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Evaluating environmental impacts and techno-economic feasibility of an integrated and novel wastewater and sludge treatment system for circular economy objectives[☆]

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ABSTRACT

Wastewater and sewage sludge present major global challenges today, necessitating innovative approaches and systems, especially those aligned with circular economy principles. In order to identify the most sustainable and circular solutions, there is an urgent need for research that investigates such novel systems and technologies, especially the use of hydrothermal carbonization (HTC) in wastewater and sludge treatment processes. Currently, no study has analyzed the environmental impacts and techno-economic feasibility of such an integrated system at a large scale within municipal and a centralized setting. Thus, this study aims to fill this gap by examining a HTC-based circular model through a life cycle assessment to quantify the environmental impacts and employing a life cycle costing approach for economic evaluation. We compare a baseline scenario with a circular HTC-integrated scenario using three alternative strategies that vary by mud/sludge age of 10, 20, and 40 days. Overall, the results revealed that the waterlines generated more environmental impacts than the sludgelines, primarily due to high energy and chemical consumption. The most significant impact categories identified were climate change, marine eutrophication, use of fossil resources and acidification. The model with a 10-day sludge age emerged as the optimal strategy for the circular HTC-integrated scenario. In the baseline scenario, the largest cost was related to sludge disposal. In contrast, the HTC-based solution significantly reduced both disposal and energy costs, while also showing potential for revenue generation by selling recovered hydrochar. This novel system has the potential to save three million euros annually, with a payback time of less than three years. In addition, the cost of environmental externalities was reduced from €0.073/m^3 in the baseline scenario to €0.061/m^3 for the innovative HTC-integrated system.

1. Introduction

The sustainable use and management of water resources is one of the pressing challenges of the contemporary world. The increasing world population, coupled with changing economic conditions and lifestyle has driven a significant rise in water usage (Lombardi et al., 2019) that ultimately increases wastewater generation. It is estimated that annually, around 380 billion m^3 of wastewater are produced globally that is a five-times the volume of water passing through Niagara Falls each year (Qadir et al., 2020). The global wastewater generation is expected to grow by 24 % by 2030 over its current levels (Qadir et al., 2020). Moreover, the effluents discharged from the wastewater treatment (WWT) plants are the major source of poor quality of surface waters (Pesqueira et al., 2020). Furthermore, sewage sludge produced by WWT facilities is another rapidly growing environmental and economic issue. The sludge handling and management alone costs 50 % of the total WWT process (Almahbashi et al., 2021).

The annual approximate production of sewage sludge is about 40 million tons in the United States and 50 million tons across Europe (Kelessidis & Stasinakis, 2012; L. Wang et al., 2019). Because of organic

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content and biological activity, the dewatering process of sewage sludge is normally inefficient. The mechanical dewatered sludge still contains a moisture content higher than 65 % (Wang et al., 2019). This high moisture content poses a significant challenge to effective sewage sludge handling. Moreover, various compounds (carbon, nitrogen, phosphorous, etc.) and hazardous substances (heavy metals, pathogens, etc.) are present in the sludge. This makes the conventional use of sludge as agriculture fertilizer a hazard. Additionally, the option of landfilling sludge is under pressure owing to limited land space and potential risks to soil and groundwater quality.

Moreover, as the circular economy (CE) (Gherghel et al., 2019) awareness grows, the conventional WWT procedures, especially thermal technologies such as incineration and gasification are facing increasing criticism because of their high energy consumption, huge amount of activated sludge generation, greenhouse gas emissions and lack of energy and resource recovery (Zhang & Liu, 2022). CE principles recognize sludge not as waste, but as a wasted resource. Resultantly, it is urgently required to incorporate new technologies into WWT systems. This paradigm shift of implementing new technologies and CE principles has the potential to improve both the environmental and socio-economic performances of these systems. New technologies developed especially for CE and sustainability objectives could enable the adoption of CE practices in the companies (Sassanelli et al., 2023) and redesigning supply chains for the CE objectives (Bressanelli et al., 2019; Elfarouk et al., 2023).

Hydrothermal carbonization (HTC) is a low-energy thermochemical process and technology that transforms biomass, such as sewage sludge into solid biofuel, liquid, and gaseous by-products (Czerwińska et al., 2022). Compared to conventional sludge treatment (ST), HTC can be advantageous, because it requires no prior drying and produces high quality hydrochar (Tasca et al., 2019). Various related fields have recognized the utility and benefits of HTC. For instance, a recent study on agri-food waste (Somorin et al., 2023) demonstrated that integrating HTC with anaerobic digestion (AD) shows superior performance than standalone AD, yielding higher fuel recovery while minimizing environmental impacts. Similarly, a study focused on dairy ST showed that HTC-based approaches show better environmental performance than other treatment models (Behjat et al., 2024). Despite HTC is receiving an increasing attention as a sustainable ST process, most of the worldwide research on this topic for municipal WWT remains confined to laboratory-scale studies (Tasca et al., 2019). Thus, there is an urgent need to develop and implement HTC-based WWT systems at the municipal level to improve both their environmental sustainability and economic performance. In this context the extant literature reports various methods and tool to measure and evalaute the performance of various circular models, such as design for X, lifecycle assessment, material flow analysis, multi criteria decision methods, etc., (Aragonés & Torralvo, 2024; Sassanelli et al., 2019).

Among these tools, in order to quantify and compare the impacts and performance of alternative circular models, as outlined in ISO standards 14040 (ISO, 2006a) and 14044 (ISO, 2006b), the lifecycle assessment (LCA) is a robust tool for evaluating the environmental burdens linked with products, processes, facility, technologies, etc., (Ahmad et al., 2023; Daddi et al., 2024). In addition to the analysis of environmental impacts, the life cycle costing (LCC) (European, 2022; Orfanidou et al., 2023) approach provides an economic assessment of various alterntaive solutions (Aqib et al., 2024). Such environmental and economic analyses provide a comprehensive understanding of whether an alternative solution creates additional environmental benefits at any stage of its lifecycle, along with its techno-economic viability. Such comprehensive analyses could provide a support in redesigning industrial systems while implementing sustainability and CE principles for achieving net-zero objectives.

The existing literature has highlighted several studies examining various WWT systems and/or ST technologies to assess their environmental impacts and/or techno-economic implications (Bartolozzi et al., 2020; Boldrin et al., 2022; Buonocore et al., 2018; Molinos-Senante et al., 2012; Niero et al., 2014). A comprehensive review and analysis of this literature is presneted in the next section. Notably, most of these HTC-based studies for WWT and/or ST systems are limited to lab-scale investigations to determine the optimal conditions. This observation is consistent with findings by (Aragón-Briceño et al., 2020) that most HTC studies on ST have been conducted using batch reactors in laboratory environments. Furthermore, the literature analysis also reveals that the scope of related LCA and/or LCC studies are mainly limited to just WWT processes, often neglecting the implications of sludge handling from environmental and economic perspectives.

So, in order to address the identified research gaps, this study introduces and integrates the HTC with WWT plant at the municipal (industrial) level, positioning it as a sustainable ST and resources recovery technology. In addition to presenting a novel circular WWT system (integrated with HTC technology for ST), this study quantifies and compares both the environmental impacts and techno-economic implications of the baseline scenario (currently in practice) with the innovative HTC-based integrated scenario, providing a thorough analysis. The novelty of this study further lies in its comprehensive nature as it evaluates six different alternative strategies, three for each system. In order to achieve these objectives, LCA and LCC approaches were employed for the environmental and economic impact assessments, respectively. Furthermore, unlike typical LCC studies that are normally based on a Conventional LCC analysis (direct costs only), this study also includes the environmental LCC (indirect costs or enviromental externalities) along with the direct costs.

2. Literature review

In HTC based processing, biomass is heated to temperatures ranging from 150 – 250 °C under an average pressure of 20 bars. In a period of 1 to 12 h, the feedstock is transformed into three fractions: a solid coal-matrix (hydrochar), water and gas (mainly CO_2). A more detailed overview of the HTC-based process is presented in the Supplementary Material (see Section 1, Fig. 1 and Table 1). Among the outputs, hydrochar stands out for its excellent fuel properties because of its dense carbon-rich structure. In addition, hydrochar is also suitable as a soil conditioner due to its high porous structure. HTC can process biomass with a high moisture content (ranging from 75 % to 99 %) and requires no pre-treatment (Tasca et al., 2019). This makes HTC an ideal technology for integration within WWT systems for the effective treatment of sludge.

While HTC is not a new technology, its use for ST has only gained attention in recent years. Before presenting the detailed environmental and economic analyses of the HTC-based WWT system, this study provides a concise literature review structured into two subsections. The first subsection is based on research related to HTC as a ST technology. The second subsection highlights studies that evaluate the environmental and/or economic aspects of WWT and ST systems. In order to examine recent trends and developments, we reviewed relevant studies published from 2012 to 2023. A total of 28 studies were analyzed.

2.1. HTC as a sewage ST technology

As research on the usage of HTC for ST is a recent trend, the available literature does not provide comprehensive information on the state of the art (Tasca et al., 2019). In response to this knowledge gap, a brief literature survey was conducted to analyze the utility and effectiveness of HTC as a ST technology. Additionally, the objective is also to highlight the environmental and economic impacts of HTC, as reported in related LCA and/or LCC studies.

