

Article

Energy and Environmental Impacts of Sludge Management in the Integrated Water Service: A Comparative Life Cycle Assessment

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Abstract

Growing pressures on water resources, exacerbated by climate change, resource depletion, and population growth, underline the need for sustainable and energy-efficient wastewater management. Wastewater treatment plants (WWTPs) are among the most energy-intensive elements of the Integrated Water Service, and their environmental performance depends on infrastructure design, resource availability, and treatment configuration. Improving resource efficiency while reducing energy demand and environmental impacts is therefore a priority for water utilities seeking innovative decision-support tools. Within the national project “WATERGY—Energy Efficiency of the Integrated Water Service”, this study proposes a life-cycle-based framework to assess the sustainability of technological interventions in WWTPs. A comparative gate-to-grave Life Cycle Assessment (LCA) was applied to the municipal WWTP of Potenza (Southern Italy). Three sludge End-of-Life Scenarios were assessed: the current landfill-based configuration, an enhanced oxygenation–nitrification setup, and anaerobic digestion with biogas-based cogeneration. Compared to the current scenario, anaerobic digestion with cogeneration reduces Global Warming Potential by 17% and decreases freshwater ecotoxicity by approximately 30%. Compost production shows the highest reduction in ecotoxicity (−51%) but increases fossil resource depletion and acidification due to higher energy demand. Overall, energy recovery pathways, particularly anaerobic digestion with cogeneration, provide the most balanced environmental benefits, supporting more sustainable WWTP operation within the Integrated Water Service.

Keywords: energy efficiency; environmental sustainability; Integrated Water Service; Life Cycle Assessment (LCA); sludge valorization



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1. Introduction

Wastewater management is essential to strategies aimed at improving environmental sustainability, resource efficiency, and the transition towards a circular economy [1]. In particular, wastewater treatment plants (WWTPs) face increasing pressure to reduce their environmental footprint while ensuring high treatment efficiency and operational reliability [2]. WWTPs generate multiple sludge streams of complex biological and chemical composition, including organic matter, nutrients, microorganisms, heavy metals, and micropollutants [3–6]. Although these facilities are indispensable for protecting aquatic ecosystems and preventing eutrophication, they remain highly energy-intensive systems, where the energy demand of both water and sludge treatment processes contributes significantly to the overall environmental impact [7–10].

Achieving an optimal balance between resource consumption and recovery within a WWTP has therefore become a central challenge in the water sector [9–11]. Sludge management, in particular, plays a decisive role: proper sludge handling across the entire treatment chain, from generation to final disposal or reuse [12], can enable substantial improvements in eco-efficiency, especially when aligned with the European “reduce–reuse–recycle” waste hierarchy [13]. As a biologically active matrix rich in organic compounds, nutrients, and trace contaminants, sludge represents both a burden and an opportunity for valorization through technologies such as anaerobic digestion, composting, or advanced reduction processes [14].

Since the early 2000s, Life Cycle Assessment (hereinafter also termed LCA for brevity) has been increasingly adopted worldwide to support decision-making in sludge treatment and disposal [15], allowing a quantitative comparison of technological options by evaluating energy use, resource depletion, emissions, and environmental loads across the entire lifecycle [7,16–18]. The LCA methodology is the most suitable and comprehensive method for describing and analyzing the interconnections between water and energy [7,15,19,20], which are present in all the activities that comprise Integrated Water Services (IWSs). Unlike environmental footprint methodologies (Carbon Footprint and Water Footprint), which focus on a specific thematic area [21,22], the LCA analysis provides a broader and more detailed overview of environmental impacts, while simultaneously considering multiple performance indicators dedicated to describing different areas of impact. Recent contributions have extended the use of LCA to assess innovative strategies for sludge reduction and valorization, including ultrasound treatment, anaerobic side-stream reactors, ozonation, and nutrient/energy recovery technologies [7,11,23,24]. These studies confirm LCA’s importance as a reliable tool for decision-making for evaluating alternative sludge management processes under different operational and environmental conditions.

More broadly, WWTPs have a variety of impacts on the environment that can be systematically categorized and compared through LCA. Several applications in the water sector demonstrate the method’s effectiveness in evaluating recycling strategies at the household level [4,7,9,13,25,26], smart water technologies [25], and sustainability-based benchmarking systems [27]. Eco-efficiency assessments and performance benchmarking approaches applied to WWTPs further corroborate the relevance of LCA in identifying environmental hotspots and guiding technological innovation [27]. Despite the extensive application of Life Cycle Assessment to wastewater and sludge management, several research gaps remain. In particular, limited attention has been paid to the integrated evaluation of sludge End-of-Life strategies within the operational context of medium-sized municipal WWTPs, where plant scale, energy efficiency constraints, and regional electricity mixes strongly influence environmental outcomes. Moreover, comparative assessments that explicitly quantify trade-offs between energy recovery and material recovery pathways within the Integrated Water Service are still scarce, especially when incremental technological upgrades are considered rather than radical redesigns.

In this issue, the current research applies a comparative LCA to the municipal WWTP of Potenza (Southern Italy), evaluating three alternative operational scenarios for sludge management and treatment that represent progressive and realistically implementable technological improvements. The objective is to assess the environmental trade-offs associated with incremental technological improvements—specifically, enhanced nitrification–oxygenation and anaerobic digestion with cogeneration—offering practical insights to support sustainable planning within the Integrated Water Service.

2. Materials and Methods

The LCA presented in this study aims to evaluate the environmental sustainability of technological interventions and innovations implemented in WWTPs for sludge management. The environmental impacts were assessed using the LCA methodology [16,27], which is a widely adopted approach for evaluating wastewater treatment processes [7,26,28–31]. The LCA framework consists of four phases regulated by ISO 14040 [32] phases: (i) definition of the goal and scope, the objective of the analysis, setting of the functional unit, and identification of the system boundaries; (ii) inventory and scenario analysis; (iii) impact assessment with assignment of the impact potential of the unit flows to the category indicators and impact factors; and (iv) interpretation of the results. These phases are illustrated in Figure 1 and described in the sections below.

