



Wastewater recovery for sustainable agricultural systems in the circular economy – A systematic literature review of Life Cycle Assessments

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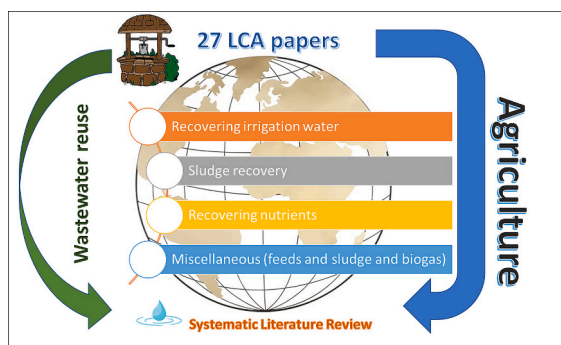
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HIGHLIGHTS

- A review of the LCAs in the field on agriculture wastewater reuse was carried out.
- Recovering irrigation water was investigated.
- Sludge production from wastewater recovery was analysed.
- Recovering nutrients from wastewater reuse was investigated.
- LCA resulted as a valid tool for assessment/improvement wastewater recovery.

GRAPHICAL ABSTRACT



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ABSTRACT

Water availability and quality are known to affect agricultural production and nutrition. The aim of this study was to elaborate a systematic literature review of the most sustainable ways of wastewater treatment towards achieving circular economy (CE) in agro-industry activities. From the SLR, the authors selected twenty-seven papers that they classified into the three research themes of recovery of wastewater into irrigation water, extraction of sludge for production of bio-based compounds, and recovery of nutrients for soil amendment, including recovering of feeds for aquaculture, and recovery of nutrient biosolids for soil amendment. Results underlined that the recovery of nutrients biosolids for soil amendment can generate a GWP gain up to - 37 kg CO₂-eq. So, the review highlighted that wastewater recovery for multiple purposes can be truly effective for the environmental sustainability of agricultural systems, and that LCA is a valid tool to assess and improve that sustainability. Under this perspective, this SLR's findings can stimulate public administrations at national and local scales in their planning and funding activities towards implementing circular bioeconomy paths based upon wastewater recovery for a sustainable, resilient agriculture. Overall, the authors believe that their article was effective in overviewing the current wastewater recovery paths in the CE context, and in highlighting key methodological aspects and findings of the reviewed LCAs, to advance the specialised literature and knowledge, and to guide practitioners for future LCA applications in the field.

Finally, through its main findings, the article effectively contributes to the whole research project which it is part of and which the authors are deeply involved in. That research is performed under the Progetto GRINS

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1. Introduction

Agriculture is proven to contribute to human health and prosperity: 60 % of the food consumed globally is in fact produced from crop cultivation (Zhou et al., 2023). In spite of this, agriculture is responsible for major environmental impacts that include resource consumption and global warming (Ingrao et al., 2015). The global population is projected to grow from 8 billion in 2022 up to 10 billion in 2050, according to the latest report released by the United Nations' information centre (UN, 2020). Such will lead to increasing the demand for food in the following decades, which is expected to put more pressure on water, land and other inputs for food production, whilst climate change is likely to pose increasing challenges to agricultural production (Ingrao et al., 2015).

Globally, agriculture and foods are two of the sectors that most largely contribute to land use (50 % of world's habitable lands), water (80 % of global water consumption), energy consumption (4 % of the annual available energy), and to the emission of greenhouse gases (18 % of the global emissions) (Crovella et al., 2022). This should be attributed mainly to the production and application of chemical fertilisers and pesticides, and to the production and combustion of fossil fuels for farming activities. Alarming impacts are then reflected upon climate change, over-exploitation of soils and fossil primary-energy resources, and loss of human health and ecosystem quality (Crovella et al., 2022). Particularly, it was documented that, in the period 1991–2022, agriculture along with livestock breeding accounted for 72–83 % of the total water consumption, thereby representing one important environmental stressor (Zhou et al., 2023). So, it emerges that agricultural production is highly dependent upon freshwater consumption, and is increasingly subjected to water risks, like those related to water stress and pollution (Ingrao et al., 2023).

