medio Ambiente, Polígono Industrial Cabezo Beaza, C/ Sofía 6-13, 30353, Cartagena (Murcia), Spain; Email: david.fernandez@cetenma.es (D.F.-G.)
2 Design of Environmental Processes Laboratory, School of Chemical and Environmental Engineering, Technical University of Crete, 73100, Chania, Greece; Emails: amanali@tuc.gr (A.M.); ktsamoutsoglou@tuc.gr (K.T.); pgikas@tuc.gr (P.G.)

* **Correspondence:** Andrés Lara Guillén; Email: alara@cetenma.es

## Abstract

**Background:** The daily use of water causes its degradation and must be reclaimed to protect the environment. Wastewater treatment plants (WWTPs) have environmental burdens associated with energy consumption and sludge management. These burdens are linked, for instance, to energy consumption and sludge management. To diminish the environmental impact of the WWTPs, solutions like the developed one in the LIFE B2E4sustainable-WWTP project (B2E) arose. The B2E solution seeks to decrease some of the WWTP burdens by managing *in situ* the sludge generated in the WWTP through a gasification stage, valorising the syngas obtained in a cogeneration engine to produce both thermal and electrical energy. This reduces both the environmental impacts and costs derived from the sludge treatment by an external entity, being a self-sustainable solution in terms of energy. The B2E solution is designed for midsize WWTPs (10,000 and 100,000 PE), the majority of the European WWTPs.

**Methods:** The Life Cycle Assessment (LCA) was selected to evaluate the environmental performance of the B2E system. Six impact categories were analysed under the environmental footprint methodology (EF 3.0): climate change, freshwater ecotoxicity, freshwater eutrophication, human toxicity (cancer and non-cancer) and resource use (fossils). To check if the B2E solution reduced the environmental burdens, a comparison with a baseline (BS) system, typically implemented in midsize WWTPs, was performed.

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**Results:** The B2E system showed an environmental improvement compared to the BS in the six studied impact categories. The largest difference was observed in both human toxicity (cancer and non-cancer) impact categories. Their impacts were 99% lower compared to the BS. The reduction of the environmental impact for the rest of the categories ranged between 19% and 48%.

**Conclusions:** These results demonstrate from an environmental point of view that the B2E system has the potential to be implemented in midsize WWTPs in the near future. However, the technology should confirm these results under an operational environment to test the whole system by obtaining only representative primary data, which would enable future implementation strategies towards more efficient and sustainable WWTPs.

**Keywords:** biosolid thermal valorisation; energy saving; sludge management; sludge gasification; syngas production

## 1. Introduction

Freshwater is a vital natural resource; however, it is scarce, representing only 3% of all water on Earth. Freshwater use in agriculture, households and industry produces wastewater, which must be treated prior to release to the environment or use in irrigation. This treatment is achieved by wastewater treatment plants (WWTPs), which use diverse processes to remove the pollutants that wastewater possesses in its composition according to the legal framework and depending on the final reclaimed water use [1]. WWTPs have been designed to protect public human health and natural aquatic systems, through wastewater recovery. However, the operation of the WWTPs presents environmental burdens linked to energy and water use, by-product production, chemical consumption, loss of scarce resources *etc*. [2,3]. Hence, there is an opportunity to reduce their environmental impacts in light of achieving the current climate change and emissions reduction goals without compromising either human health or the environment.

Life Cycle Assessment (LCA) is one of the most frequently applied methodologies to evaluate the environmental performance of WWTPs [4]. This methodology applied to WWTPs calculates and correlates the utilization of raw materials and chemicals, the quality of treated wastewater, the several emissions (gaseous, particulate matters *etc*.), the production of primary and secondary sewage sludge, *etc*. to characteristic indicators of specific environmental impacts [3]. The expected result of each environmental LCA is not only the inventory of the energy balance of the WWTP, but also to investigate optimization of the relationship between energy quality and wastewater. Hence, an LCA is carried out to evaluate the environmental performance of a WWTP, where those areas of improvement (hotspots) are identified [5].

The environmental performance of WWTPs has attracted attention of both the wastewater sector and scientific community. In this way, there has been extensive global LCA research on wastewater treatment and sewage sludge management. Some examples related to the present manuscript are studies to show: (i) the environmental benefits of reclaiming wastewater for its reuse in agriculture [6,7]; and (ii) the impacts testing diverse sludge treatments, where biological, chemical, thermal-chemical options were examined [8–12]. According to Suh and Rousseaux, among five sludge management treatments, the friendliest scenario was a combination of anaerobic digestion and a subsequent application in fields due to lower emissions and energy requirements [8]. In addition, this option was better concerning nutrient recovery [9]. Anaerobic digestion was also one of the best options to manage sludge together with pyrolysis and supercritical water oxidation according to Teoh and Li [10], who evaluated different studies; whereas, incineration in cement kilns resulted in better balance in terms of global warming over pyrolysis [11]. Finally, among other management options, composting was the best cost-savings over incineration and landfilling [12]. The latter group of studies [8–12] are directly linked to the LIFE B2E4sustainable-WWTP (henceforth, B2E), begun in 2016. The B2E solution aims to manage the sludge generated in the WWTP *in situ* through a gasification stage, valorising the syngas obtained in a cogeneration engine to produce both thermal and electrical energy [13]. Therefore, what the B2E project pursues is the management of the sludge within the WWTP (reducing the costs derived from its external treatment) and the reduction of energy consumption since the B2E system was designed as a self-sustainable solution in terms of energy. The B2E solution is at Technology Readiness Level (TRL) 7 and being tested to reach TRL 8 in the following months. To the best of the authors' knowledge, this integrated solution has not been studied before.

The objective of this study is to compare the environmental impacts of the conventional sludge management method (Baseline, BS) used in the majority of European wastewater treatment plants (10,000–100,000 PE with an extended aeration biological treatment and lacking primary settling and anaerobic digestion) with a new integrated solution (B2E) that enables on-site management. The B2E system is an innovative and efficient solution that reduces the environmental burdens in comparison with the conventional sludge management option as shown in the present study. On the other hand, as mentioned before, as the sludge is managed in its own facility, the exploitation cost might be lower. However, this fact depends on the sludge management treatment that are currently being carried out by each facility as reported by Rostami *et al.* [12]. In addition, by mitigating environmental impacts, this approach has a positive influence on society by preventing the release of pollutants into the environment and thereby improving human health.

In conclusion, this study seeks to demonstrate that gasification can serve as a viable short-term solution for sludge management, aligning with the three pillars of sustainability: economic, environmental and social considerations.

## 2. Materials and Methods

### 2.1 LCA methodology

The LCA is a multi-criteria tool to evaluate the environmental burdens linked to a product or a service through its value chain [14]. An LCA study is composed of four steps [15,16]:

(i) Goal and scope definition,
(ii) Life Cycle Inventory (LCI) analysis,
(iii) Environmental impact assessment (Life Cycle Impact Assessment, LCIA),
(iv) Results interpretation.

In detail, the first step defines the objective, the system boundaries and the Functional Unit (FU) of the study. In the LCI analysis (second step), the inputs and outputs (energy, raw materials, waste, emissions, *etc*.) quantification of the studied system are gathered and calculated by using the adequate procedures. Moreover, these inputs and outputs are referred to the FU [17]. The environmental impact assessment is the third step, where the impacts of those inputs and outputs on the environment are quantified. Finally, results from the LCI and the LCIA are interpreted (fourth step) following the stated goal and scope [17].