As mentioned earlier, although research on HTC as a sustainable ST technology is getting attention, a substantial portion of this research is conducted at the laboratory scale. As illustrated in Table 1, around 79 % (11 out of 14) studies fall into this category. Only Scrinzi et al. (2022)

Table 1
Review of studies on HTC-based sludge treatment.

No.	HTC app. level	Main objective/s	Environ. analysis	Economic analysis	Country	Reference
01	Laboratory- scale study (2000 mL reactor)	Investigated the effect of temperature on syngas production, and the decomposition of sewage sludge.	No	No	China	(Feng et al., 2023)
02	District (industrial) level sludge treatment	Investigated how to reduce sludge production and improve nutrient and energy recovery.	No	Yes	Italy	(Scrinzi et al., 2022)
03	Laboratory- scale study (5 L reactor)	Life Cycle Analysis used to evaluate the environmental impacts.	Yes	No	Chile	(Pérez et al., 2022)
04	Laboratory- scale study (4 L reactor)	Investigated the energy recovery from sewage sludge in aqueous phase reforming.	No	No	Spain	(Oliveira et al., 2022)
05	Feasibility of HTC based small plant	Study of a hypothetical plant capable of processing 267.14 t per year of food waste and 105.12 t per year of sludge.	Yes General discussion	Yes General discussion	UK	(Bevan et al., 2021)
06	Laboratory- scale study (500 mL reactor)	Analyzed the influence of solid loading on the composition of hydrochar and process water.	No	No	UK	(Aragón-Briceño et al., 2020)
07	Laboratory- scale study (1L reactor)	Examined four wet waste streams at three different temperatures.	No	No	Sweden	(Niinipuu et al., 2020)
08	Laboratory- scale study (500 mL reactor)	Calculated energy yield from sewage sludge at different conditions.	No	No	Israel	(Gaur et al., 2020)
09	Review based on study of parameters	Analyzed the relation between char yields, physicochemical properties and process parameters.	No	No	Italy	(Tasca et al., 2019)
10	Laboratory- scale study (500 mL reactor)	Evaluated the effects of temperature, catalysts on solid yield, heavy metal contents, etc.	No	No	China	(X. Xu & Jiang, 2017)
11	Laboratory- scale study (500 mL reactor)	Studied the char production with different waste biomass temperature levels.	No	No	China	(Zhai et al., 2017)
12	Laboratory- scale study (250 mL reactor)	Investigated the effects of temperature and time on product characteristics for sewage sludge.	No	No	UK	(Danso-Boateng et al., 2015)
13	Laboratory- scale study	Studied influence of temperature and content of hydrogen and carbon of solid fuel.	No	No	South Korea	(Kim et al., 2014)
14	Laboratory- scale study	Treated municipal sewage sludge for arsenic removal from contaminated water.	No	No	China	(El-Deen & Zhang, 2012)

expanded its scope to the district level. However, this study was primarily aimed at discussing potential efficiencies and financial gains, overlooking detailed environmental and economic analyses. Another study (Bevan et al., 2021) from the UK investigated the feasibility of a small HTC-based plant. However, it did not provide a thorough analyses of the environmental and economic footprints. Most of these studies analyzing HTC were based on lab-scale investigations conducted in batch reactors (Aragón-Briceño et al., 2020). Kossińska et al. (2023) noted that while HTC is a promising technology, its implementation faces significant barriers, normally due to the lack of authoritative data on its long-term economic and environmental benefits. Table 1 also shows that except for a few studies, the majority of reviewed studies failed to undertake environmental and/or economic analyses using established tools, such as LCA and LCC. Thus, in order to better evaluate the environmental and/or economic impacts of the WWT and ST systems (not limiting only to HTC), the scope of this literature review was extended.

2.2. *Environmental and economic analyses of WWT and ST systems*

Various studies have reported environmental and/or economic impact assessment of different WWT and/or ST systems and technologies by using LCA, LCC and other related methodologies. LCA is a standardized tool that quantifies potential environmental impacts throughout a product's life cycle (Ahmad et al., 2019; Boldrin et al., 2022). The LCA consists of four key stages: (i) goal and scope definition; (ii) inventory analysis; (iii) impact assessment; and (iv) results' interpretation. For an economic analysis, the LCC approach evaluates the total costs of a system across its various life cycle phases. According to Kalbar et al. (2012) the LCC includes various cost components, including electricity usage, chemical consumption, maintenance, repairs, and waste disposal. For the review, data were extracted from 14 pertinent studies and the summary is presented in Table 2. The studies were analyzed based on various themes and characteristics, such as the type of WWT technologies, ST methods, assessment boundaries, assessment levels, countries of origin and major findings or results.

Table 2 shows that more reviewed studies were centered on LCA compared to LCC. However, it is important to recognize that relying solely on the environmental analysis, while ignoring economic implications is insufficient for informed decision making. The table also reveals that a majority of the reviewed studies addressed WWT (11 out of 14) rather than ST (8 out of 14). In addition, only 5 studies, such as Prateep Na Talang et al. (2022), Limphitakphong et al. (2016), etc., provided a comprehensive analysis of both WWT and ST systems. Moreover, only 3 studies (Liu et al., 2023; Notarnicola et al., 2023; C. Xu et al., 2014) focused exclusively on ST. This suggests a gap in research concerning ST, even related to conventional sludge thickening approaches. Overall, the majority of the reviewed studies were limited to WWT, ignoring the ST and its impacts.

Furthermore, most of the studies reviewed for ST were mainly based on traditional and conventional ST and management approaches. For example, Liu et al. (2023), Limphitakphong et al. (2016), etc., were focused on mechanical dewatering, sun-drying, landfilling and anaerobic digestion. Only Notarnicola et al. (2023) focused on treating sludge to obtain biodiesel. The results indicated that various WWT and/or ST technologies and configurations showed different environmental and economic impacts ((Prateep Na Talang et al., 2022; Resende et al., 2019; C. Xu et al., 2014). This could be linked with differences in energy and resources consumption, and material and operational costs. Therefore, it is crucial to reduce these impacts by employing innovative technologies and converting sludge into useful resources. As mentioned earlier, HTC-based ST is one of the promising technologies for achieving CE objectives. However, none of the reviewed studies was focused on both environmental and economic assessments of WWT systems while including HTC as a ST technology.

3. Methodology and system under study

As mentioner before, the objective of this study is to present a novel HTC-based ST technology integrated into a WWT system at an industrial scale. Additionally, the study is also aimed to evaluate the environmental and economic impacts of the baseline system and the new

Table 2
Review of LCA/LCC studies for wastewater and sludge treatment systems.

No.	Country of study	WWT system	Sludge treatment system	FU	LCA system boundary	LCC details	Assessment level	Major findings	Reference
01	Italy	–-	Sewage sludge to biodiesel	1 kg of biodiesel	Cradle-to-gate	–-	Midpoint	• 7 scenarios were developed at pilot plant level. • Most impacts from electricity consumption.	(Notarnicola et al., 2023)
02	China	–-	Sludge incineration	1 tonne of sludge	Gate-to-gate	Average cost and revenues	Midpoint	• 7 sludge incineration technologies were evaluated. • Environmental impacts of coal and natural gas were around 100 times higher than biomass.	(Liu et al., 2023)
03	Thailand	Centralized (C) and decentralized (D)	Dewatering, sun-drying and anaerobic decomposition	1 m^3 treated effluent	Cradle-to-grave	Net cash flow, net present value	Midpoint and endpoint	• Four scenarios C-D (dewatering and fertilizer) were evaluated. • The C-fertilizer scenario was the most viable.	(Prateep Na Talang et al., 2022)
04	Brazil	Integrated water and wastewater	–-	1 m^3 of wastewater treated	Cradle-to-gate	–-	Midpoint	• Most impacts from electricity consumption and methane emissions. • Different impacts of different wastewater treatment technologies.	(Boldrin et al., 2022)
05	Italy	Alternative treatment (disinfection) methods	–-	1 m^3 of treated wastewater	Cradle-to-gate	Capital and operating costs	Midpoint	• Membrane modules were responsible for 24 % of the total cost. • Nutrients and heavy metals in water had the most damaging environmental impacts.	(Foglia et al., 2021)
06	Italy	Integration of a microalgae unit with WWT	–-	1000 m^3 of influent wastewater	Cradle-to-gate	–-	Midpoint impacts	• Significant electricity savings and environmental improvement due to algal based pond.	(Tua et al., 2021)
07	Brazil	D-type small-scale WWT and wetlands	–-	1 m^3 of treated water	–-	Costs related to all lifecycle phases	Midpoint impacts	• Electricity consumption contributed 7 % to climate change. • Technologies that reduced direct emissions were better for the environment.	(Resende et al., 2019)
08	Spain	Small WWT (hypothetical)	–-	1 m^3 of treated water	Cradle-to-grave	Capital, operation and maintenance costs	Midpoint impacts	• Nature-based solutions were 3–5 times environmentally friendly. • Constructed wetland was more expensive than high rate algal pond.	(Garfí et al., 2017)
09	Thailand	C-type WWT systems	Dewatering, anaerobic digestion	1 m^3 of wastewater influent	Gate-to-gate	Only operational costs	Midpoint impacts	• The highest potential impacts on eutrophication. • Medium plant provided better performance in chemical use and operating costs.	(Limphitakphong et al., 2016)
10	South Korea	WWT and integrated management	Anaerobic digestion and incineration	1 m^3 of influent wastewater	Cradle-to-gate	Economic efficiency analysis	Midpoint impacts	• Integrating two lines enhanced anaerobic digestion and produced less sludge. • Incineration with integrated sludge	(Piao et al., 2016)