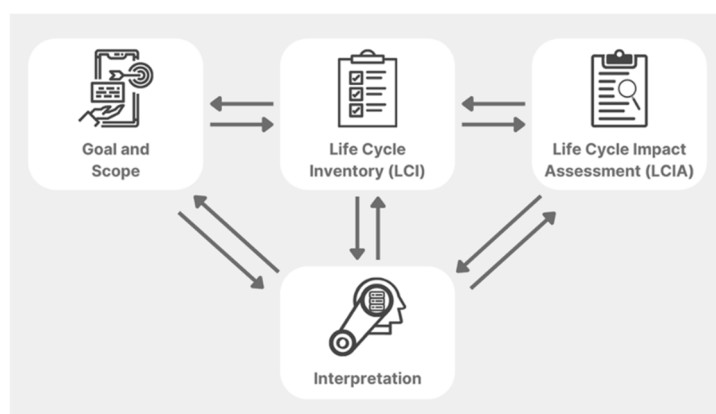


Figure 1. ISO framework for LCA ISO 14040 [32].

SimaPro 9.2 software was used for the analysis in combination with the Ecoinvent v.3.8 [33,34] database. This setup enabled a systematic and transparent modeling of multiple life cycle stages and supported the evaluation of environmental impacts associated with the selected processes, allowing the identification of critical hotspots along the entire chain [33,35]. SimaPro and Ecoinvent are commonly adopted in LCA studies due to their extensive and reliable datasets, user-friendly interfaces, and high interoperability. Ecoinvent offers a broad, rigorously validated database of environmental information, while SimaPro provides an intuitive platform that facilitates LCA implementation and data handling. When combined, they guarantee accuracy, consistency, and comparability in the findings, which is why environmental impact assessment researchers and practitioners favor them as tools. Additionally, the CML-IA method applied for the impact assessment is a validated and widely recognized methodology across major LCA software packages.

This study represents one of the pilot actions undertaken to evaluate the sustainability of the interventions and innovations planned for the Integrated Water Service of the Basilicata Region in Southern Italy. The WWTP currently treats wastewater corresponding to 95,000 population equivalents (p.e.), generating approximately 3.05×10^{-5} t of sludge per m^3 of influent wastewater. The reported sludge production refers to the sludge as dry substance (d.s.) on an as-received basis; this value is consistent with operational data from medium-sized municipal WWTPs in Southern Italy.

The impact analysis was focused on the wastewater treatment plant that is considered the most affected by the water–energy relationship, the most energy-intensive, and for which the most significant improvements can be expected [36].

2.1. Goal and Scope Definition

The aim is to evaluate the environmental impacts related to different End-of-Life (EoL) scenarios for sludge produced at the WWTP of Potenza, located in the Basilicata Region in Southern Italy. Three alternative sludge EoL configurations were examined: the current system, which serves as the baseline; a scenario featuring improved oxygenation and nitrification efficiency; and a scenario incorporating anaerobic digestion of thickened sludge combined with biogas-based cogeneration. The specific objective is to quantify the environmental impacts of the municipal WWTP from the wastewater inlet to the final release of sludge into the environment (Figure 2). The analysis only examined the WWTP's operational phase; construction and maintenance operations were left out.

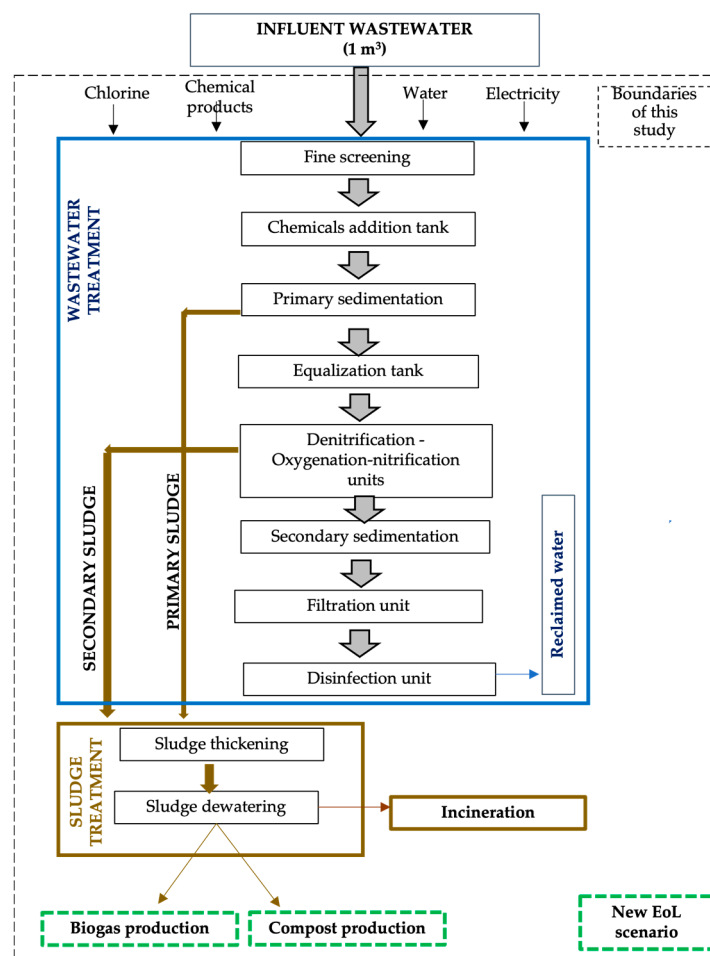


Figure 2. WWTP phases and system boundary.

The functional unit (FU) provides a consistent reference for comparing the different stages by defining the relationship between inputs and outputs [27]. In LCAs focusing on WWTPs, inputs are typically selected as the FU [34]. In this study, the FU was defined as 1 m³ of treated wastewater, focusing the attention on the energy and operational efficiency of the system. A gate-to-grave comparative assessment was then carried out.

2.2. Boundaries

The inputs consist of water, energy, and chemical products entering the unit process, while the outputs include the products, waste, and emissions generated [37].

In the LCA, a gate-to-grave approach and three EoL scenarios of sludge treatment were assumed. The LCA considered the entire operational phases of the WWTP (presented in Figure 2).