#### *2.1.1 Goal and scope definition*

The objective of the present study was the evaluation of the environmental impacts linked to the entire WWTPs with a treatment capacity between 10,000 and 100,000 PE after implementing the B2E process. In addition, the B2E solution was compared to the current scenario (BS) present in the activated sludge WWTPs. The type of LCA considered a "cradle-to-grave" study since the following stages were taken into account: extraction of the raw materials (input wastewater) and energy sources, production processes, product use and final recycling/disposal of the wastes generated [15,16]. It is required to point out that the sludge obtained in the BS is composted and subsequently applied in agriculture (external management); whereas, the B2E system allows the sludge management *in situ*, producing both heat and electricity and saving in operating costs. Therefore, the B2E is a complementing process within the WWTP, being the comparison carried out as follows: BS and BS + B2E. Figure 1 shows the flows and processes included in the study within the BS, whereas Figure 2 displays the B2E system. The boundary systems are also presented.

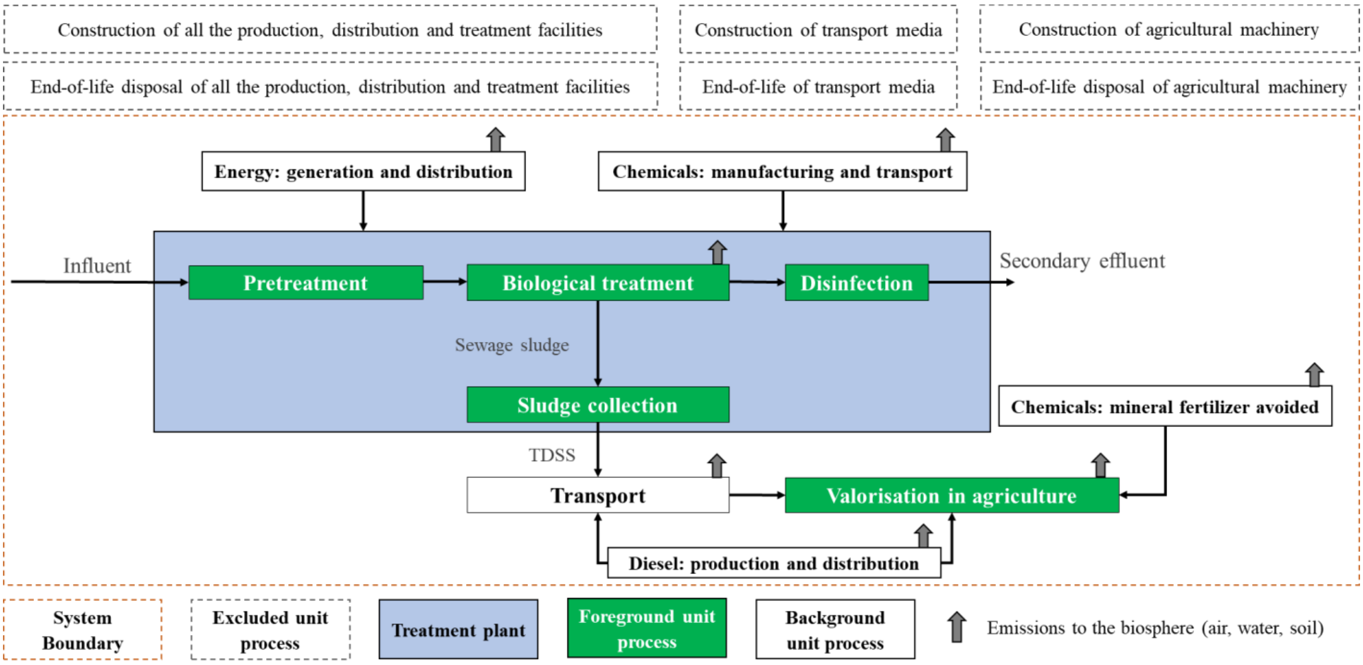



**Figure 1.** Descriptive scheme of the BS system, where the TDSS is composted and applied in agriculture.

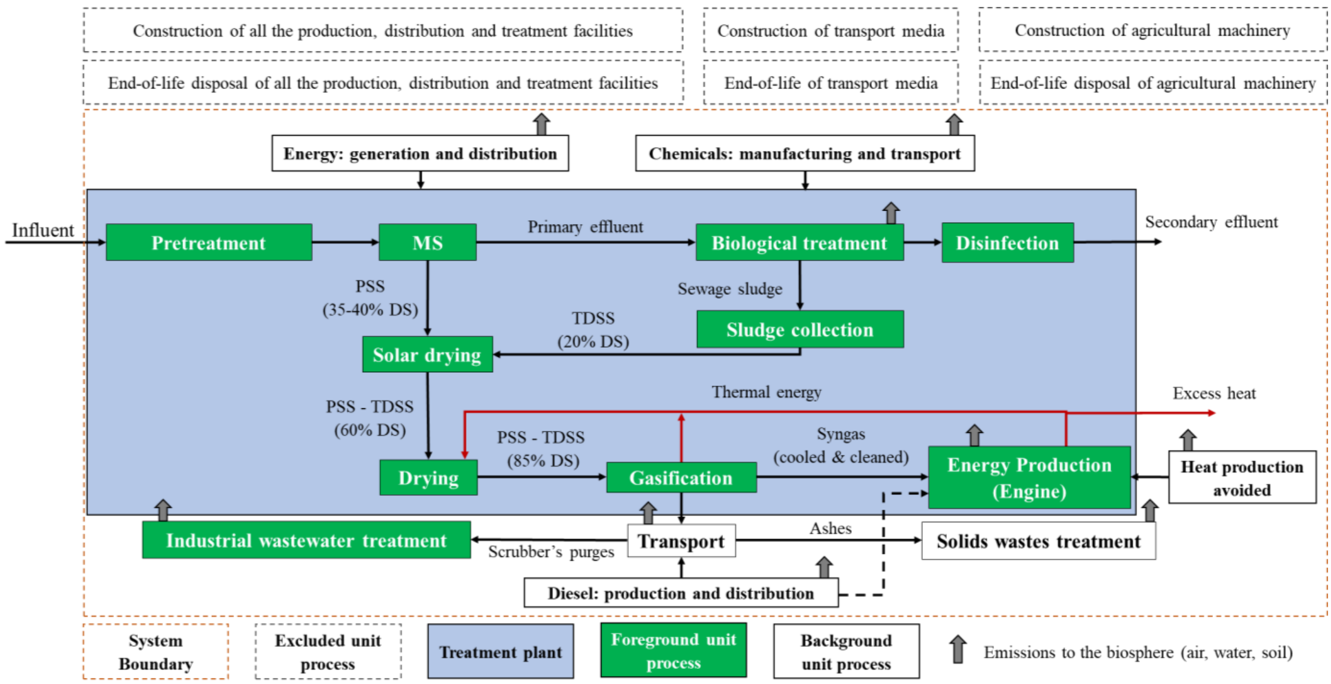



**Figure 2.** Descriptive scheme of the B2E system, where PSS (biosolids from MS) and TDSS (biological sludge, thickened and dewatered) are thermally treated (drying and gasification), resulting to energy production.