(continued on next page)

Table 2 (*continued*)

No.	Country of study	WWT system	Sludge treatment system	FU	LCA system boundary	LCC details	Assessment level	Major findings	Reference
								management was most economical method.	
11	Denmark	Various WWT technologies	Anaerobic digestion and combustion	1 m^3 of inlet wastewater	Cradle-to-gate	–-	Midpoint impacts	• For climate change and fossil depletion, recycling phosphorus to soils was better option than incineration.	(Niero et al., 2014)
12	China	–-	13 sludge treatment scenarios	1 tone of dry sludge	Gate-to-grave	Material, labor, energy, transport, maintenance costs	Midpoint impacts	• Anaerobic digestion showed better environmental and economic benefits. • More human toxicity due to heavy metal emissions from landfill and incineration.	(C. Xu et al., 2014)
13	China	Various WWT systems	Dewatering and anaerobic digestion	200000 m^3/d of municipal wastewater	Gate-to-gate	–-	Midpoint impacts	• Six biological anaerobic/anoxic/oxic WWT systems were evaluated. reduced GHG emissions. • Bioenergy recovery from biogas combustion	(X. Wang et al., 2012)
14	Spain	Small-scale WWT systems	–-	–-	–-	Cost–benefit analysis	–-	• Nine different WWT technologies were evaluated. • Extended aeration was the most expensive and pond systems were cheapest.	(Molinos-Senante et al., 2012)

circularity-oriented HTC-based system. An overview of the methodology employed in this study is presented in Fig. 1.

The WWT system selected for this study employs a traditional biologically activated ST with a modified Ludzack-Ettinger process (Zhang et al., 2021). The present baseline scenario for ST is grounded on both primary and secondary processes. This WWT facility is located in

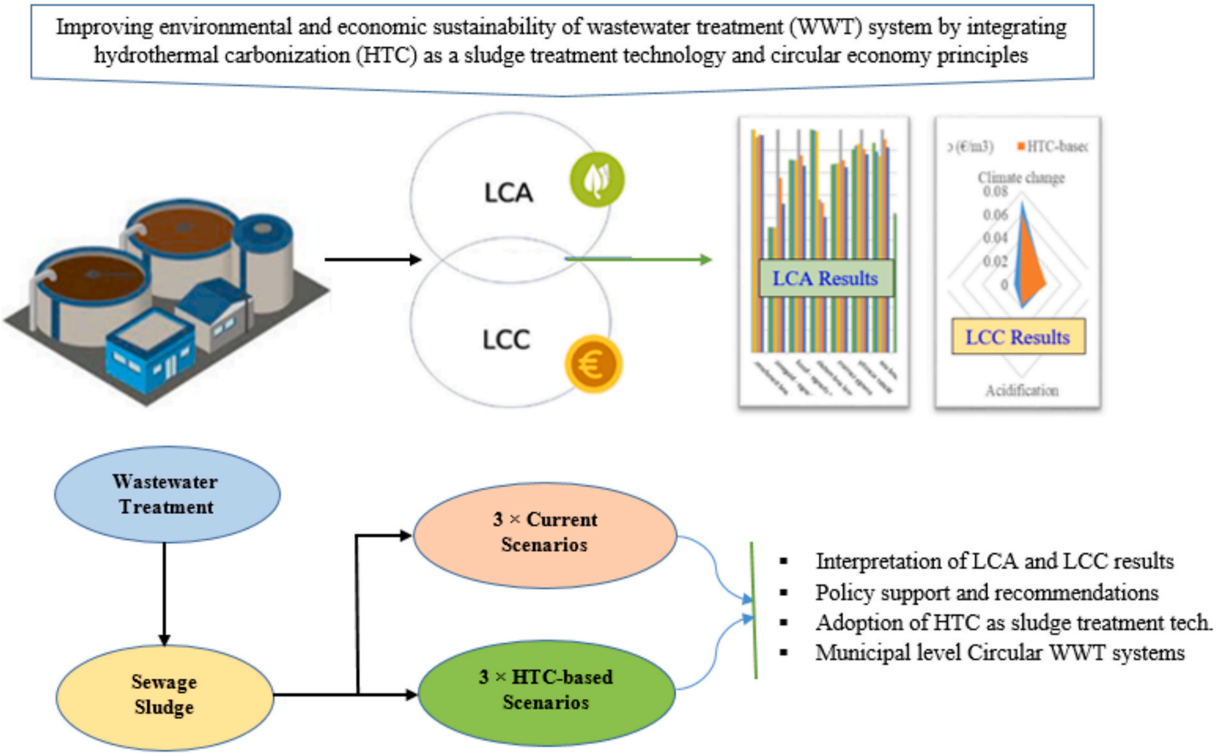

Fig. 1. Overall study methodology.

the municipality of Lastra a Signa, situated in Florence (FI), Italy. It manages an average daily wastewater flow of 212,697 m^3, serving eight different municipalities. The associated ST facility is located in Case Passerini within the Municipality of Sesto Fiorentino and receives sludge from the WWT plant through a sludge pipeline.

The treatment chain is made up of two main components: the waterline and the sludge line. The waterline includes processes, such as screening treatments, grit/oil removal, primary sedimentation, dephosphatization, denitrification and oxidation of biologically activated sludge, secondary sedimentation and disinfection. The sludge line involves mechanical thickening treatments, anaerobic digestion (with the recovery of biogas) and mechanical dehydration. In the baseline scenario, the digested sludge is transported outside the city for final treatment and disposal. Three distinct baseline scenarios were modelled depending on the age of the sludge, with primary data to support each model.

The integrated HTC-based system was developed around three hypothesized scenarios. All the integrated scenarios employed HTC as the ST technology. The HTC consists of a thermochemical conversion process conducted in an aqueous environment through which a biomass is transformed into a carbon-rich solid product (hydrochar), as well as water-soluble organic fraction and a small portion of a gaseous fraction. The HTC technology was applied to sewage sludge with an average dry matter content of around 20–25 % and it did not require an energy-intensive pre-treatment process.

3.1. Environmental impact assessment

This study employed a four-stage LCA methodology included within the ISO technical standards (Daddi et al., 2024; ISO, 2006a; ISO, 2006b). The first step for an LCA study is the clear definition of goal and scope. This critical step serves as a foundation, guiding key decisions and influencing subsequent phases, including data collection and inventory analysis (Ahmad et al., 2023; Bartolozzi et al., 2020). The life cycle inventory stage entails quantifying the raw materials and energy needed, as well as measuring air emissions, solid wastes, and other residues linked with a product, process, or technology (Ahmad et al., 2019).

The third step is about the impact assessment that involves measuring the impacts caused by consumption of resources as inputs and environmental emissions as outputs from the system being studied (Hauschild et al., 2018; Khan et al., 2023). The fourth and final phase is the life cycle interpretation, which connects all the LCA phases as well as the recommendations and conclusions (Laurent et al., 2020). Next, this section provides details regarding the functional unit, system boundary, primary data collection methods, databases and software, as well as the approach used for impact assessment. The analysis was carried out using the SimaPro 9 and the impact assessment was based on the EU's Environmental Footprint (EF 2.0) characterization method (De Rosa-Giglio et al., 2018).

3.1.1. Functional unit and system boundary

The functional unit serves as the benchmark for the environmental impacts and is used to calculate reference flows. Most related studies in the literature has used a functional unit equal to 1 m^3 of treated wastewater. Thus, to ensure consistency and enable future comparisons, this study also adopts 1 m^3 of treated wastewater as its functional unit. The system boundaries applied in LCA studies regarding WWT and/or ST systems are often defined differently, and not all refer to the cradle-to-grave perspective. In some cases, the system boundaries are limited to the operational phase alone. The system boundaries delineate which lifecycle phases are included and which are omitted from the analysis (Ahmad et al., 2023). Figs. 2 and 3 illustrate the system boundaries for the baseline and HTC-based integrated scenarios, respectively.