The process inputs include the influent wastewater stream entering the treatment plant, electrical power supplied from external sources, water used for the processes, and additional chemical substances required for the wastewater treatment process.

The process outputs are divided into two main categories:

1. As sources of environmental loads, including (a) a treated wastewater stream, which, although characterized by significantly reduced concentrations of the analyzed parameters that determine its harmfulness, still contains substances that have a negative impact on the environment; and (b) sewage sludge, which is then directed to anaerobic digesters for the production of the methane-rich biogas, which is next used for energy generation or compost production. Both the generation and use of energy or compost can result in positive and negative environmental impact (e.g., emissions associated with biogas combustion, etc.);
2. As sources of indirect environmental benefits, including (a) the avoided impacts resulting from differences in the values of standardized parameters characterizing wastewater streams, raw and treated; (b) the amount of environmental effects that are prevented by energy generation, which enables the avoidance of consuming an equivalent quantity of energy from outside sources; and (c) generation of “new” products, e.g., compost production, for agricultural purposes.

2.3. Life Cycle Inventory (LCI) Analysis

The primary inventory analysis was carried out thanks to the data provided by the Acquedotto Lucano utility. An ad hoc checklist for primary data collection was developed. Data were gathered through interviews with technicians and plant managers of the Acquedotto Lucano utility and were integrated with the relevant documentation. The set of data included the series of information on the water and sludge lines of the WWTP of Potenza, Southern Italy, with a capacity of 95,000 p.e. Specifically, the data collected were as follows: the WWTP treatment capacity; the type of treatment carried out in the WWTP; the monthly average flow; the volume of produced raw sludge and its TS content; the data concerning the quantities and typologies of chemicals employed in the process (i.e., Polyelectrolyte, Sodium Hypochlorite, Sodium Hydroxide, and Aluminum Polychloride); and the water and electricity consumption of the WWTP.

In addition, the monthly flow data were provided together with comprehensive information on the wastewater streams, which were modelled using a set of standardized parameters, including COD, BOD₅, Total Suspended Solids (TSSs), Total Nitrogen (TN), Total Phosphorus (TP), Iron, Manganese, Nickel, Lead, Copper, Zinc, Chromium, Cadmium, Aluminum, Sulfates, Phosphorus, and Phenols. Additionally, monthly datasets were aggregated into annual average values and subsequently normalized to the functional unit of 1 m³ of treated wastewater, in accordance with ISO 14040, documented in Table S1. Where available, Italian regionalization factors were applied.

To obtain product-specific data, material quantities were estimated through accurate measurements of machinery components, considering both their dimensions and types to ensure assessment precision. Furthermore, process-specific data were meticulously gathered by performing a comprehensive time study analysis of each phase involved. Secondly, the collected data underwent rigorous scrutiny and evaluation to build the LCA model, guaranteeing its reliability and robustness. Finally, both primary data gathered directly from observations and measurements and secondary data obtained from reliable sources were synergically integrated to refine and enrich the study’s modeling process. Background data were taken from the Ecoinvent v 3.08 database, as well from the relevant literature [7,29–31].

The inventory of phases analyzed in this LCA study, as defined using SimaPro 9.2 software, is described in the following subsections. Table 1 summarizes the list of items included in or excluded from the LCA inventory based on the specific LCA phase considered.

Table 1. Summary of included and excluded items across the analyzed LCA phases.

LCA Phase	Included in the Analysis	Excluded from the Analysis
Wastewater Treatment	Primary ww treatment plant and reclaimed water: i.e., fine screening, chemicals additional tank, primary sedimentation, equalization tank, denitrification–oxygenation–nitrification units, secondary sedimentation, filtration unit, disinfection unit	Production, construction, and EoL of various units' treatment
Sludge Treatment	Sludge thickness and sludge dewatering	Production, construction, and end-of-life of various units' treatment

2.3.1. Various Phases of LCA Analyzed

In the analyzed WWTP, wastewater undergoes primary treatment that consists of a primary sedimentation process, used to separate suspended solids from wastewater by exploiting differences in specific weight, and resulting in the deposition of solids at the tank bottom. This yields an initial separation of biological sludge (primary sludge). Equalization and homogenization stages then regulate physico-chemical parameters such as flow and pollutant concentration. Wastewater is collected in a buffer tank designed to reduce flow variability within limits acceptable for downstream treatments. At the end of the cycle, the plant produces sludge and treated water suitable for reuse in various applications. Currently, the WWTP owned by Lucano Aqueduct considers landfill disposal as the End-of-Life Scenario (Baseline Scenario).

One of the alternative scenarios consists of composting part of the generated sludge. Composting is an aerobic process occurring outdoors or in enclosed vessels. Through the decomposition of organic materials, it produces a humid substance that can be used as fertilizer or as a soil amendment. Composting is modelled assuming the addition of standard lignocellulosic bulking agents (e.g., green waste), without introducing site-specific additives or chemical conditioners. The other scenario involves producing biogas from sludge treated at the plant.

2.3.2. Assumptions

For the purposes of the LCA, several assumptions and model hypotheses were established. The following list details the assumptions made, specifying included and excluded aspects.

- Secondary literature data were used for process water.
- Three End-of-Life scenarios were selected: a Baseline Scenario representing the current sludge disposal pathway, and two alternative scenarios aimed at improving environmental and economic sustainability. Specifically, the alternative scenarios assume either agricultural reuse of composted sludge (Scenario 2) or biogas production (Scenario 1).
- Transport of sludge to landfill or composting facilities was excluded because the average distance is below 100 km. ISPRA data indicate the closest landfills are located 36 km away in Sant'Arcangelo and 73 km away in Guardia Perticara, with an average distance of 55 km [38]. The Global Warming Potential impact calculated using the

CML-IA Midpoint method is 0.00564 kg CO₂-eq per kg of sludge transported by Euro 0–6 truck (22 t total weight, 17.3 t maximum payload).