The studied BS scenario is the one where the produced sewage sludge is allowed to be used in agriculture only whether it is previously composted, since the direct application of sewage sludge (without being composted or anaerobically digested) is more and more restricted in the European Union. In this case, the BS system is a WWTP with composting of the dewatered sludge and application of compost in agriculture (Figure 1). Firstly, the influent raw wastewater goes first through a pre-treatment, where settleable solids, sands, greases and oils are separated. Subsequently, the wastewater is pumped to the biological aerobic reactor to reduce the concentration of biodegradable organic matter and nutrients (Nitrogen - N and Phosphorus - P compounds) to proper limits. The treated wastewater produced from the aeration process, which is called secondary effluent, is finally disinfected with sodium hypochlorite (NaClO) for reducing the pathogenic parameters and remove non-biodegradable Chemical Oxygen Demand (COD). The Secondary Sludge (SS) produced by the biological reactors is thickened by gravity and dewatered using polyelectrolyte. Finally, the sludge is composted and valorised in agriculture.

The scenario for comparison in the present study was the B2E solution. As observed in Figure 2, an industrial Microsieve (MS), with a belt of 110 cm width and 350 μm pore opening, acting as an alternative primary treatment, is placed between the pretreatment and the biological process. This stage removes about 35–40% of the Total Solids, thus producing Primary Sieved Solids (PSS) with 60–65% moisture content. Afterwards, the PSS are blended with Thickened Dewatered Secondary Sludge (TDSS) in a ratio of 19–81% (w/w), containing about 80% of moisture. The PSS–TDSS blend is then dried in a solar drying system (greenhouse type dryer with a mechanical turning of the sludge bed) up to 60% Dry Solids (DS). Afterwards, the PSS–TDSS blend is passing through an electrical dryer, ending up having 85% DS (optimum for the upcoming gasification process), and then it is shaped into briquettes and gasified in a downdraft gasifier. The generated syngas is combusted in a co-generation engine, which is fed by a diesel-syngas mixture (energy substitution ratio of 88%), producing both electric and thermal energy. The thermal energy from syngas cooling, from the gasifier and from the engine is used to dry the PSS–TDSS blend up to 85% DS, as mentioned before. Finally, two residues are generated from the gasification-syngas treatment process: ash and scrubber effluents, being *ex-situ* managed. The scrubber effluents from the syngas cleaning process are considered as industrial wastewater, so they are not suitable to be treated in a WWTP; they have to be treated under specific conditions.

Regarding the FU, the treatment of 1 PE per year (1 PE·y) was selected since it can be applied to different types of wastewaters, which do not have similar contaminant loads. This is an advantage compared to using 1 $m^3$ of wastewater treated, which present this issue and the comparison between two different WWTPs cannot be performed under the same conditions. Therefore, using the organic load linked to a PE per year, the parameters defining the WWTP influent stay similar as 1 PE estimates a Biochemical Oxygen Demand (BOD) value of 60 g/day and, thus, the comparison between different WWTPs can be carried out. The present FU (1 PE·y) was also reported in other studies [18–21].

*2.1.2 Life Cycle Inventory (LCI) analysis*

The LCI analysis is formed of both data collection and calculations required to quantify the inputs (energy and raw materials) and outputs (emissions to air, soil and water) of the studied systems, according to the FU [14]. Data collection was divided into two sources: primary and secondary data. Primary data came from the experimental phase of the B2E project, whereas the secondary data were obtained from bibliographic sources and Sphera LCA software database used in the present study. Table 1 gathers the references used in each stage. The database was used for defining the LCI of the background processes. In the case of foreground processes, secondary data were used only when primary data were not available or representative at industrial scale. The required information for defining the inventories was completed with expert estimates, when appropriate. Additionally, it is important to mention that each inventory flow was estimated using either primary or secondary and, thus, neither secondary datum was directly used in the inventories constructed for the B2E solution.

**Table 1** References used in the present study to complete the inventories. The references were gathered as a function of the item.

| Item | Reference | Item | Reference |
|---|---|---|---|
| Wastewater quality and removal yield | [22,23] | Electricity and fuel consumption linked to the composting process | [8,40,42] |
| Aeration electricity consumption | [22,23] | Emissions of diesel in non-road industrial mobile machinery | [42] |
| Yield and electricity consumption in the sludge line and its quality | [24–27] | Emissions derived for the compost use in agriculture | [24,26,27, 30,43–45] |
| Chemical consumption rate | [22,24,28,29] | Fuel consumption linked to the agricultural machinery | [46,47] |
| $N_2O$ emissions | [27,30] | Atmospheric emissions linked to fuel consumption used in agricultural machinery | [42] |
| WWTP electricity consumption | [31–39] | Sludge calorific value and gasification yield | [35,48] |
| Direct emissions linked to the composting process | [40,41] | Direct emissions due to the diesel use in the dual engine | [30,42] |

Tables 2 and 3 show the LCI of the foreground processes included in the WWTP and in the sludge valorisation system, respectively, for a WWTP of 60,000 PE, in the case of BS.

**Table 2** LCI of the WWTP in BS case (FU: 1 PE·y).

| Inputs From the technosphere | | Outputs To the technosphere | | | |
|---|---|---|---|---|---|
| Influent flow | 62,571 $m^3$ | Sewage sludge (dewatered) | 52.8 kg | | |
| | | **Emissions to air** | | | |
| Influent BOD | 21.9 kg | $N_2O$ | 0.016 kg | | |
| Influent TSS | 13.1 kg | **Emissions to freshwater** | | | |
| Influent Total Kjeldahl Nitrogen (TKN) | 4.8 kg N | BOD | 0.8 kg | $NH_3$ | 0.01 kg |
| Influent Total Phosphorus (TP) | 0.7 kg P | TSS | 1.1 kg | $PO_4$ | 0.19 kg |
| $FeCl_3$ (100%) | 3.1 kg | $NO_3$ | 1.4 kg | Treated water | 62,519 $m^3$ |
| Polyelectrolyte (acrylonitrile, 100%) | 0.1 kg | N (organic) | 1.0 kg | | |
| NaClO (14%) | 3.13 kg | | | | |
| Electricity | 128.4 MJ | | | | |
| Chemicals transport | 3.16 t-km | | | | |

**Table 3** LCI of the sludge valorisation system in BS case: composting and agricultural application (FU: 1 PE·y).

| Composting of dewatered sludge | | | | | |
|---|---|---|---|---|---|
| **Inputs From the technosphere** | | **Outputs To the technosphere** | | | |
| Sewage sludge | 52.8 kg | Compost | 10.2 kg | | |
| Dry solid in sewage sludge | 10.6 kg | Dry solid in compost | 6.6 kg | | |
| Nitrogen in sewage sludge | 0.53 kg | Nitrogen in compost | 0.51 kg | | |
| Phosphorus in sewage sludge | 0.59 kg | Phosphorus in compost | 0.59 kg | | |
| Diesel | 0.084 kg | **Emissions to air** | | | |
| Sewage sludge transport | 5.28 t-km | $NH_3$ [1] | 12.7 g | $CO_2$ [2] | 0.27 kg |
| Electricity | 1.90 MJ | $N_2O$ [1] | 10.6 g | $NO_x$ [2] | 1.27 g |
| | | $CH_4$ [1] | 106 g | $N_2O$ [2] | 0.012 g |
| | | $CH_4$ [2] | 0.003 g | $SO_2$ [2] | 0.0017 g |
| | | CO [2] | 0.60 g | *NMVOCs [2] | 0.116 g |
| | | $NH_3$ [2] | 0.0007 g | *PM10 [2] | 0.066 g |
| | | *PM2.5 [2] | 0.066 g | | |
| **Compost application in agriculture** | | | | | |
| **Inputs From the technosphere** | | **Outputs Emissions to air** | | | |
| Compost | 10.2 kg | $NH_3$ [3] | 0.085 kg | $N_2O$ [4] | 0.0006 g |
| Dry solid in compost | 6.6 kg | $N_2O$ [3] | 0.009 kg | $SO_2$ [4] | 0.0001 g |
| Nitrogen in compost | 0.51 kg | $CH_4$ [4] | 0.0002 g | NMVOCs [4] | 0.006 g |
| Phosphorus in compost | 0.59 kg | CO [4] | 0.031 g | PM10 [4] | 0.003 g |
| Diesel | 0.004 kg | $CO_2$ [4] | 0.013 kg | PM2.5 [4] | 0.003 g |
| Compost transport | 0.25 t-km | $NO_x$ [4] | 0.068 g | | |
| N fertiliser subst. (27N, CAN) | −1.17 kg | **Emissions to freshwater** | | | |
| P fertiliser subst. ($46P_2O_5$, TPS) | −1.98 kg | $PO_4^{3-}$ | 0.096 kg | | |
| | | **Emissions to agricultural soil** | | | |
| [1] From composting process; | | Cd | 0.32 g | Ni | 3.7 g |
| [2] From diesel consumption in composting machinery; | | Cr | 13.2 g | Pb | 10.3 g |
| [3] From compost application in soils; | | Cu | 14.5 g | Zn | 34.3 g |
| [4] From Diesel consumption in agricultural machinery. | | Hg | 0.2 g | $PO_4^{3-}$ | 0.008 kg |