Starting from the upstream processes, electricity, natural gas and the

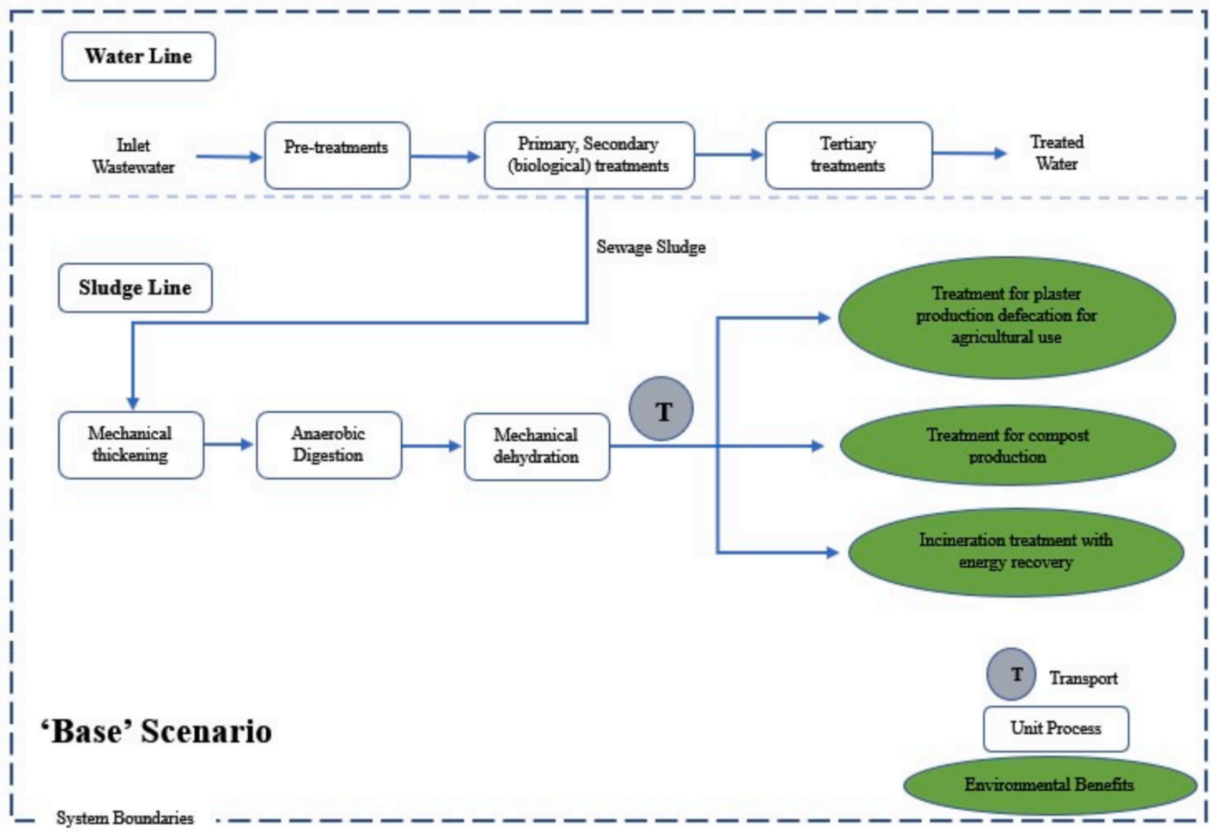

Fig. 2. System boundary of baseline/base scenario.

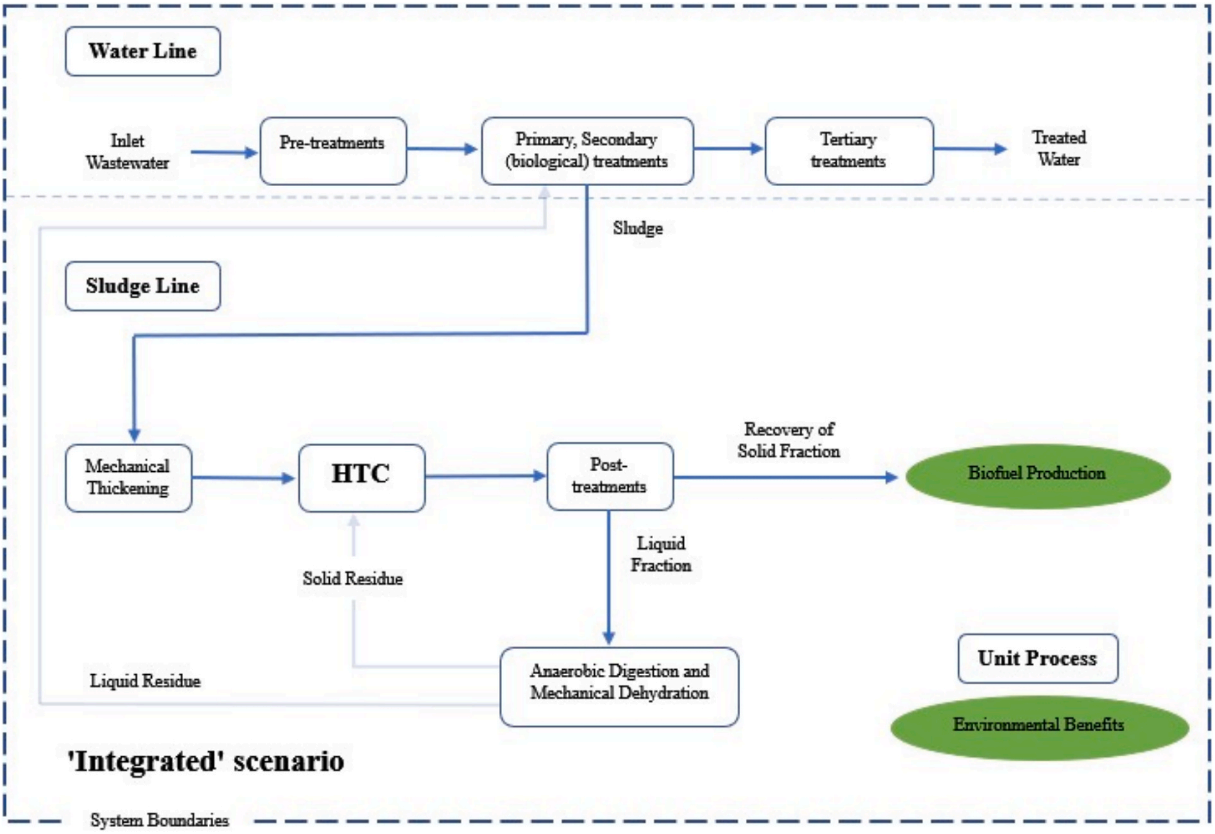

Fig. 3. System boundary of integrated scenario.

production of chemicals are included in the system boundary. For input wastewater, the analysis starts from the point where the wastewater physically enters the WWT plant. The freshwater usage, wastewater collection and transfer to the WWT facility are not part of the analysis. This exclusion is due to the significant variations in water distribution and wastewater transfer systems. Given the lack of available data, the use phase and the end-of-life phase of the products recovered from biological sludge are also excluded from the analysis. Previous related LCA studies have shown that the construction phase of the WWT plants has negligible impacts compared to the operational and maintenance phases (Amini et al., 2015). Therefore, this phase has also been omitted from the analysis. Since the plant works with 40-days sludge age, the relevant data were used for modelling the first alternative configuration. Later, the two other scenarios were modelled considering sludge ages of 20 days and 10 days.

3.1.2. *Data collection and lifecycle inventories*

Overall, the primary data (generally about the foreground processes) are driven from actual data related to processes' inputs and outputs that are collected through in-person industrial visits and face-to-face interviews conducted at the relevant plant or company (Ahmad, 2023). Whereas, in case when the primary data are unavailable, the secondary data (mostly for background processes) are acquired from already published scientific literature and/or different commercial databases (Khan et al., 2023). For this study, the inventory data (for the baseline scenario) related to the water and sludge lines were obtained for the Italian plant described earlier.

The inventory data gathered for the foreground processes were related to the consumption of energy at each processing stage and associated emissions. Regarding the consumption of chemicals in the waterline, the data were derived from the environmental declarations of Publiacqua S.p.A., the company responsible for managing plant operations in Florence, Italy. The calculation for the consumption of ferrous chloride used in the sludge line was based on Andreoli et al. (2007), while for the consumption of acrylonitrile an average usage of 8 g/kg dry substance was assumed. Additionally, the pertinent data regarding the HTC-based integrated scenario, especially the consumption of energy, water, oxygen and emissions were obtained from similar primary and secondary sources.

For the background processes, the Ecoinvent database v3.5 was used for collecting data related to the impacts of various waste management processes. In particular, data regarding the final treatment of dewatered sludge leaving the plant were sourced from the database and relevant literature (Hospido et al., 2005; Poulsen & Hansen, 2003). For transport data, the final treatment facilities were located outside of Tuscany (Florence) region, with an average distance of 200 km from the plant. Regarding the end-of-life, it was assumed that 95 % of the sludge is treated and repurposed for agricultural uses (to produce defecation plaster or compost), while only 5 % is recovered through waste-to-energy for the baseline scenario. The inventory data for foreground processes can be found in the additional file (Supplementary Material, Tables 2 and 3 for baseline and HTC-integrated scenarios, respectively). The data are presented to reflect the two systems under study, each with three alternative process strategies.

3.1.3. *Lifecycle impact assessment*

The environmental impact assessment was performed using the EF method. The impact assessment involves the characterization of various inputs and outputs to environmental burdens in the form of various impact categories. For this purpose, the characterization was carried out at midpoint impact levels. The results of each impact category provide insights into the optimal process strategies for both systems. The environmental impact categories considered for the analyses included climate change or global warming, ozone depletion, ionizing radiation-human health, photochemical ozone formation-human health, particulate matter, human toxicity-non-carcinogenic, human toxicity-carcinogenic, acidification, eutrophication of fresh water, marine eutrophication, terrestrial eutrophication, freshwater ecotoxicity, land use, water consumption, and consumption of fossil resources.

3.2. Economic impact assessment

For evaluating the economic impacts and implications, the LCC approach was used to calculate the monetary costs associated with various lifecycle phases of the technical systems under study and compare the long-term costs tied to different alternative strategies (Andhov et al., 2019). The LCC framework provides decision-makers with crucial economic insights that can be used to understand and highlight areas where cost reduction efforts could be most effective, along with evaluating potential alternative strategies. There are two commonly applied LCC methodologies that provide information to decision-makers. The conventional LCC (CLCC) provides an investor's perspective, focusing on direct financial implications. In contrast, for including an external 'eco-costs' of environmental damages and a supply-chain actor perspective, the environmental LCC (ELCC) is adopted (Miah et al., 2017).