Under this perspective, considering its vital role, improving water management is essential for contributing to sustainable agricultural and food production systems, whilst mitigating the risk of water stress and pollution (OECD, 2023).

Freshwater resources continue, however, to decline, also due to climate change, groundwater pollution and salinization (Kalboussi et al., 2022). This is mainly because climate change is one of today's global concerns that alters rainfall patterns and make extreme climate events increasingly frequent and characterised by long periods of drought and flood (Harris et al., 2020; Ercin et al., 2019). Those events contribute to reducing water availability and quality, and the capacity of ecosystem services to supply water to humans to meet their needs (Borsato et al., 2018).

Hence, it can be asserted that there is increasing water scarcity, due to the combined effect of climate change and the unstoppable rise in freshwater requirements for producing foods and feeds, developing industrial processes, and sustaining urban and rural populations' needs (Hoekstra et al., 2012). Climate change is recognised today as one of the largest global concerns, as it alters precipitation patterns and makes extreme climate events increasingly frequent and severe: the result of this is extreme periods of droughts and floods (Ingrao et al., 2023). Those events have negative effects upon water availability and water quality, and cause reduction of the capacity of ecosystems to provide adequate supplies of water to fulfil human needs, including those for agriculture and food production (Ingrao et al., 2023).

Consequently, there is the problematic difficulty of satisfying the demand for water for daily life, and for economic and industrial activities (Huang et al., 2023). In particular, water scarcity negatively affects agriculture leading to a reduction in crop yields and agricultural production (Huang et al., 2023; Mekonnen and Hoekstra, 2016; Porkka et al., 2016). Currently, 97 % of water is found in the oceans, 3 % is

freshwater, 2.5 % of which is not available because it is unreachable and located in glaciers, polar ice caps, atmosphere or highly polluted (USBR, 2023). So, it is understood that, only 0.5 % of freshwater is available mainly in the form of groundwater for humans and their activities (Ingrao et al., 2023; USBR, 2023). For this reason, recovering wastewater could be one of the solutions to overcome the shortage of water resources. Additionally, future climate change could affect water scarcity by increasing water availability due to melting of snow and glaciers which however will also devastate the arctic and mountain ecosystem (Huang et al., 2023).

Such puts emphasis upon the urgent need of transitioning towards sustainable agricultural and food-production systems, that imply reduced consumption of freshwater resources compared with the conventional ones that have been carried out thus far (van der Werf et al., 2014; Pellegrini et al., 2016). Modern crop cultivation systems should, indeed, be developed based upon strategies for a more environment-friendly and consumer-oriented agriculture (Lo Giudice et al., 2014; Ingrao et al., 2019). In the field of agricultural water management, that would be achievable through the adoption of water-conservation oriented practices, including the treatment of wastewater to obtain water usable for irrigation purposes (Pellegrini et al., 2016). In doing so, this paper's authors recommend, however, to take care in preserving soil quality, as well as the yield, quality, and safety of agro-foods, whilst making sure that the next generations will also have water to produce foods, fibres, nutrients, and other bio-based materials to responsibly, equitably satisfy their needs (Pellegrini et al., 2016).

In this context, the design and management of sustainable supply chains that enable freshwater resource preservation has emerged as a major challenge in the corporate and policy agenda (Aivazidou et al., 2016). The sixth Sustainable Development Goal (SDG #6) targets, in fact, improvements of water quality, increases in water-use efficiency, and reductions of water degradation and scarcity on the global scale.