* Particulate Matter 2.5 μm or less in diameter (PM2.5); Non-Methane Volatile Organic Compounds (NMVOCs); Particulate Matter 10 μm or less in diameter (PM10).

Subsequently, the inventories of the foreground processes considered for the WWTP with the B2E solution implemented on it are shown. Specifically, these processes are divided in the three following systems: WWTP without B2E solution (Table 4), B2E solution (Table 5) and industrial wastewater (scrubber effluents) treatment coming from the syngas cleaning process (Table 6).

**Table 4** LCI of the WWTP without B2E solution (FU: 1 PE·y).

| **Inputs From the technosphere** | | **Outputs To the technosphere** | | | |
|---|---|---|---|---|---|
| Influent flow | 62,571 $m^3$ | Biological sludge (dewatered) | 45.7 kg | | |
| Influent BOD | 21.9 kg | **Emissions to air** | | | |
| Influent TSS | 13.1 kg | $N_2O$ | 0.013 kg | | |
| Influent TKN | 4.8 kg N | **Emissions to freshwater** | | | |
| Influent TP | 0.7 kg P | BOD | 0.8 kg | $NH_3$ | 0.01 kg |
| $FeCl_3$ (100%) | 2.96 kg | TSS | 1.1 kg | $PO_4$ | 0.19 kg |
| Polyelectrolyte (acrylonitrile, 100%) | 0.08 kg | $NO_3$ | 1.4 kg | Treated water | 62,515 $m^3$ |
| NaClO (14%) | 3.13 kg | N (organic) | 1.0 kg | | |
| Electrical energy (net) | 104.0 MJ | | | | |
| Electrical energy (WWTP) | 115.5 MJ | | | | |
| Electrical energy from biosolids treatment system | −11.4 MJ | | | | |
| Chemicals transport | 3.08 t-km | | | | |

**Table 5** LCI of the biosolids treatment (PSS and TDSS drying-gasification-energy production) (FU: 1 PE·y).

| **Inputs From the technosphere** | | **Outputs To the technosphere** | |
|---|---|---|---|
| Influent to MS | 62,571 $m^3$ | MS effluent | 62,561 $m^3$ |
| Biological sludge (dewatered) | 45.7 kg | BOD to biological treatment | 19.1 kg |
| Tap water | 2.22 kg | N to biological treatment | 4.7 kg |
| $H_2SO_4$ (96%) | 0.89 kg | P to biological treatment | 0.6 kg |
| NaOH (50%) | 0.44 kg | Industrial wastewater | 4.4 kg |
| NaClO (14%) | 0.44 kg | Ashes | 2.6 kg |
| Diesel | 0.39 kg | **Electrical energy (net)** | 11.4 MJ |
| **Electrical energy (net)** | 0.00 MJ | Electrical energy (from engine) | 41.5 MJ |
| Electrical energy (MS) | 9.09 MJ | Electrical energy (self-consumed) | −30.1 MJ |
| Electrical energy (solar drier) | 3.79 MJ | **Thermal energy (net)** | 53.1 MJ |
| Electrical energy (dryer) | 4.43 MJ | Thermal energy (from gasifier + engine) | 77.4 MJ |
| Electrical energy (gasifier) | 12.76 MJ | Thermal energy (self-consumed) | −24.4 MJ |
| Electrical energy (self-consumed) | −30.07 MJ | Industrial wastewater transport | 0.22 t-km |
| **Thermal energy (net)** | 0.00 MJ | Ashes transport | 0.13 t-km |
| Thermal energy (drier) | 24.4 MJ | **Emissions to air** | |
| Thermal energy (self-consumed) | −24.4 MJ | $CH_4$ [1] | 52.2 g |
| Chemicals transport (gas cleaning) | 0.53 t-km | CO [1] | 455.5 g |
| | | $CO_2$ [1] | 1.23 kg |
| [1] From syngas-diesel combustion in engine. | | $NO_x$ [1] | 40.6 g |
| | | $N_2O$ [1] | 0.01 g |
| | | $SO_2$ [1] | 0.78 g |
| | | NMVOCs [1] | 0.83 g |
| | | PM10 [1] | 0.50 g |
| | | PM2.5 [1] | 0.50 g |

**Table 6** LCI of the industrial wastewater (scrubber effluents) generated from syngas cleaning process (FU: 1 PE·y).

| Inputs<br>From the technosphere | | Outputs<br>To the technosphere | |
|---|---|---|---|
| Industrial wastewater | 4.4 kg | Dewatered sludge to landfill | 0.0044 kg |
| $FeCl_3$ (100%) | 0.001 kg | Treated water to a WWTP | 4.36 kg |
| Electrical energy | 0.0046 MJ | | |
| Industrial wastewater transport | 0.22 t-km | | |
| $FeCl_3$ transport | 0.0007 t-km | | |
| Dewatered sludge transport | 0.0002 t-km | | |

*2.1.3 Life Cycle Impact Assessment (LCIA)*

The LCIA aims at evaluating the significance of potential environmental impacts, which were evaluated by using the Environmental Footprint (EF) v3.0 methodology, included in Sphera LCA software (v10.5, Sphera Solutions GmbH, Chicago, IL, USA). Among the 16 impact categories analysed by the EF methodology, only 6 impact categories were included in the present study: (i) climate change, (ii) freshwater ecotoxicity, (iii) freshwater eutrophication, (iv) human toxicity (cancer), (v) human toxicity (non-cancer), and (vi) resource use, fossils. These impact categories were selected according to the specification of the LIFE B2E project proposal, which stated that the LCA was going to be focused on the following indicators: carbon footprint, energy footprint, water footprint, impacts on human health and impacts on ecosystems, as well as according to the criteria of the developer of this work. In principle, another impact category to consider is water use. However, both systems showed pretty similar positive effect on freshwater consumption: BS (–2,669 $m^3_{eq}$) and B2E (–2,667 $m^3_{eq}$). Hence, this impact category was not considered.

*2.1.4 Interpretation of results*

A contribution analysis was performed to determine the weight on the total environmental impacts linked to each process of the studied systems. This step served to identify the most relevant stages (hotspots), in line with the goal and scope previously defined.