The CLCC involves measuring and calculating all direct costs associated with a product during its various life cycle phases. Unlike ELCC, the CLCC is focused on market-realted factors and does not consider elements such as the damages caused by enviornmental emissions. Usually, the CLCC model is divided into four main phases which refer to the four important cost components (Ristimäki et al., 2013). These cost elements are the initial investment costs, operating costs, maintenance costs and decommissioning or disposal costs. The other two critical parameters include the evaluation time frame and the discount rate. Compared to CLCC, the ELCC involves combining elements of the LCC along with components of an LCA model. It considers the environmental externalities (indirect costs) incurred. Basically, the ELCC provides a financial accounting view of the life cycle of a product based on the environmental data related to pollutions and emissions. To facilitate this, the Intergovernmental Panel on Climate Change (IPCC) provides methodologies for assessing the costs associated with such externalities, including emissions (Dejaco et al., 2020; IPCC, 2007). More details on the IPCC's eco-costs (valuation of externalities) of emissions for different categories can be found in the Supplementary Material (Section 2 and Table 4).

Without including external environmental costs, an economic analysis can lead to a skewed understanding of the total costs, resulting into ill-informed decision-making based on incomplete information (Miah et al., 2017). So, this study includes both conventional and environmental aspects into the economic analysis. The overall integrated LCC approach (CLCC-ELCC) employed in this study is shown in Fig. 8 of the Supplementary Material. The LCC analysis was divided into the construction, use and end-of-life phases. In the construction phase, the investment cost for the construction of the HTC plant was used to distinguish between the baseline scenario and HTC-based integrated scenario. In the use stage, the operating costs and maintenance costs relating to the machinery were quantified. For the end-of-life phase, we estimated costs related to waste disposal/recovery. The dismantling of the plant, treatment and personnel costs were not taken into account due to data limitations and the high uncertainty surrounding these costs. The system boundary for the economic analysis is illustrated in Fig. 9 of the Supplementary Material.

The economic costs were first estimated on an annual basis and subsequently calculated in relation to the functional unit. A useful lifetime of twenty years was chosen for the plant. Since the investment cost for the WWT plant (focused solely on wastewater prior to ST) remains the same for both scenarios, only the investment cost for the HTC plant was included in the analysis. The costs for transporting and transferring the sludge to the treatment plants (waste-to-energy, defecation plasters, composting) and the costs for grating/sand disposal from the ST plant were included. The analysis also accounted for the costs of disposal of aggregates from the HTC plant. For estimating investment costs, maintenance costs, operating costs of the plant (energy, chemicals, etc.) and costs related to the waste disposal/recovery, the data were provided by the participating plant. For the ELCC, the CML impact categories were used for monetization factors to convert the environmental impacts into externalities (Durão et al., 2019).

4. Results and discussion

4.1. Environmental performance analysis

The environmental impact scores are presented separately for the water and sludge lines in Table 3 for the baseline scenario. Table 4 presents results for the waterline, HTC process and sludge line for the HTC-integrated scenario.

The results from the baseline scenario (see Table 3) indicate that the waterlines generated significantly more impacts than the sludge lines. For example, in the scenario with 40-day sludge age, the waterline accounted for an average of 77 % of the impacts across nearly all impact categories. Similar patterns were observed for the other two strategies, with the waterline responsible for 74 % of impacts in the 20-day sludge age scenario and 67 % in the 10-day sludge age scenario. These comparisons across all three baseline scenarios are presented in Figs. 2–4 of the Supplementary Material. The main elements responsible for these impacts associated with the waterline were the consumption of aluminum polychloride and energy. A comparative analysis of these results is presented in Fig. 4.

Table 3 and Fig. 4 illustrate that the baseline scenario with a 10-day sludge age demonstrated superior environmental performance compared to the other two alternatives. Additionally, Fig. 4 emphasizes that the baseline scenario with a 40-day sludge age showed much higher impacts than both the 10-day and 20-day sludge age scenarios. These results are in agreement with the basic principles of sludge treatment, which indicate that both viability and sludge production yield tend to decrease as the sludge gets older (Canales et al., 1994). In addition, previous research suggests that the optimal sludge age is normally less than 20 days in a nutrient removal activated sludge process (Ge et al., 2013; Johns, 1995). The results for the HTC-integrated scenarios are detailed in Table 4, reflecting three different alternative strategies based on sludge age.

The results presented in Table 4 for HTC-based integrated scenario show that waterlines are the predominant contributors to total impacts across all three sludge age strategies (10-day, 20-day and 40-day). Specifically, for the 40-day sludge age, waterlines accounted for an impressive 92 % of all impact categories, with the exception of the aquatic eutrophication category, where their contribution was 78 %. In contrast, the HTC unit contributed an average of 5 % across all categories, with notable increases in photochemical ozone formation and both aquatic and terrestrial eutrophication, where its contribution peaked at 21 %. The sludge line affected the impact categories by an average of 3 %, except in the case of ecotoxicity in freshwater, where the contribution was 24 %. The comparisons of the water line, sludge line and HTC unit are presented for all three HTC-integrated scenarios in the additional figures (Supplementary Material, Figs. 5–7). The overall comparison of the results for the three HTC-based alternatives is shown in Fig. 5.

The HTC-based integrated scenario with a 10-day sludge age showed significantly lower impacts on the environment than the other two alternatives, as depicted in Fig. 5. Notably, the difference in environmental performance between the HTC-based alternative with a 40-day sludge age and the other two alternatives was only marginally greater than what was observed in the baseline scenarios. Overall, in both categories (baseline and HTC-integrated), the alternative scenarios with a 10-day sludge age indicated better environmental performance than those with 20-day and 40-day sludge ages. So, in order to find the overall optimal system among all the six strategies, the alternatives with a 10-

Table 3
Environmental impacts of alternative strategies for baseline scenario.

No.	Impact category	Unit	10-days (sludge age)		20-days (sludge age)		40-days (sludge age)	
			Water line	Sludge line	Water line	Sludge line	Water line	Sludge line
01	Climate change – total	kg $\mathrm{CO}_{2\ \mathrm{eq.}}$	4.79E-01	3.57E-02	4.78E-01	7.58E-02	4.73E-01	1.72E-01
02	Climate Change – fossils	kg $\mathrm{CO}_{2\ \mathrm{eq.}}$	4.06E-01	2.08E-02	4.05E-01	4.60E-02	4.01E-01	1.13E-01
03	Climate Change – biogenic	kg $\mathrm{CO}_{2\ \mathrm{eq.}}$	7.20E-02	1.49E-02	7.20E-02	2.99E-02	7.20E-02	5.93E-02
04	Climate changes – land transformation	kg $\mathrm{CO}_{2\ \mathrm{eq.}}$	6.76E-04	1.07E-05	6.73E-04	6.23E-06	6.65E-04	4.45E-06
05	Ozone depletion	kg CFC-11 $_{\mathrm{eq.}}$	1.07E-05	1.95E-09	4.73E-08	3.44E-09	4.70E-08	7.44E-09
06	Ionizing radiation, human health	kBq U235 $_{\mathrm{eq.}}$	1.94E-02	8.42E-04	1.91E-02	1.55E-03	1.85E-02	2.94E-03
07	Photochemical ozone formation, human health	kg NMVOC $_{\mathrm{eq.}}$	1.02E-03	4.28E-04	1.02E-03	7.81E-04	1.01E-03	1.45E-03
08	Particulate matter	Disease incidence	1.92E-08	4.70E-09	1.92E-08	5.40E-09	1.91E-08	7.78E-09
09	Human toxicity, non-carcinogenic	CTUh	4.65E-08	1.19E-07	4.63E-08	1.22E-07	4.59E-08	1.26E-07
10	Human toxicity, carcinogenic	CTUh	9.45E-09	2.25E-08	9.44E-09	2.30E-08	9.40E-09	2.37E-08
11	Acidification	mol H+ $_{\mathrm{eq.}}$	2.68E-03	7.18E-04	2.67E-03	8.56E-04	2.65E-03	1.21E-03
12	Eutrophication of fresh water	kg P $_{\mathrm{eq.}}$	2.12E-05	2.18E-06	2.11E-05	1.50E-06	2.06E-05	8.42E-07
13	Marine eutrophication	kg N $_{\mathrm{eq.}}$	7.67E-03	8.43E-05	8.45E-03	1.05E-04	1.05E-02	2.40E-04
14	Terrestrial eutrophication	mol N $_{\mathrm{eq.}}$	4.96E-03	3.27E-03	4.95E-03	3.63E-03	4.90E-03	4.71E-03
15	Freshwater ecotoxicity	CTUe	1.84E-01	4.36E+00	1.84E-01	4.44E+00	1.82E-01	4.55E+00
16	Land use	Dimensionless (pt)	2.10E+00	3.55E-01	2.08E+00	4.67E-01	2.04E+00	6.46E-01
17	Water consumption	m^3 world $_{\mathrm{eq.}}$	2.38E-01	4.04E-03	2.36E-01	1.27E-02	2.29E-01	4.57E-02
18	Consumption of fossil resources	MJ	5.05E+00	1.98E-01	5.02E+00	4.20E-01	4.93E+00	1.43E+00
19	Consumption of mineral resources and metals	kg Sb $_{\mathrm{eq.}}$	5.60E-07	1.84E-07	5.59E-07	1.44E-07	5.57E-07	1.32E-07

Table 4
Environmental impacts of alternative strategies for HTC-based integrated scenario.