2.4. Life Cycle Impact Assessment

Comprehensive information from the Life Cycle Inventory (LCI) is used to assess the importance of any environmental effects. In accordance with ISO 14040:2006 [32], the analysis entails connecting particular impacts with the inventory data. This rigorous technique efficiently translates the LCI results into the environmental impacts from each scenario taken into consideration, offering important insights into the environmental consequences of the activities that have been analyzed.

This study examined midpoint impact categories utilizing the CML-IA 2 baseline v 3.08/EU25 approach, with a focus on the following eleven (11) impact categories: Abiotic Depletion (ADP), Abiotic Depletion fossil fuel (ADPff), Global Warming Potential (GWP100a), Ozone Layer Depletion Potential (ODP), Human Toxicity Potential (HTP), Fresh Water Aquatic Ecotoxicity (FWAE), Marine Aquatic Ecotoxicity (MAE), Terrestrial Ecotoxicity (TE), Photochemical Oxidation (PO), Acidification Potential (AP), and Eutrophication Potential (EP). These impact categories were selected after an extensive literature review and based on their application in environmental impact assessments of wastewater treatment plants [5,16,18–21].

3. Results

Potential environmental impacts were calculated using the CML-IA baseline v3.08 method across eleven midpoint impact categories. Figures 3 and 4 compare the Baseline Scenario (landfill disposal) with the two alternative End-of-Life options—Scenario 1 (biogas production via anaerobic digestion) and Scenario 2 (compost production). A full comparison across all three scenarios is reported in Figure 5, while Table 2 provides quantitative outcomes normalized to 1 m³ of treated wastewater.

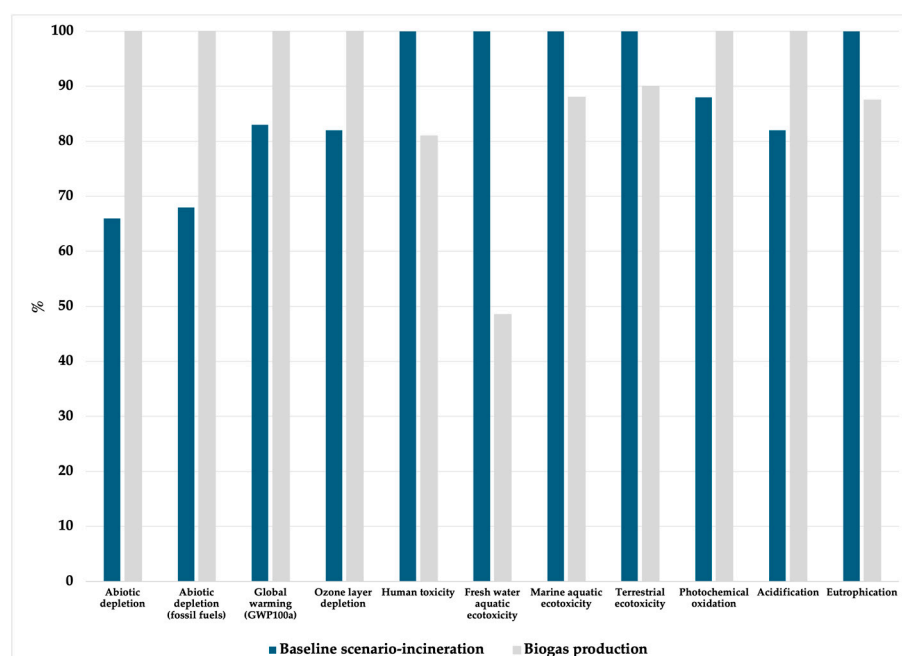


Figure 3. Life Cycle Impact Assessment. CML-IA baseline V3.08 results—Comparison of Baseline Scenario vs. biogas production (Scenario 1).

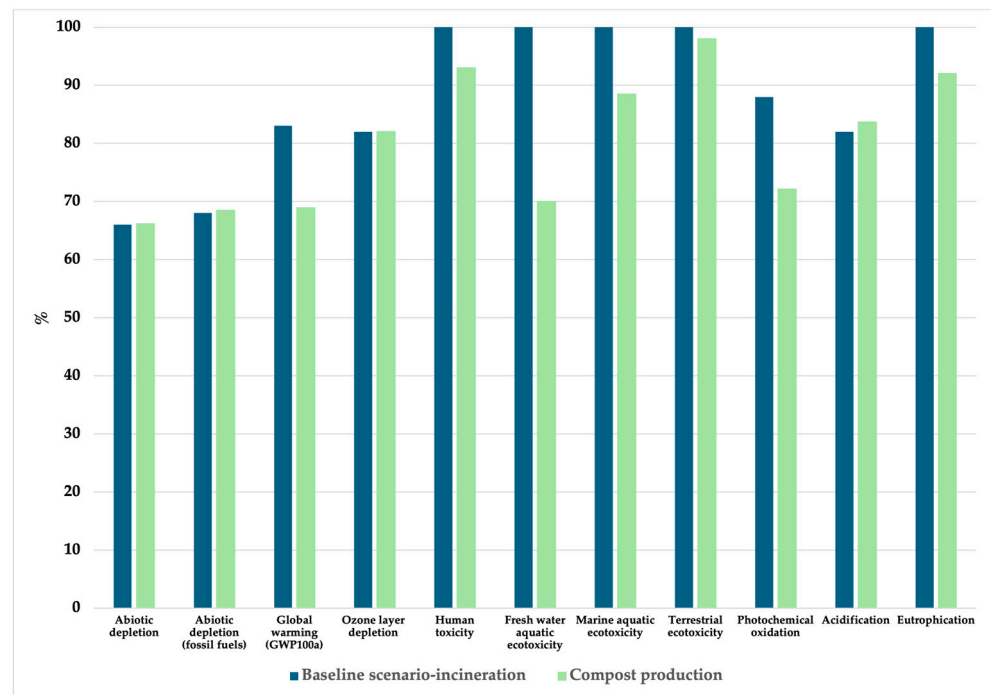


Figure 4. Life Cycle Impact Assessment. CML-IA baseline V3.08 results—Comparison of Baseline Scenario vs. compost production (Scenario 2).