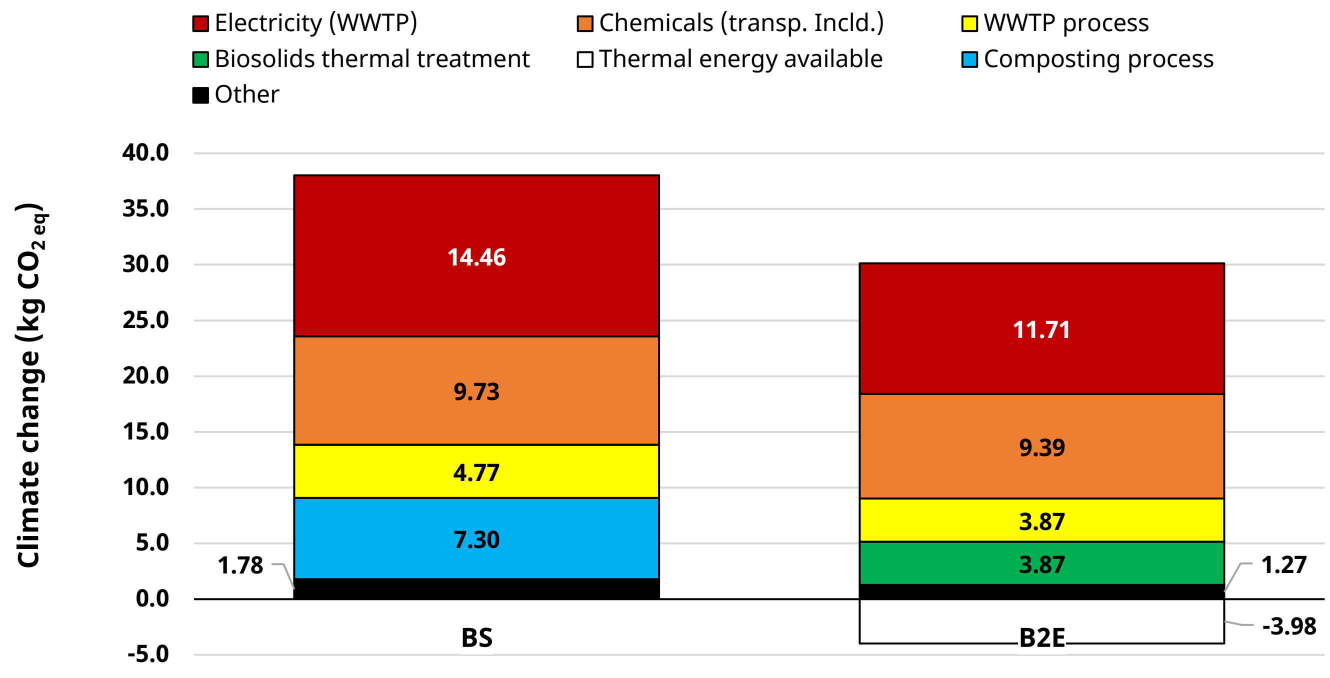
## 3. Results and Discussion

### 3.1 Environmental impacts related to the Baseline (BS) and Biosolids to Energy (B2E) systems

In the present section, the results of the environmental impacts related to each scenario are shown and discussed. For a better understanding to the general audience, a short description of the units used in each impact category is provided in Table 7.

**Table 7** Description of the different impact units depending on the impact category evaluated.

| Impact category | Impact units | Description |
|---|---|---|
| Climate change | Kg $CO_{2\text{-eq}}$ | Metric measure to compare the emissions from various GHGs on the basis of their global-warming potential, converting the amounts of other gases to the equivalent amount of $CO_2$ with the same global warming potential. |
| Freshwater ecotoxicity | $CTU_e$ | The $CTU_e$ expresses the estimated potentially affected fraction of species integrated over time and the volume of the freshwater compartment per unit of mass of the chemical emitted |
| Freshwater eutrophication | Kg $P_{eq}$ | Indicator of the enrichment of the freshwater ecosystem with nutritional elements, due to the emission of nitrogen or phosphor-containing compounds |
| Human toxicity (cancer and non-cancer) | $CTU_h$ | The $CTU_h$ expresses the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases/kg) |
| Resource use, fossils | MJ | Indicator of the depletion of natural fossil fuel resources. |




"Other" in the BS included: sludge transport, composting (electricity and diesel production), compost use (transport, spreading and fertilising) and the fertilisers substitution. "Other" in the B2E included: chemicals for cleaning gases (gasification) and its transportation, tap water and diesel production, ashes (transport and landfilling) and industrial wastewater (transport and treatment).

**Figure 3** Contribution of the most relevant items involved in both BS and B2E solution within the climate change impact category.

(i) Climate change

Figure 3 shows the results related to the most relevant processes within both studied systems and their contribution to the climate change impact category, as the mass of carbon dioxide equivalent ($CO_{2\text{-eq}}$). As observed, the BS system contributed a total of 38 kg $CO_{2\text{-eq}}$, while the B2E solution reduced that impact by 31.3%, up to 26.1 kg $CO_{2\text{-eq}}$. This is directly linked to the valorisation of the sludge generated throughout the wastewater treatment as mentioned below.

Going deeply to the studied systems, the largest contributor was the electricity consumed in the WWTP for both cases, contributing about 38% and 44.8% of the total impact for BS (14.5 kg $CO_{2\text{-eq}}$) and B2E (11.7 kg $CO_{2\text{-eq}}$), respectively. Also, the weight of electricity was higher on the B2E system compared to the BS, but its contribution was 19.3% lower. The lower electricity consumption of the B2E system with respect to the BS is attributed to the following two factors: (i) Firstly, the removal of a part of the Total Suspended Solids (TSS) through the microsieving process helps to reduce the load reaching the biological reactors. This contributes to the reduction of the electricity required for aeration and the energy consumption to dewater the biological sludge since its production is lower. (ii) Secondly, the B2E solution produces enough electricity (coming from the co-generation engine) to supply the whole system (including MS), so there is a surplus of electricity that is consumed in the rest of the facility, further decreasing its net consumption. After the electricity item, chemicals used in the WWTP were the second (9.7 and 9.4 kg $CO_{2\text{-eq}}$ for the BS and B2E, respectively) largest contributors for both systems in this impact category. As previously mentioned, the MS removes part of the TSS, which cause a reduction of the chemicals required in the biological stage ($FeCl_3$ to precipitate phosphates) and sludge concentration (polyelectrolyte to dewater the sludge).

In the case of the BS system, the composting process results 7.3 kg $CO_{2\text{-eq}}$ (19.2% of the total impact) being the third process in importance. The impact was mainly caused by methane ($CH_4$) and nitrous oxide ($N_2O$) emissions generated when the organic matter is stabilized, as indicated by other authors like González *et al*. [49] and Li *et al.* [50]. In the case of the B2E system, the third process with the greatest impact (−4.0 kg $CO_{2\text{-eq}}$) is the use of excess thermal energy from the facility. After biosolids drying with the generated heat, there is a surplus which could be used in another facility out of the WWTP. In this case it is a negative value, since said use would mean the avoided production of an equivalent amount of thermal energy by using natural gas to obtain steam.

Another significant impact over the whole system was the corresponding of the processes involved in the WWTP, being the fourth in importance, both in BS and B2E systems (4.8 kg $CO_{2\text{-eq}}$ and 3.9 kg $CO_{2\text{-eq}}$, respectively). In this case, the emission is entirely due to the generation of $N_2O$ that takes place during the wastewater treatment process. The lower impact of the B2E solution was because a part of the N contained in the wastewater comes out in the primary sludge generated by the MS, decreasing the N load in the biological reactor and, thus, there are lower $N_2O$ emissions in this step. Finally, the impact of the B2E system can be highlighted, contributing with 3.9 kg $CO_{2\text{-eq}}$, due to the Greenhouse Gases (GHG) emissions coming entirely from the dual engine within the item "Biosolid Thermal Treatment".