No.	Impact category	10-days (sludge age)			20-days (sludge age)			40-days (sludge age)		
		Water line	HTC process	Sludge line	Water line	HTC process	Sludge line	Water line	HTC process	Sludge line
01	Climate change – total	4.83E-01	2.43E-02	6.12E-03	4.80E-01	2.66E-02	6.45E-03	4.76E-01	3.13E-02	7.12E-03
02	Climate Change – fossils	4.10E-01	2.42E-02	5.16E-03	4.08E-01	2.65E-02	5.44E-03	4.03E-01	3.12E-02	6.00E-03
03	Climate Change – biogenic	7.21E-02	9.14E-05	9.60E-04	7.21E-02	1.01E-04	1.01E-03	7.20E-02	1.20E-04	1.12E-03
04	Climate changes – land transformation	6.82E-04	2.69E-06	3.13E-06	6.78E-04	3.31E-06	3.30E-06	6.69E-04	4.55E-06	3.63E-06
05	Ozone depletion	4.78E-08	3.77E-09	3.32E-10	4.76E-08	4.23E-09	3.50E-10	4.72E-08	5.14E-09	3.86E-10
06	Ionizing radiation, human health	1.98E-02	8.59E-04	1.66E-04	1.95E-02	9.87E-04	1.75E-04	1.88E-02	1.24E-03	1.93E-04
07	Photochemical ozone formation, human health	1.03E-03	1.32E-04	3.47E-05	1.02E-03	1.68E-04	3.65E-05	1.02E-03	2.00E-04	4.03E-05
08	Particulate matter	1.93E-08	1.20E-09	2.86E-10	1.92E-08	1.51E-09	3.02E-10	1.91E-08	1.91E-09	3.35E-10
09	Human toxicity, non-carcinogenic	4.68E-08	1.09E-09	2.11E-09	4.66E-08	1.23E-09	2.24E-09	4.62E-08	1.51E-09	2.50E-09
10	Human toxicity, carcinogenic	9.48E-09	8.75E-11	3.70E-10	9.46E-09	1.06E-10	3.94E-10	9.42E-09	1.42E-10	4.40E-10
11	Acidification	2.71E-03	2.07E-04	4.61E-05	2.69E-03	2.55E-04	4.86E-05	2.67E-03	2.97E-04	5.38E-05
12	Eutrophication of fresh water	2.16E-05	5.67E-06	3.42E-07	2.13E-05	5.97E-06	3.60E-07	2.08E-05	6.54E-06	3.97E-07
13	Marine eutrophication	8.57E-03	4.45E-05	1.16E-05	9.27E-03	5.68E-05	1.23E-05	1.14E-02	6.72E-05	1.36E-05
14	Terrestrial eutrophication	5.01E-03	6.04E-04	1.27E-04	4.98E-03	7.48E-04	1.34E-04	4.94E-03	8.80E-04	1.49E-04
15	Freshwater ecotoxicity	1.85E-01	1.28E-02	6.22E-02	1.84E-01	1.43E-02	6.62E-02	1.83E-01	1.73E-02	7.41E-02
16	Land use	2.13E+00	1.86E-01	3.28E-02	2.11E+00	2.57E-01	3.46E-02	2.06E+00	4.00E-01	3.83E-02
17	Water consumption	2.44E-01	9.96E-03	1.70E-03	2.40E-01	1.13E-02	1.79E-03	2.33E-01	1.40E-02	1.97E-03
18	Consumption of fossil resources	5.12E+00	1.60E-01	7.77E-02	5.07E+00	1.88E-01	8.19E-02	4.98E+00	2.46E-01	9.03E-02
19	Consumption of mineral resources and metals	5.62E-07	1.82E-08	3.42E-08	5.61E-07	2.05E-08	3.60E-08	5.58E-07	2.51E-08	3.97E-08

day sludge age of both the baseline and HTC-integrated scenarios were compared. The results of this comparison are presented in Fig. 6.

The comparison of both scenarios with a 10-day sludge age clearly shows that the alternative scenario based on HTC-integration has fewer environmental impacts than the baseline scenario. As illustrated in Fig. 6, out of 16 evaluated impact categories, 11 categories (climate change, ozone depletion, acidification, etc.) were more adversely impacted in the baseline scenario than in the HTC-integrated scenario. In contrast, the HTC-integrated scenario showed only slightly higher impacts in five categories (ionizing radiation, eutrophication of fresh water, etc.). Overall, the results of the LCA analysis reveal that integrating the HTC process into the WWT system considerably reduces environmental impacts compared to the traditional baseline scenario. Using the PEFCR guidelines, we also identified the most significant impact categories, which together account for at least 80 % of the total impacts. The results of these critical impact categories are displayed in Fig. 7.

In order to highlight the most significant impact categories, normalization and weighting of the LCA results were performed. Fig. 7 shows the percentage contribution of each impact category for the three strategies within the HTC-based integrated scenario. The most critical categories for the integrated systems include climate change, marine eutrophication, use of fossil resources, and terrestrial and aquatic acidification. In contrast, all remaining impact categories collectively accounted for around 20 % of the total impacts.

4.2. *Economic performance analysis*

The conventional economic analysis, based on direct costs, is presented in Table 5, for both scenarios (baseline and HTC-integrated). From an environmental perspective, the best alternative for both scenarios was the one with a 10-day sludge age. Consequently, the economic analyses were conducted only for these two environmentally sustainable options. To protect industrial secrecy, we provide cost

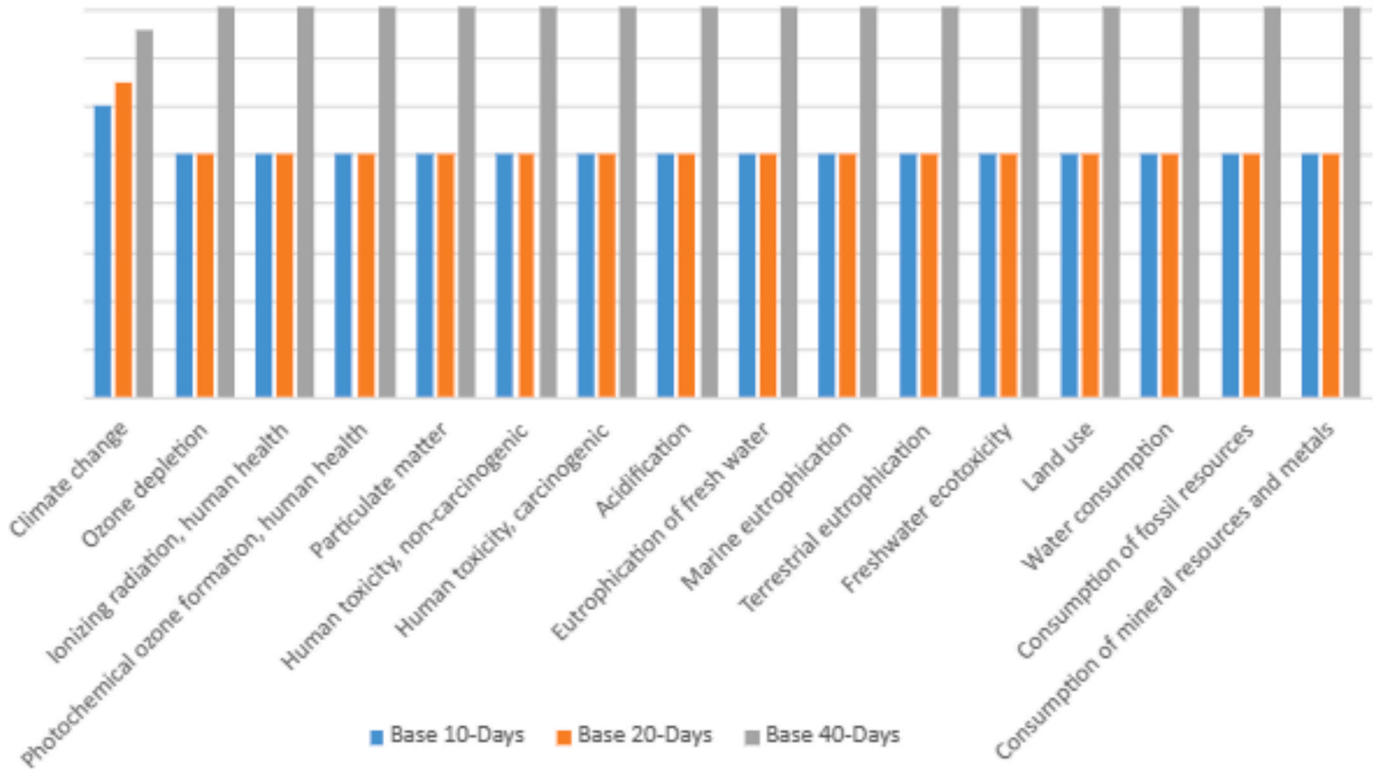

Fig. 4. Comparison of alternative strategies for the baseline scenario.