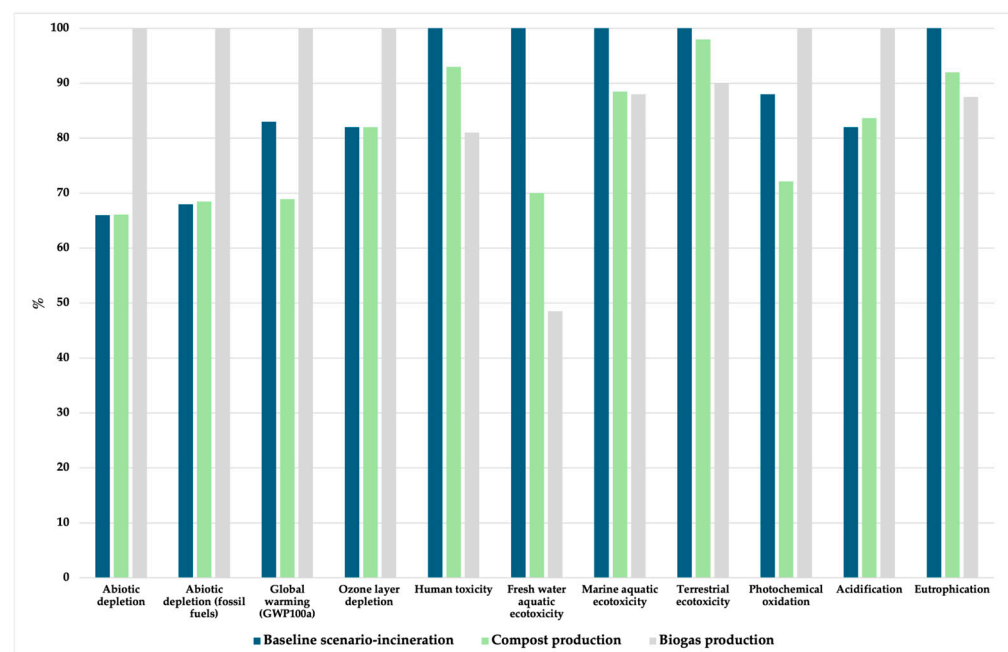


Figure 5. Life Cycle Impact Assessment. CML-IA baseline V3.08 results—Comparison of Baseline Scenario vs. compost production and biogas production.

Overall, the Baseline Scenario exhibited the highest impact values in most categories, confirming that sludge disposal remains a major environmental hotspot in wastewater treatment [15]. Electricity consumption and chemical use were found to drive most impacts, in line with previous sludge-management LCAs showing strong dependence on upstream energy processes [7–9]. In fact, its Global Warming Potential (GWP100a) reaches 22.835 kg CO₂-eq, the highest value across the scenarios. This result reflects the combined contribution of sludge disposal and electricity consumption within the plant, two factors repeatedly identified in LCA literature as major emission hotspots in WWTPs. A similar ten-

dency is observed for the toxicity-related categories, where the Baseline Scenario presents 4082 kg 1.4-DB-eq of Freshwater Aquatic Ecotoxicity (FWAE) and 857 kg 1.4-DB-eq of Marine Aquatic Ecotoxicity (MAE), both markedly higher than the alternative scenarios. These high values are mostly attributable to the upstream production of chemicals and electricity, corroborating findings from Ding et al. [7] and Havukainen et al. [8].

Table 2. Impact assessment results for the three assumed EoL scenarios.

Impact Category	Units	EoL Scenarios		
		Baseline Scenario	Scenario 1	Scenario 2
Abiotic depletion (AD)	kg Sb eq	2.719×10^{-3}	2.725×10^{-3}	4.120×10^{-3}
Abiotic depletion fossil fuel (ADff)	MJ	19.332	19.471	28.430
Global warming (GWP100a)	kg CO ₂ eq	22.835	18.951	27.510
Ozone layer depletion (ODP)	kg CFC-11 eq	8.456×10^{-3}	8.456×10^{-3}	1.031×10^{-2}
Human toxicity (HT)	kg 1.4-DB eq	25.710	23.911	20.812
Fresh water aquatic ecotoxicity (FWAE)	kg 1.4-DB eq	4082	2857	1980
Marine aquatic ecotoxicity (MAE)	kg 1.4-DB eq	857	759	754
Terrestrial Ecotoxicity (TE)	kg 1.4-DB eq	672	658	605
Photochemical oxidation (PO)	kg C ₂ H ₄ eq	29.047	23.820	28.733
Acidification	kg SO ₂ eq	2.357	2.404	2.873
Eutrophication	kg PO ₄ - eq	1479	1360	1294

Note: Values refer to functional unit of 1 m³ of treated wastewater.

Scenario 1 (biogas production), based on anaerobic digestion with biogas fuel cogeneration, shows a consistent reduction in impacts compared to the Baseline Scenario. The most notable improvement occurs in climate change, where GWP100a decreases from 22.835 to 18.951 kg CO₂-eq, corresponding to a 17% reduction. This improvement arises mainly from the avoided consumption of grid electricity, since biogas combustion within the cogeneration unit supplies part of the plant's energy demand. Similar trends are visible in toxicity-related indicators: FWAE drops from 4082 to 2857 kg 1.4-DB-eq, and MAE falls from 857 to 759 kg 1.4-DB-eq. These reductions reflect the lower reliance on external energy production, which is known to be a key driver of ecotoxicity impacts according to previous LCA studies on sludge digestion [9]. HT also decreases, from 25.710 to 23.911 kg 1.4-DB-eq, again reflecting the reduced upstream emissions due to partial energy self-sufficiency.

These improvements reflect lower upstream electricity burdens. Scenario 2 (compost production) showed the greatest improvements in toxicity-related categories, with FWAE reduced by 51% and TE by 10%. However, it exhibited higher impacts in energy-related categories such as ADff (+47%), AP (+22%), and ODP (+22%), mainly due to process emissions and the aeration energy demand during composting. These trends match observations from Ding et al. [7] and Sara et al. [24].