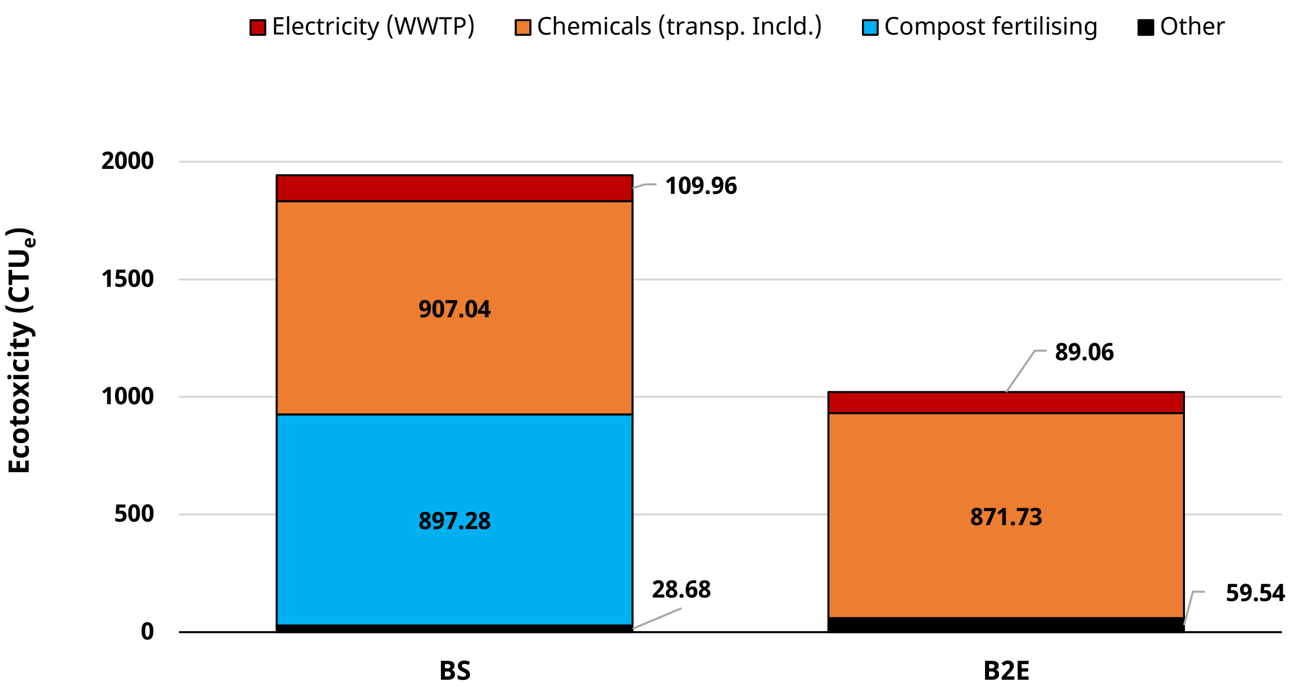
According to Rashid *et al.* [51], the generation and distribution of the electricity is the main indirect contributor to the $CO_2$ emitted by a WWTP, ranged between 14% and 36%. In the present study, this was in line with the contribution of the electricity in the BS, which was 34.7% (13.2 kg $CO_{2\text{-eq}}$). In the case of the B2E, this percentage contribution was higher, 41.4%. However, the amount of the emitted indirect $CO_2$ was lower (10.8 kg $CO_{2\text{-eq}}$) due to the valorisation of sludge within the B2E system. On the other hand, another important contributor to the climate change category is the $N_2O$ formed in the biological stage, where its contribution ranges between 23% and 43% [51]. The weight of $N_2O$ in the present study was not within this range, being lower than that one in both cases: 12.6% (4.8 kg $CO_{2\text{-eq}}$ in the BS) and 14.8% (3.9 kg $CO_{2\text{-eq}}$ in the B2E). This might be explained because the $N_2O$ released varies not only depending on the technology (removal of N percentage) but also on the ratio of outlet N released as $N_2O$ considered to create the inventories. In the present study, this ratio was 0.005 kg $N_2O$/kg N [34]; whereas, other authors like Chai *et al.* [52] used 0.035 kg $N_2O$/kg N, seven times higher.

(ii) Freshwater ecotoxicity

In the case of the ecotoxicity impact category (Figure 4), the BS contributed a total of 1,943 Comparative Toxic Units ($CTU_e$), whereas the B2E could reduce this impact by 47.5% (1,020 $CTU_e$). The main two contributors for the BS system were the item chemicals (manufacturing and transport of $FeCl_3$, polyelectrolyte and NaClO) and compost fertilising, 46.5% and 46% of the total impacts, respectively. In the case of the B2E solution, the main contributor (85.3% of the total impact) were the chemicals used during the wastewater treatment, being only 3.9% lower (871.7 $CTU_e$) compared to the chemicals of the BS case (907 $CTU_e$). The lower used of chemicals in the case of the B2E was explained in the previous subsection of climate change.

Therefore, the main difference came from the use of compost as a fertiliser (897.3 $CTU_e$), which is not required in the B2E solution. The compost contains heavy metals, which enter the ecosystem by its spreading on fields. In this case, the main impact came from copper (Cu), contributing 760 $CTU_e$ (39.1% of the total ecotoxicity impact and 84.7% of the sludge valorisation). The rest of the heavy metals contributed 6.35% (Nickel, Ni), 4.11% (Cadmium, Cd), 2.80% (Zinc, Zn) and 1.73% (others). The complete management of the sludge in fields (including sludge transport, electricity and diesel in composting, *etc.*) resulted in an impact of 901 $CTU_e$ (897.28 $CTU_e$ from compost fertilising item and 3.74

$CTU_e$ from compost management in agriculture, included in "Other"). Regarding the B2E system, the whole biosolids treatment also including the MS, the ash and industrial wastewater (scrubber effluents) treatment, but not the reduction of energy consumption of the remaining WWTP, only contributed 34.6 $CTU_e$; which is 26-folds lower compared to the BS system.




"Other" in the BS included: WWTP processes, sludge transport, composting (process, electricity and diesel production), compost use (transport and spreading) and the fertilisers substitution. "Other" in the B2E included: WWTP processes, chemicals for cleaning gases (gasification) and its transportation, tap water and diesel production, biosolids thermal treatment and thermal availability, ashes (transport and landfill) and industrial wastewater (transport and treatment).

**Figure 4** Contribution of the most relevant items involved in both BS and B2E solution within the ecotoxicity impact category.

(iii) Freshwater eutrophication

The total impact on the freshwater eutrophication was 0.093 and 0.063 kg $P_{eq}$ for the BS and B2E systems, respectively. This meant a reduction by 32.7% implementing the B2E technology in the WWTP. It is interesting to mention that the main contributor was the WWTP process: 0.063 kg $P_{eq}$ in both cases. This emission to freshwater was caused by the phosphate contained in the treated wastewater. As observed checking the mentioned data, it was the only significant contributor in the case of the B2E system. For the BS case, compost fertilising contributed as well with a weight of 33.2% of the total impact (0.032 kg $P_{eq}$), due to the P content in the compost and part of that is released into the freshwater by runoff as phosphate form [28]. Finally, it is interesting to mention that applying sludge in agriculture avoids the use of chemical fertiliser. In this way, the item "compost fertilising substitution" resulted in a positive effect (−1.38 x $10^{-3}$ kg $P_{eq}$) within the present impact category.