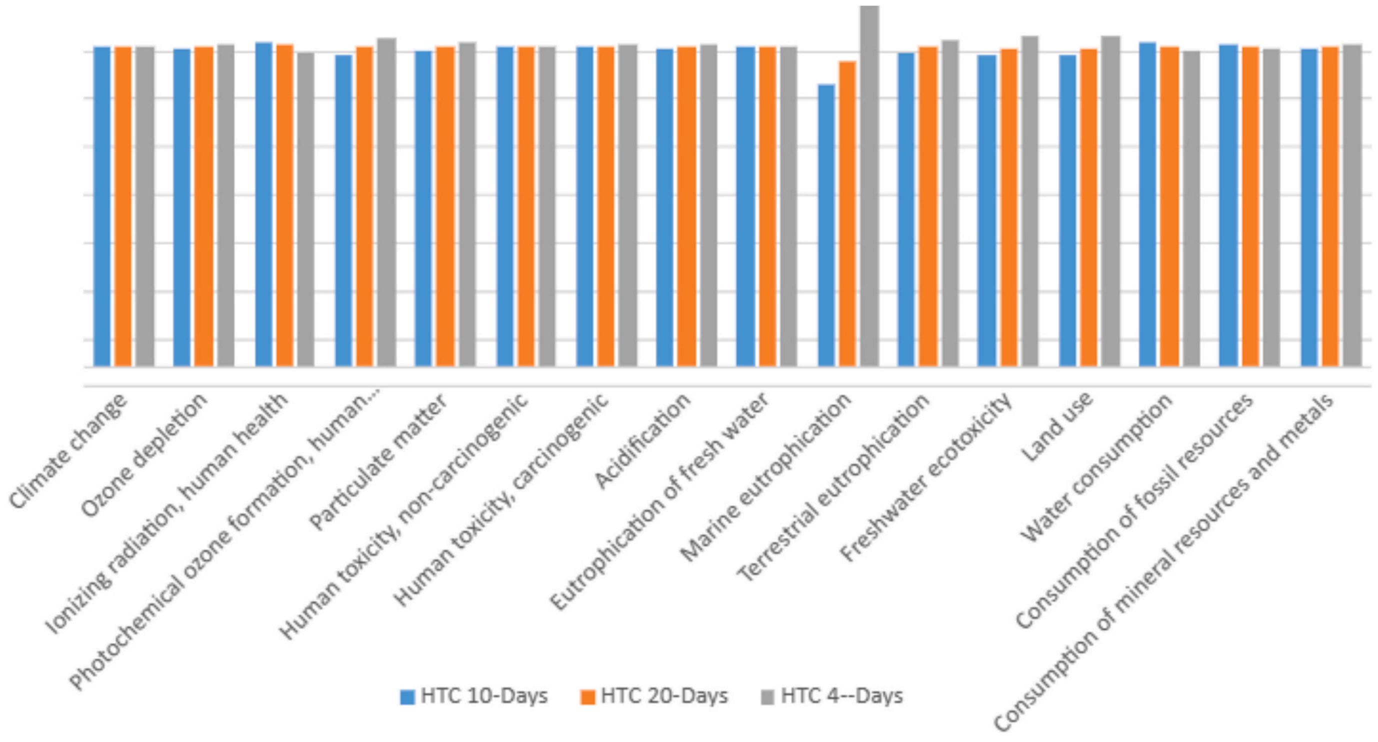

Fig. 5. Comparison of alternative strategies for HTC-based integrated scenario.

information categorized broadly, without disclosing further details at the sub-category level. Table 5 shows that the most significant costs in the baseline scenario are related to the disposal/recovery of excess sludge.

Table 5 reveals that integration of HTC represents an economically feasible and beneficial innovative solution. HTC did not only cost less for the disposal/recovery of dehydrated sludge than the baseline scenario, it also showed potential economic gains through the sale of hydrochar and other materials recovered from the sludge, along with cost savings achieved from enhanced energy efficiency. When comparing the total

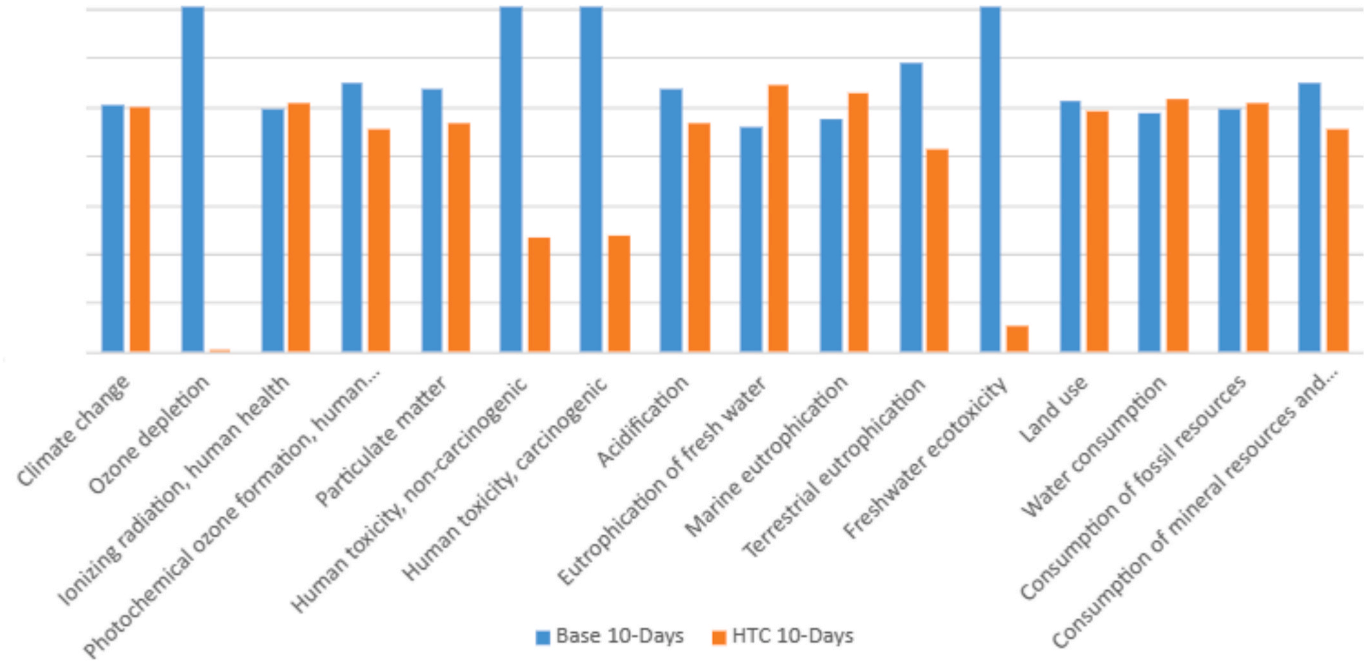

Fig. 6. Comparison of best scenarios.

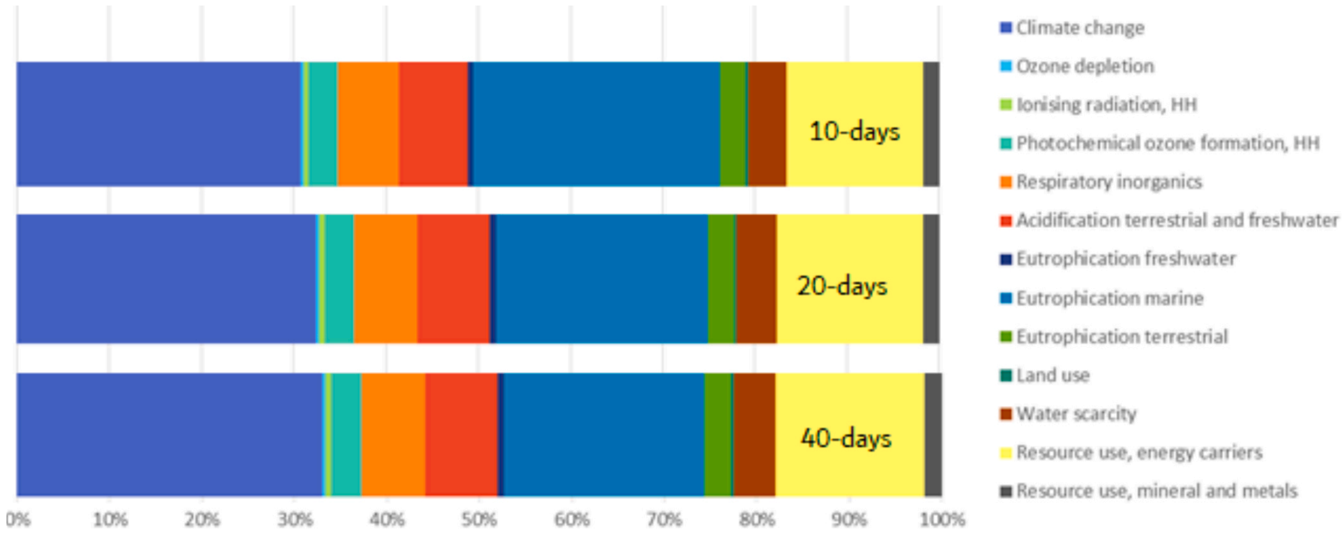

Fig. 7. Most relevant impact categories for HTC-based integrated scenario.

costs of the two systems (€8,117,664 per year for the baseline scenario versus €5,084,522 per year for the HTC-based scenario) a notable difference of €3,003,142 per year emerged. This highlighted the cost-effectiveness of the HTC approach. Additionally, an analysis based on the functional unit (1 m^3 of treated wastewater) indicated that the cost for the baseline scenario was €0.1045/m^3 and €0.0628/m^3 for the HTC-based integrated system. Comparatively, considering 77,634,405 m^3 treated wastewater in one year, the cost analysis revealed an economic saving of about 37 % for the HTC-integrated scenario. This cost saving reduced the investment payback time for the HTC-process to only 2 years and 10 months.