Under this perspective, water footprint assessments in agriculture are particularly needed to support the implementation of sustainable circular bioeconomy paths that enable preserving water resource quality and availability (Crovella et al., 2022). This is particularly relevant in regions like the Mediterranean one that, for most of its extension, grow under high and extremely-high water stress conditions, and often go through long periods of droughts that end up limiting water withdrawals. The increased water demand and degradation, mainly because of urbanisation, agriculture intensification, and climate change have become, in fact, a major concern in that region (Saraiva et al., 2020a, 2020b). This remarks the importance of finding tools to assess and monitor water resource exploitation and pollution in agro-food systems and its damage to human health, resources, and ecosystem quality, as the starting point to find sustainable, effective mitigation solutions (Pfister et al., 2009; Pellegrini et al., 2016). To this end, one effective way to save freshwater and to address the current and likely future water-scarcity problems could be that of wastewater recovery in a circular economy (CE) context (Maesele and Roux, 2021). As a matter of fact, the CE addresses the ways to reuse, repair, and recycle items, thus reducing waste and, overall, enhancing the sustainability level of manufacturing and consumption systems, according to sustainable development and its principle. In addition to this, the CE approach contributes to saving energy and to avoiding irreversible environmental damages coming from resource extraction and usage at a replenishment-exceeding rate (Wojnarowska et al., 2022). Such is valid also in the field of water resource management, as water has a global natural hydrological cycle, which leads to the CE of wastewater being considerable, in fact, as the CE of water. Under this perspective, in the CE, water is used efficiently and its losses are minimized. Additionally, the substances

dissolved in the water during its use and the bounded energy can be recovered and recirculated. To that end, it is desirable that less fresh water is used, and upstream water is reused. When wastewater is more concentrated, nutrients and materials can be recovered, which makes it possible to reduce the size of the treatment plants. When all contained valuables are collected, wastewater can be treated into water that can be re-used for agricultural, industrial and, even domestic purposes (Bruun-van Bergen et al., 2020). The thermal energy recovered from wastewater could be utilised for district heating/cooling, agricultural greenhouses, and even for drying dewatered sludge (Hao et al., 2020).

Assessments are needed, however, to identify the actions that need to be taken to make sure that agricultural wastewater management and recovery is performed in compliance with the principles of a sustainable circular bioeconomy. The way the authors see it is that Life Cycle Assessment (LCA) can make a relevant contribution in that regard, as it provides a multi-criteria scientifically-based approach to assess the environmental performance of a product or a service throughout its life cycle (Cascone et al., 2020). In addition to this, the literature has documented it to be a perfect complement to the idea of a CE, in order to make it holistically sustainable, by: measuring the environmental performance of various product and supply chain configurations; comparing circular strategies; and ensuring positive environmental balances from the design of new circular products or services (Vegter et al., 2023).

In this context, considering its relevance for a sustainable circular agriculture, a systematic literature review (SLR) of LCAs of wastewater treatment (WWT) systems was performed and presented in this article. The SLR was conducted according to the PRISMA model (Page et al., 2021), and was aimed at overviewing the current and likely-future valorisation paths of wastewater in the agricultural field, to obtain reusable water, value-added bio-based materials, and energy, according to previously-published literature like Bruun-van Bergen et al. (2020) and Hao et al. (2020). The SLR was applied because, according to Snyder (2019), Page et al. (2021), and Scrucca et al. (2023), it provides an explicit, rigorous, and reproducible design from which to “identify, assess and interpret the existing large body of completed and recorded work from researchers, scholars, and practitioners”.

Under this perspective, the SLR is expected to deliver useful insights on:

- wastewater recovery strategies in the context of a sustainable CE;
- key methodological aspects related to LCA application; and
- the improvements that can be made for enhanced sustainability of agricultural systems.

Those insights can be useful to academics, professionals, scholars, farmers, producers and other stakeholders to develop LCA-based research on wastewater recovery in agriculture. Doing so will make it possible for the authors to stimulate promotion of sustainability-oriented strategies to achieve a circular economy in those two sectors.

Finally, the development of this review study, as well as the writing of this document, were done through the phases depicted in Fig. 1.