(iv)–(v) Human toxicity—cancer and non-cancer

These two impact categories (human toxicity—cancer and non-cancer), are indicators related to the impact of toxic substances on humans emitted to the environment. The main contributor of the BS system was the process of "compost fertilising", which contributed more than 99% of the total impact in both categories (Table 8). On the other hand, in the B2E solution, the main contributors (for human toxicity—cancer) were the electricity and the chemicals consumed in the WWTP: about 37% and 48%, respectively. Their weight within the total burdens contributed with more than 85%, while these were only 0.6% in the case of the BS. However, the value in electricity was 19% higher in the case of the BS, compared to the implementation of the B2E solution and there was no significant difference in the item "chemicals". These results, besides the fact that the biosolids are completely valorised by gasification and, thus, no compost is used in fields, explained why the B2E solution showed 99.4% lower impact in the impact category "human toxicity—cancer". Going deeply into the compost fertilising stage of the BS case, the impact was due to agricultural soil emissions (1.77 x $10^{-6}$ $CTU_h$), mainly caused by the presence of four heavy metals: mercury (Hg) with 45.28%; chromium (Cr) with 37.70%; lead (Pb) with 8.82%; and Ni with 5.96%. In comparison, within the biosolids treatment process of the B2E solution, the heavy metals resulted in 7.28 x $10^{-10}$ $CTU_h$; being Hg (53.16%) and Cr (31.32%) the main compounds released into the environment. This was 2,431 times lower compared to the BS, demonstrating that the B2E is a very good option to valorise the sludge in the present impact category. The high difference is attributed to the fact that in the case of B2E system, heavy metals are ended up into the ash generated during the gasification stage, which are managed by confining them into landfills; significantly reducing its impact on the environment.

Something similar can be observed in the case of the impact category "human toxicity—non-cancer", whose difference between BS and B2E system was 99.1% lower in the latter case (Table 8). Chemicals used in the WWTP was the largest contributor (58.04%) for B2E solution, representing only 0.58% in the case of the BS. However, the result for this item was very similar for both systems (9.36 x $10^{-7}$ and 9.57 x $10^{-7}$, respectively), being the emissions of Hg (47.65%) and chlorine (44.44%) the main contributors from NaClO and $FeCl_3$ (manufacturing and transport), respectively. These compounds are released during the chemicals manufacturing, being indirect emissions of the studied processes. In the case of the compost fertilising stage (BS system), the impact was also caused by the emissions of heavy metals to the agricultural soil; mainly Hg (57.88%) and Pb (33.45%). On the contrary, for B2E solution, practically the only responsible of the impact associated to the biosolids treatment (99.8% of its impact) was the emission of carbon monoxide (CO) generated in the dual engine (syngas valorisation stage).

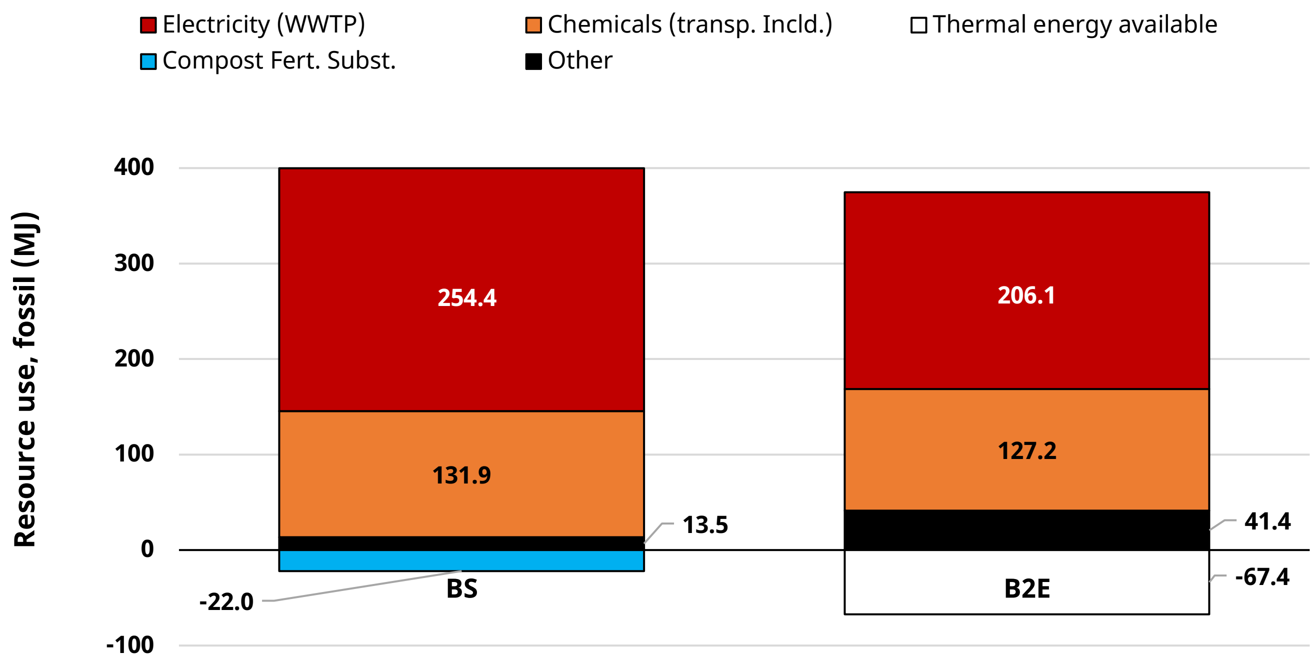
**Table 8** Value ($CTU_h$) and weight of the total impact (%) of the main contributors (items) in both BS and B2E solutions in the human toxicity impact category.

| Human toxicity—cancer ($CTU_h$) | | | | |
|---|---|---|---|---|
| **Item** | **Value of BS** | **Weight of BS** | **Value of B2E** | **Weight of B2E** |
| Electricity (WWTP) | $5.12 \times 10^{-9}$ $CTU_h$ | 0.29% | $4.15 \times 10^{-9}$ $CTU_h$ | 36.97% |
| Chemicals in WWTP (transport and distribution) | $5.47 \times 10^{-9}$ $CTU_h$ | 0.31% | $5.41 \times 10^{-9}$ $CTU_h$ | 48.19% |
| Compost fertilising | $1.77 \times 10^{-6}$ $CTU_h$ | 99.34% | 0.00 | 0.00% |
| **Human toxicity—non-cancer ($CTU_h$)** | | | | |
| **Item** | **Value of BS** | **Weight of BS** | **Value of B2E** | **Weight of B2E** |
| Chemicals in WWTP (transport and distribution) | $9.57 \times 10^{-7}$ $CTU_h$ | 0.58% | $9.36 \times 10^{-7}$ $CTU_h$ | 58.04% |
| Biosolids thermal treatment | 0.00 | 0.00% | $4.92 \times 10^{-7}$ $CTU_h$ | 30.50% |
| Compost fertilising | $1.65 \times 10^{-4}$ $CTU_h$ | 99.36% | 0.00 | 0.00% |

(vi) Resource use, fossils

The overall environmental burden of the B2E solution was 18.7% lower compared to the BS system. Figure 5 shows the environmental burdens of the main contributors to the impact category of non-renewable energy resources use linked to both studied systems. In both cases, the electricity consumed in the WWTP contributed the most significant impact, 60.3% and 46.6% for the BS and B2E systems, respectively. The difference between the electricity consumption was deeply explained in climate change subsection.