In order to assess the current value of the costs, a discount rate of 3.5 % and an annual increase rate of 2.4 % were considered, over the 20-year time span. We obtained the present value of the costs by discounting the annual expenses projected over these two decades. Table 5 of the Supplementary Material shows the comparison of both the alternative systems based on the present value. The comparison indicated that the baseline scenario was relatively expensive, mainly because of the higher costs linked to sludge disposal and recovery. Specifically, the total discounted life cycle costs were 0.095 €/m^3 and 0.057 €/m^3 for the baseline scenario and the HTC-integrated scenario, respectively. This reflected a cost reduction of about 39 % for the HTC-based scenario. Overall, the results favored the HTC- integrated scenario, as it presented a lower long-term costs than the baseline scenario.

The economic analysis further incorporated the ELCC that was based on the indirect environmental costs. Table 6 and Fig. 8 show a comparative analysis of both the systems (baseline and HTC-integrated scenarios), These environmental costs reflect the cost of damages inflicted by the environmental impacts, which require subsequent financial investments necessary to mitigate these impacts or damages and restore the environment to a sustainable threshold.

In order to illustrate and compare the cost of environmental damages, we use an example of the climate change category. The results (see Table 6 and Fig. 8) indicated that the systems could offset the

Table 5
Comparison of systems based on conventional economic analysis.

No.	Cost Category	Baseline Scenario	HTC-Integrated Scenario
01	HTC plant integration costs	0	425,000[a] €/year
02	HTC system maintenance costs	0	255,000 €/year
03	Operating costs (energy and chemicals)	5,181,881 €/year	4,369,068 €/year
04	Waste disposal/recovery costs	2,935,783[b] €/year	35,454[c] €/year
05	Revenues from HTC (sale of hydrochar, etc.)	0	206,521 €/year
06	Costs for total m^3 of treated wastewater per year	8,117,664 €/year	4,878,000 €/year
07	Costs per 1 m^3 (UF) of treated wastewater	0.1046 €/m^3	0.0628 €/m^3
08	Cost delta Integrated scenario/base scenario	−3,033,143 €/year −0.0417 €/m^3 −37 %	
09	Time to payback investment HTC integration	2 years 10 months	

Table 6
Comparison based on the indirect environmental costs (ELCC results) per FU.

No.	Impact category	Unit cost (IPCC)	Indirect cost of baseline scenario	Indirect cost of HTC integrated scenario
01	Climate change	0.135 €/ kg CO_2eq	0.073 €/m^3	0.061 €/ m^3
02	Eutrophication	3.90 €/ kg PO43-eq.	0.023 €/ m^3	0.025 €/ m^3
03	Acidification	8.25 €/ kg SO_2eq.	0.021 €/ m^3	0.017 €/ m^3
04	Photochemical ozone formation	9.70 €/ kg C2H4eq	0.008 €/ m^3	0.001 €/ m^3

environmental damages caused by emissions by investing €0.073/m^3 in the baseline scenario and €0.061/m^3 in the HTC-integrated scenario. Moreover, a comparison of the indirect environmental costs, as indicated by the ELCC results, reveals that the baseline scenario incurs higher costs related to damages from climate change, acidification, and photochemical ozone formation compared to the HTC-integrated scenario.

5. Conclusions

A significant amount of sludge generated from WWT systems is either incinerated or applied to agricultural land, leading to a range of complex environmental and social-economic problems. This study introduces an innovative circular model for WWT and ST system that enables the recovery and enhancement of biological sludge by transforming it into hydrochar and other valuable products. Furthermore, this research presents a detailed analysis of environmental impacts along with techno-economic feasibility of a new HTC-based ST technology integrated within a WWT plant. Overall, the study is based on two systems (baseline and HTC-integrated scenarios) of analysis, each evaluating three alternative strategies based on sludge aging: 40-days, 20-days and 10-days. The baseline scenario consisted of existing WWT and ST system for an urban municipality in Italy. In contrast, the integrated scenario incorporated the baseline system with HTC technology.

The results of the environmental impact assessment showed that overall, waterlines accounted for over 70 % of the impacts across nearly all environmental categories when compared to sludge lines. This significant contribution was mainly because of the use of aluminum polychloride and energy consumption. Due to better material and energy efficiency, the HTC-integrated system demonstrated superior environmental performance than the baseline scenario. Among the various alternatives evaluated, the HTC-integrated scenario utilizing a 10-day sludge age emerged as the most optimal option. Overall, the WWT and ST systems showed the most substantial negative impacts on the categories of climate change, depletion of fossil resources and acidification.

Unlike most LCC studies reported in the literature, this research conducted an extensive economic analysis based on the CLCC and the ELCC, including both the direct costs and indirect costs (environmental externalities). Additionally, the analysis also included assessments of payback periods and present value calculations. The most favorable alternative scenarios based on their environmental performance, for both the baseline and HTC-integrated scenarios were further evaluated from an economic standpoint. The results revealed that in the baseline scenario, the most significant costs were related to sludge disposal. Overall, the baseline scenario incurred costs approximately 37 % (€3,003,142/year) higher than the HTC-integrated system.

The HTC-based scenario not only reduced the energy and disposal costs but also provided a potential revenue stream through the sale of products recovered from the sludge. For every cubic meter (1 m^3) of treated wastewater, the costs associated with the baseline scenario and the HTC-integrated system were €0.1045 and €0.0628, respectively. The

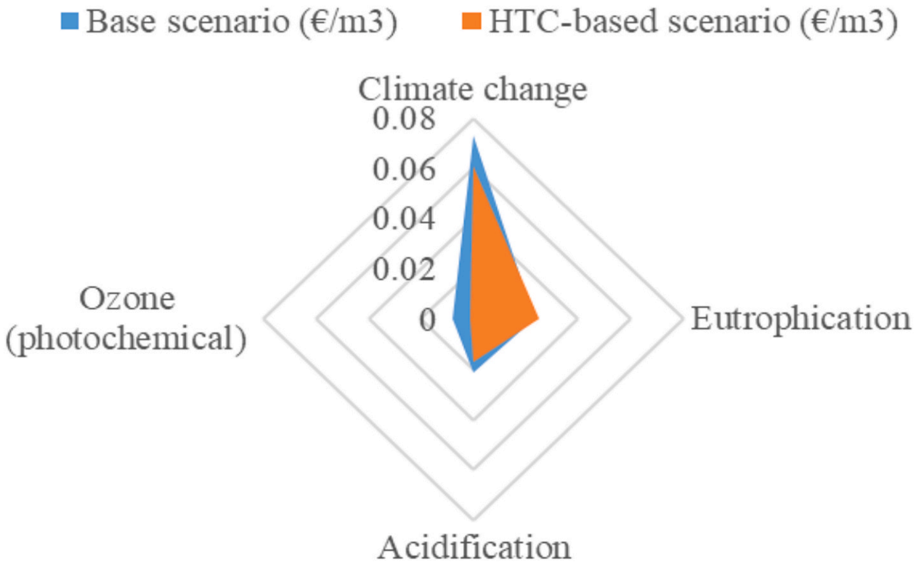

Fig. 8. Comparison based on indirect cost analysis (environmental externalities).

investment payback period for the HTC system was an impressive 2 years and 10 months. In terms of environmental externalities, the cost of environmental damages was found to be €0.073/m^3 for the baseline scenario and €0.061/m^3 for the HTC-based integrated approach.

In conclusion, this study provides detailed answers to various pertinent questions of scientists, researchers, economists, and politicians who increasingly recognize the challenges posed by wastewater, water pollution and sludge management, at both national, or international levels. The findings provide vital technical support for policymakers seeking to apply CE models in wastewater and sludge management, with an aim to redesign them for energy efficiency, net-zero objectives, environmental sustainability and economic benefits. Moreover, the results also highlight the utility of LCA and LCC approaches to support decision-making while implementing CE principles for WWT and sludge management. These approaches facilitate the evaluation of various lifecycle phases and alternative scenarios, ensuring informed choices.

In order to further strengthen and validate the findings of this study, future research could explore data from other plants and countries. This would contribute to a more robust understanding of the findings' accuracy and generalizability. Evaluating the social impacts of CE models in wastewater and/or sludge management should also be considered in subsequent studies, as it is essential to create a holistic view of the benefits and challenges associated with these approaches.

CRediT authorship contribution statement

Shamraiz Ahmad: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Tiberio Daddi:** Writing – review & editing, Supervision, Resources, Project administration, Conceptualization. **Alessio Novi:** Writing – review & editing, Project administration, Formal analysis, Conceptualization. **Luca Marrucci:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cie.2025.111035.

Data availability

Data will be made available on request.

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