Scenario 2, involving compost production, shows a more complex behavior. On one hand, this scenario achieves the largest reductions in toxicity categories: FWAE drops to 1980 kg 1.4-DB-eq, which represents a 51% decrease relative to the Baseline Scenario, while MAE declines to 754 kg 1.4-DB-eq, the lowest among the three options. Terrestrial Ecotoxicity also improves, decreasing from 672 to 605 kg 1.4-DB-eq. These favorable outcomes result from the avoided burdens associated with producing synthetic fertilizers, consistent with the mechanisms described by Ding et al. [7], where replacement of mineral fertilizers often leads to reduced ecotoxicity.

However, Scenario 2 also introduces specific environmental trade-offs. The ADff increases substantially, from 19.332 to 28.430 MJ, because the composting process requires additional aeration and handling operations that increase overall energy demand. Similarly, Acidification rises from 2.357 to 2.873 kg SO₂-eq, and ODP from 8.456×10^{-3} to 1.031×10^{-2} kg CFC-11-eq, indicating that emissions associated with aerobic degradation processes outweigh the avoided burdens linked to fertilizer substitution. These trade-offs are widely reported in LCA studies evaluating composting systems, including the analyses of Sara et al. [24], where aerobic treatments typically show higher energy-related impacts compared to anaerobic digestion.

Across all three scenarios, MAE remains the most influential category, with values between 754 and 857 kg 1.4-DB-eq, confirming that the upstream electricity mix used in Italy exerts a dominant influence on ecotoxicity indicators. This trend mirrors the observations of Lorenzo-Toja et al. [28], who demonstrated that energy-related background processes often overshadow direct emissions in WWTP assessments.

Overall, the numerical comparison indicates that Scenario 1 provides the most balanced environmental improvements, reducing impacts in nearly all categories and particularly in climate change, while Scenario 2 achieves the strongest benefits in toxicity-related categories but introduces higher burdens in fossil depletion and acidification. These patterns highlight the importance of carefully evaluating the trade-offs associated with sludge valorization pathways.

4. Discussion

The comparative LCA clearly demonstrates that sludge EoL strategies substantially influence the environmental footprint of the Potenza WWTP. The Baseline Scenario, which reflects the current landfill disposal configuration, consistently shows the highest environmental burdens, particularly in climate change and ecotoxicity-related categories. These findings are coherent with several LCA analyses documenting how sludge disposal and electricity consumption constitute the primary operational hotspots in WWTPs [7,8]. In the present study, the Baseline Scenario reaches 22.835 kg CO₂-eq in GWP and 4082 kg 1.4-DB-eq in FWAE, highlighting how the combined effect of grid-electricity dependency and disposal activities amplifies the environmental load. This behavior aligns with literature pointing to the significant upstream emissions associated with electricity production and chemical manufacturing, which dominate most WWTP related impacts.

Scenario 1, which incorporates anaerobic digestion with biogas-based cogeneration, illustrates how energy recovery can substantially mitigate these emissions. The reduction of GWP to 18.951 kg CO₂-eq reflects the key role of avoided electricity production, a mechanism extensively discussed in studies assessing the sustainability of sludge digestion [9]. The same dynamic explains improvements in toxicity categories. By decreasing reliance on the grid and reducing upstream emissions from energy production, Scenario 1 lowers FWAE from 4082 to 2857 kg 1.4-DB-eq and MAE from 857 to 759 kg 1.4-DB-eq. These changes confirm that anaerobic digestion represents an efficient solution for improving the overall eco-efficiency of sludge management, especially when biogas is reintegrated into plant operations. The modest but consistent decrease in HT (from 25.710 to 23.911 kg 1.4-DB-eq) reinforces this point and reflects a cumulative reduction in the energy-related upstream burdens.

Scenario 2, based on compost production, presents a contrasting picture. On one hand, the reductions in FWAE (1980 kg 1.4-DB-eq) and TE (605 kg 1.4-DB-eq) demonstrate that substituting synthetic fertilizers with compost significantly lowers ecotoxicity impacts. This trend is well documented in the literature: nutrient recovery and soil improvement via compost use can avoid environmentally intensive fertilizer manufacturing and thus

compensate for part of the emissions generated during sludge treatment [6,7]. The slight reduction in MAE to 754 kg 1.4-DB-eq supports this interpretation. However, Scenario 2 also produces higher values in several categories associated with fossil resource use and atmospheric emissions. The increase in ADff from 19.332 to 28.430 MJ, and in acidification from 2.357 to 2.873 kg SO₂-eq, indicates that the composting process itself requires significant aeration energy and generates additional emissions linked to aerobic degradation. These outcomes align with the conclusions of Sara et al. [24], who reported similar trade-offs in advanced sludge reduction and composting treatments, where biological stabilization increases energy consumption and thus impacts fossil depletion.

One recurring pattern across all scenarios is the persistence of high values in MAE (754–857 kg 1.4-DB-eq). This indicates that upstream electricity production retains a dominant influence regardless of the sludge management method. Lorenzo-Toja et al. [28] reached a similar conclusion in a broad benchmarking study, noting that energy-related background processes often overshadow direct emissions in WWTP life cycles. The fact that even Scenario 1, despite producing electricity on-site, still shows substantial MAE values suggests that further benefits could be unlocked through renewable energy procurement or improvements in process energy efficiency.

Overall, the results indicate that no single sludge management option can fully mitigate all associated environmental burdens. Yet, Scenario 1 stands out for achieving the most consistent reductions across categories, suggesting that energy-oriented recovery pathways provide a systemic advantage. Scenario 2, while valuable from a circular economy perspective, exhibits pronounced trade-offs that require careful consideration in planning sustainable WWTP operations.

5. Conclusions

This LCA demonstrates that sludge management strategies substantially affect the environmental impacts of the Potenza WWTP. The current landfill-based scenario shows the highest impacts, driven mainly by electricity consumption and upstream emissions. Introducing anaerobic digestion with biogas-based cogeneration markedly improves environmental performance, reducing GWP from 22.835 to 18.951 kg CO₂-eq and lowering both freshwater and marine ecotoxicity. Compost production provides the strongest reductions in toxicity-related categories due to avoided mineral fertilizer production, although it increases fossil depletion and acidification as a result of aerobic process requirements. MAE remains the dominant impact category across all scenarios, confirming the critical role of electricity generation in WWTP life cycle emissions. Overall, anaerobic digestion with cogeneration emerges as the most balanced and sustainable option for the plant, achieving broad reductions without introducing significant trade-offs.