It is worth mentioning that both technologies present a positive effect on the environment. On the one hand, using compost as a fertiliser, due to its phosphorus and nitrogen content, contributes to avoiding the extraction and manufacturing of mineral fertilisers (BS case); associated with their corresponding uses of non-renewable energy resources. On the other hand, there is a surplus of thermal energy once the biosolids are dried that could be used in other facilities, saving fossil resources (natural gas as an assumption in the present study). Comparing both impacts (−22 MJ and −67.4 MJ, BS and B2E respectively), the environmental credits are 3-folds higher in the case of the B2E system.




"Other" in the BS included: WWTP processes, sludge transport, composting (process, electricity and diesel production) and compost use (transport, spreading and fertilising). "Other" in the B2E included: WWTP processes, chemicals for cleaning gases (gasification) and its transportation, tap water and diesel production, biosolid thermal treatment, ashes (transport and landfill) and industrial wastewater (transport and treatment).

**Figure 5** Contribution of the most relevant items involved in both BS and B2E solution within the resource use impact category.

### 3.2 Comparison between BS and B2E systems without external thermal energy valorisation

In the case of the B2E solution, one of the items that reduced the environmental impacts was the generation and use of thermal energy. As mentioned throughout the manuscript, the thermal energy is used *in situ* to dry the biosolids, there being a surplus. If this surplus would be used in other facilities, the consumption of fossil resources (natural gas as an assumption) would be avoided. Therefore, it may be interesting to display the results on the studied impact categories if the surplus of thermal energy use is omitted.

As displayed in Table 9, the influence of using the surplus of thermal energy was only observed in two out of six impact categories: climate change and resource use. In the case of climate change impact category, the improvement that entails the biosolids thermal treatment increased from 20.8% to 31.3% (without and with thermal surplus use, respectively) compared to the result linked to the BS system. Between both possibilities of the B2E, the improvement on climate change was of 13.2% if thermal surplus would be used. In the same way, the resource use (fossil) category was improved by using thermal energy. In this case, it had a clear effect on the mentioned impact category since without thermal recovery, the BS and B2E systems would present almost the same impact (378 and 375 MJ, respectively). Therefore, using thermal surplus energy from the gasification and syngas valorisation stages would have a direct positive environmental effect.

**Table 9** Comparison of the BS and the B2E systems with and without the influence of thermal energy valorisation. The percentual difference between the BS and both cases of the B2E solution is also shown.

| **Impact category** | **BS** | **B2E without thermal valorisation** | **Difference** | **B2E with thermal valorisation** | **Difference** |
|---|---|---|---|---|---|
| Climate change (kg $CO_{2\ eq}$) | 38.0 | 30.1 | 20.8% | 26.1 | 31.3% |
| Ecotoxicity freshwater ($CTU_e$) | 1943 | 1021 | 47.5% | 1020 | 47.5% |
| Eutrophication freshwater (kg $P_{eq}$) | 0.093 | 0.063 | 32.7% | 0.063 | 32.7% |
| Human toxicity—cancer ($CTU_h$) | $1.78 \times 10^{-6}$ | $1.07 \times 10^{-8}$ | 99.4% | $1.02 \times 10^{-8}$ | 99.4% |
| Human toxicity—non-cancer ($CTU_h$) | $1.66 \times 10^{-4}$ | $1.59 \times 10^{-6}$ | 99.0% | $1.57 \times 10^{-6}$ | 99.1% |
| Resource use, fossils (MJ) | 378 | 375 | 0.8% | 307 | 18.7% |

## 4. Conclusions and Future Works

The present study focused on the environmental effect provided by the implementation of the B2E system in a midsize, activated sludge WWTP (capacities between 10,000 and 100,000 PE), as the majority of the European WWTPs. The B2E solution is a new way to manage the sludge generated within a WWTP. The proposed B2E solution consists of an MS as an alternative primary treatment, which removes part of the total solids of the wastewater upfront the aeration tank, reducing the biological sludge formation, electricity consumption and chemicals used in the wastewater treatment. Afterwards, the biosolids obtained from MS (called PSS, 60–65% moisture content) and from aeration-thickening-dewatering processes (called TDSS, 80% moisture content) are blended, solar dried, electrically dried and gasified, producing syngas that is combusted in a co-generation engine, generating thermal and electric energy. These *in situ* wastewater treatment and biosolids management processes reduce the energy requirements. The LCA of the mentioned system was the tool used to evaluate the environmental performance of the B2E solution once implemented in a midsize WWTP, being also compared to the current wastewater treatment (baseline).

A group of six impact categories was evaluated under the environmental footprint methodology (EF 3.0): climate change, freshwater ecotoxicity, freshwater eutrophication, human toxicity (cancer and non-cancer) and resource use, fossils. The improvement of the B2E system compared to the BS was shown in the six impact categories, particularly remarkable the impact on human toxicity where B2E was 99.4% (cancer) and 99.1% (non-cancer) lower. Regarding the rest of the assessed categories, the B2E also contributed between 18.7% (resource use, fossils) and 47.5% (freshwater ecotoxicity) lower impact.

Moreover, the B2E system may also enhance the other two sustainability areas: economic and social. On one hand, the *in-situ* sludge gasification might reduce the exploitation costs. On the other hand, better environmental performance is linked to a positive impact on human health, improving the social aspect. Therefore, the B2E system provides a novel solution not only for wastewater professionals to take sustainability decisions but also for valuable insights and information for researchers and policymakers. However, although the present assessment displays that the B2E solution is a potential system to be implemented, the technology should confirm these results by means of tests and demonstrations of the complete system. Therefore, the subsequent steps to perform are those assays that allow getting only representative primary data and evaluating the whole B2E system under an operational environment. Afterwards, the B2E system will serve policy- and decision-makers for future implementation strategies towards more efficient and sustainable WWTPs.

## Availability of Data and Material

The datasets generated and/or analysed in the study may be obtained from the corresponding author on reasonable request.

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## Competing Interests

The authors have declared that no competing interests exist.

## Author Contributions

Conceptualization, methodology, software, validation and formal analysis: A.L.G. and D.F.-G.; writing—original draft preparation: A.L.G., D.F.-G., A.M., K.T. and P.G.; writing—review and editing: A.L.G., D.F.-G., A.M., K.T. and P.G. All authors have read and agreed to the published version of the manuscript.

## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| B2E | LIFE B2E4sustainable-WWTP |
| BOD | Biochemical Oxygen Demand |
| BS | Baseline |
| COD | Chemical Oxygen Demand |
| CTU | Comparative Toxic Units |
| DS | Dry Solids |
| EF | Environmental Footprint |
| FU | Functional Unit |
| GHG | Greenhouse Gases |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| MS | Microsieve |
| NMVOCs | Non-Methane Volatile Organic Compounds |
| PE | Population Equivalent |
| $PM_{2.5}$ | Particulate Matter 2.5 μm or less in diameter |
| $PM_{10}$ | Particulate Matter 10 μm or less in diameter |
| PSS | Primary Sieved Solids |
| SS | Secondary Sludge |
| TDSS | Thickened Dewatered Secondary Sludge |
| TKN | Total Kjeldahl Nitrogen |
| TP | Total Phosphorus |
| TRL | Technology Readiness Level |
| TSS | Total Suspended Solids |
| WWTP | Wastewater Treatment Plant |

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