To complement these findings, future work will include a Life Cycle Costing (LCC) assessment. The economic sustainability of the different technological scenarios will identify all the costs and expenses that were supposed to be incurred in relation to the flows of materials, resources, and energy defined in the same inventory phase for the performed LCA analysis, allowing economic aspects to be evaluated alongside environmental performance and thus supporting a more comprehensive assessment of sustainability within the Integrated Water Service.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w18030343/s1>, Table S1: Life Cycle Inventory.

Author Contributions: Conceptualization, S.P. and A.B.; methodology, S.P.; software, S.P.; validation, A.B. and V.D.F.; data curation, S.P.; writing—original draft preparation, S.P. and A.B.; writing—review and editing, A.B. and V.D.F.; visualization, S.P.; supervision, V.D.F.; project administration,

V.D.F.; funding acquisition, V.D.F. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Zhang, T. Sustainable Wastewater Treatment and the Circular Economy. *Water* **2025**, *17*, 335. [CrossRef]
2. Silva, J.A. Wastewater Treatment and Reuse for Sustainable Water Resources Management: A Systematic Literature Review. *Sustainability* **2023**, *15*, 10940. [CrossRef]
3. Gherghel, A.; Teodosiu, C.; De Gisi, S. A Review on Wastewater Sludge Valorisation and Its Challenges in the Context of Circular Economy. *J. Clean. Prod.* **2019**, *228*, 244–263. [CrossRef]
4. Kowalski, Z.; Makara, A.; Kulczycka, J.; Generowicz, A.; Kwaśnicki, P.; Ciula, J.; Gronba-Chyla, A. Conversion of Sewage Sludge into Biofuels via Different Pathways and Their Use in Agriculture: A Comprehensive Review. *Energies* **2024**, *17*, 1383. [CrossRef]
5. Chang, H.; Zhao, Y.; Bisinella, V.; Damgaard, A.; Christensen, T.H. Climate Change Impacts of Conventional Sewage Sludge Treatment and Disposal. *Water Res.* **2023**, *240*, 120109. [CrossRef] [PubMed]
6. Raheem, A.; Sikarwar, V.S.; He, J.; Dastyar, W.; Dionysiou, D.D.; Wang, W.; Zhao, M. Opportunities and Challenges in Sustainable Treatment and Resource Reuse of Sewage Sludge: A Review. *Chem. Eng. J.* **2018**, *337*, 616–641. [CrossRef]
7. Ding, A.; Zhang, R.; Ngo, H.H.; He, X.; Ma, J.; Nan, J.; Li, G. Life Cycle Assessment of Sewage Sludge Treatment and Disposal Based on Nutrient and Energy Recovery: A Review. *Sci. Total Environ.* **2021**, *769*, 144451. [CrossRef]
8. Havukainen, J.; Saud, A.; Astrup, T.F.; Peltola, P.; Horttanainen, M. Environmental Performance of Dewatered Sewage Sludge Digestate Utilization Based on Life Cycle Assessment. *Waste Manag.* **2022**, *137*, 210–221. [CrossRef]
9. Szulc, P.; Edrzej Kasprzak, J.; Dymaczewski, Z.; Kurczewski, P. Life Cycle Assessment of Municipal Wastewater Treatment Processes Regarding Energy Production from the Sludge Line. *Energies* **2021**, *14*, 356. [CrossRef]
10. Maktabifard, M.; Zaborowska, E.; Makinia, J. Achieving Energy Neutrality in Wastewater Treatment Plants through Energy Savings and Enhancing Renewable Energy Production. *Rev. Environ. Sci. Biotechnol.* **2018**, *17*, 655–689. [CrossRef]
11. García-López, C.D.; Barajas-Álvarez, P.; González-López, M.E.; Loge, F.J.; Mahlkecht, J.; Senés-Guerrero, C.; Gradilla-Hernández, M.S. Evaluating Sludge Management Strategies Using Wastewater Treatment Plant Simulations and Life Cycle Assessment. *J. Mater. Cycles Waste Manag.* **2025**, *27*, 2972–2986. [CrossRef]
12. Kumari, A.; Maurya, N.S.; Kumar, A.; Yadav, R.K.; Kumar, A. Options for the Disposal and Reuse of Wastewater Sludge, Associated Benefit, and Environmental Risk. In *Sewage Management*; Taşeli, B.K., Ed.; IntechOpen: London, UK, 2023. [CrossRef]
13. Kacprzak, M.; Neczaj, E.; Fijałkowski, K.; Grobelak, A.; Grosser, A.; Worwag, M.; Rorat, A.; Brattebo, H.; Almås, Å.; Singh, B.R. Sewage Sludge Disposal Strategies for Sustainable Development. *Environ. Res.* **2017**, *156*, 39–46. [CrossRef]
14. Hamda, A.S.; Abo, L.D.; Daba, B.J.; Debela, A.B. Transforming Sludge to Energy: A Sustainable Strategy for Resource Recovery and Environmental Protection. *Clean. Waste Syst.* **2025**, *11*, 100298. [CrossRef]
15. Feng, L.; Chen, B. Energy-Water Nexus of Wastewater Treatment System: Conceptual Model and Framework. *Energy Procedia* **2016**, *104*, 141–145. [CrossRef]
16. Zanni, S.; Awere, E.; Bonoli, A. *Life Cycle Sustainability Assessment: An Ongoing Journey*; Elsevier Inc.: Amsterdam, The Netherlands, 2020; ISBN 9780128183557.
17. Karolinczak, B.; Walczak, J.; Bogacka, M.; Zubrowska-Sudol, M. Life Cycle Assessment of Sewage Sludge Mono-Digestion and Co-Digestion with the Organic Fraction of Municipal Solid Waste at a Wastewater Treatment Plant. *Sci. Total Environ.* **2024**, *907*, 167801. [CrossRef] [PubMed]
18. Pasciucco, F.; Pecorini, I.; Iannelli, R. Planning the Centralization Level in Wastewater Collection and Treatment: A Review of Assessment Methods. *J. Clean. Prod.* **2022**, *375*, 134092. [CrossRef]
19. Papageorgiou, A.; Björklund, A.; Sinha, R.; de Almeida, M.L.R.; Steubing, B. Coupling Material and Energy Flow Analysis with Life Cycle Assessment to Support Circular Strategies at the Urban Level. *Int. J. Life Cycle Assess.* **2024**, *29*, 1209–1228. [CrossRef]
20. Zhao, Y.; Duan, L.; Ng, H.Y.; Hermanowicz, S.W. The New Water Treatment Technology Based on the “Water-Energy-Carbon Nexus” Achieving Carbon Neutrality in Wastewater Treatment Plants. *ACS ES T Water* **2025**, *5*, 1511–1513. [CrossRef]

21. Jeswani, H.K.; Azapagic, A. Water Footprint: Methodologies and a Case Study for Assessing the Impacts of Water Use. *J. Clean. Prod.* **2011**, *19*, 1288–1299. [\[CrossRef\]](#)
22. Huang, X.; Chen, R.; Zhuang, E.H.H.; Kong, S.; Zhiqian, Y.; Kong, Y. Environmental Footprint in Specific Industries: Intellectual Base and Research Status. *Carbon Footpr.* **2025**, *4*, 18. [\[CrossRef\]](#)
23. Bonoli, A.; Di Fusco, E.; Zanni, S.; Lauriola, I.; Ciriello, V.; Di Federico, V. Green Smart Technology for Water (GST4Water): Life Cycle Analysis of Urban Water Consumption. *Water* **2019**, *11*, 389. [\[CrossRef\]](#)
24. Zanni, S.; Cipolla, S.S.; di Fusco, E.; Lenci, A.; Altobelli, M.; Currado, A.; Maglionico, M.; Bonoli, A. Modeling for Sustainability: Life Cycle Assessment Application to Evaluate Environmental Performance of Water Recycling Solutions at the Dwelling Level. *Sustain. Prod. Consum.* **2019**, *17*, 47–61. [\[CrossRef\]](#)
25. Sabet, H.; Moghaddam, S.S.; Ehteshami, M. A Comparative Life Cycle Assessment (LCA) Analysis of Innovative Methods Employing Cutting-Edge Technology to Improve Sludge Reduction Directly in Wastewater Handling Units. *J. Water Process Eng.* **2023**, *51*, 103354. [\[CrossRef\]](#)
26. Rashid, S.S.; Harun, S.N.; Hanafiah, M.M.; Razman, K.K.; Liu, Y.Q.; Tholibon, D.A. Life Cycle Assessment and Its Application in Wastewater Treatment: A Brief Overview. *Processes* **2023**, *11*, 208. [\[CrossRef\]](#)
27. European Commission—Joint Research Centre. *ILCD Handbook—General Guide on LCA—Detailed Guidance*; European Commission: Luxembourg, 2010; ISBN 9789279190926. Available online: <https://eplca.jrc.ec.europa.eu/> (accessed on 15 June 2025).
28. Lorenzo-Toja, Y.; Vázquez-Rowe, I.; Amores, M.J.; Termes-Rifé, M.; Marín-Navarro, D.; Moreira, M.T.; Feijoo, G. Benchmarking Wastewater Treatment Plants under an Eco-Efficiency Perspective. *Sci. Total Environ.* **2016**, *566–567*, 468–479. [\[CrossRef\]](#)
29. Tsangas, M.; Papamichael, I.; Banti, D.; Samaras, P.; Zorpas, A.A. LCA of Municipal Wastewater Treatment. *Chemosphere* **2023**, *341*, 139952. [\[CrossRef\]](#)
30. Negi, R.; Chandel, M.K. Life Cycle Assessment of Wastewater Reuse Alternatives in Urban Water System. *Resour. Conserv. Recycl.* **2024**, *204*, 107469. [\[CrossRef\]](#)
31. Khan, M.T.; Ahmad, R.; Liu, G.; Zhang, L.; Santagata, R.; Lega, M.; Casazza, M. Potential Environmental Impacts of a Hospital Wastewater Treatment Plant in a Developing Country. *Sustainability* **2024**, *16*, 2233. [\[CrossRef\]](#)
32. UNI EN ISO 14040:2006; Environmental Management—Life Cycle. International Organization for Standardization: Geneva, Switzerland, 2006.
33. Asadollahfardi, G.; Panahandeh, A.; Moghadam, E.I.; Masoumi, S.; Tayebi Jebeli, M. Environmental Life Cycle Assessment of Different Types of the Municipal Wastewater Pipeline Network. *Environ. Qual. Manag.* **2022**, *32*, 97–110. [\[CrossRef\]](#)
34. Guinee, J.B. Handbook on Life Cycle Assessment Operational Guide to the ISO Standards. *Int. J. Life Cycle Assess.* **2002**, *7*, 311–313. [\[CrossRef\]](#)
35. Arfelli, F.; Ciacchi, L.; Vassura, I.; Passarini, F. Nexus Analysis and Life Cycle Assessment of Regional Water Supply Systems: A Case Study from Italy. *Resour. Conserv. Recycl.* **2022**, *185*, 106446. [\[CrossRef\]](#)
36. Molinos-Senante, M.; Hernández-Sancho, F.; Sala-Garrido, R. Cost-Benefit Analysis of Water-Reuse Projects for Environmental Purposes: A Case Study for Spanish Wastewater Treatment Plants. *J. Environ. Manag.* **2011**, *92*, 3091–3097. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. The Ecoinvent Database Version 3 (Part I): Overview and Methodology. *Int. J. Life Cycle Assess.* **2016**, *21*, 1218–1230. [\[CrossRef\]](#)
38. ISPRA Catasto Rifiuti ISPRA AMBIENTE. Available online: <https://www.catasto-rifiuti.isprambiente.it/index.php?pg=gestione&width=1536&height=960&advice=si> (accessed on 5 December 2025).

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