2. Research needs and review development methodology

Consistently with the aim and scope of this paper, this section was conceived by the authors with the aim of reviewing and building upon previously-published review papers on the subject of treated wastewater reuse in the agricultural sector. The reason for this was to describe the research needs, by highlighting what has been done thus far in such a research field, and how that can be integrated and improved by this study. To do so, the authors launched the bibliographical search using pre-determined keyword sets and, from the ensemble of records identified, extrapolated just review papers.

With regard to the keywords used, the authors selected those that could best represent the research theme and the aim and scope of this study, so as to locate the highest number possible of scientific contributions in the field. To achieve a high scientific impact for this SLR development, those keywords were queried on Scopus and Web of Science (WoS), as those are widely acknowledged as the most comprehensive databases of peer-reviewed literature, that store the broadest range of scientific papers (Do et al., 2021; Zingale et al., 2022). In addition to this, there are lots of journals in those databases, that are in fields connected with this paper's research area, namely ‘*Environmental Science*’, ‘*Commodity Science*’, and ‘*Engineering*’.

As a standard practice when conducting SLRs (Do et al., 2021; Zingale et al., 2022), the authors merged those two databases to increase the probability of detecting all the relevant contributions in the field, and to provide a high level of rigor in the paper selection process.

To identify relevant papers, the authors made Boolean searches, by combining keywords with operators, such as ‘AND’, to further produce more relevant results. In particular, the search queries shown in Fig. 2 were used in combination with agricultural-sector representative keywords, including “agriculture”, “crop production”, and “crop farming”, using an ‘OR’ Boolean operator.

A total of 157 unscreened records were found, twenty-two of which were review papers: the latter were screened and reviewed by this team of authors. In addition to this, they were summarised in Table 1, in terms of aim and scope, methodological approach, and contributions to the literature. Doing so made it for possible for the authors to have a complete and exhaustive picture of what has been done thus far in terms of previously-published state-of-the-art analyses, and how that can be integrated by the here-presented review. In this way, the authors could notice a first gap in the subject literature, that is, only one of the reviews detected is a SLR, namely Morris et al.'s (2017). According to the authors, this can be motivated by SLR being a relatively-new and more complex form of a literature review, which makes it difficult to be performed.

A second gap stays in the fact that all of those twenty-two review articles just looked into single aspects of wastewater management and

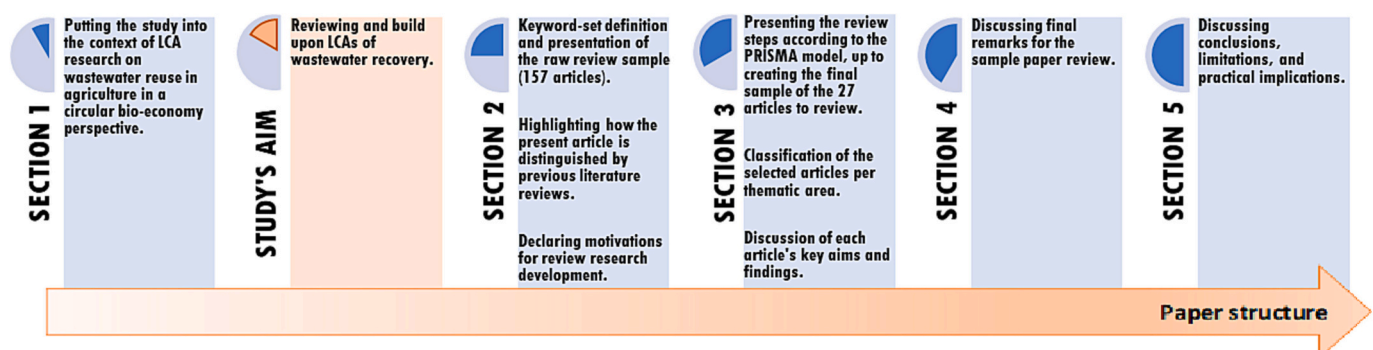


Fig. 1. The figure depicts the five phases in which this review article has been broken down into, and its aim and scope.

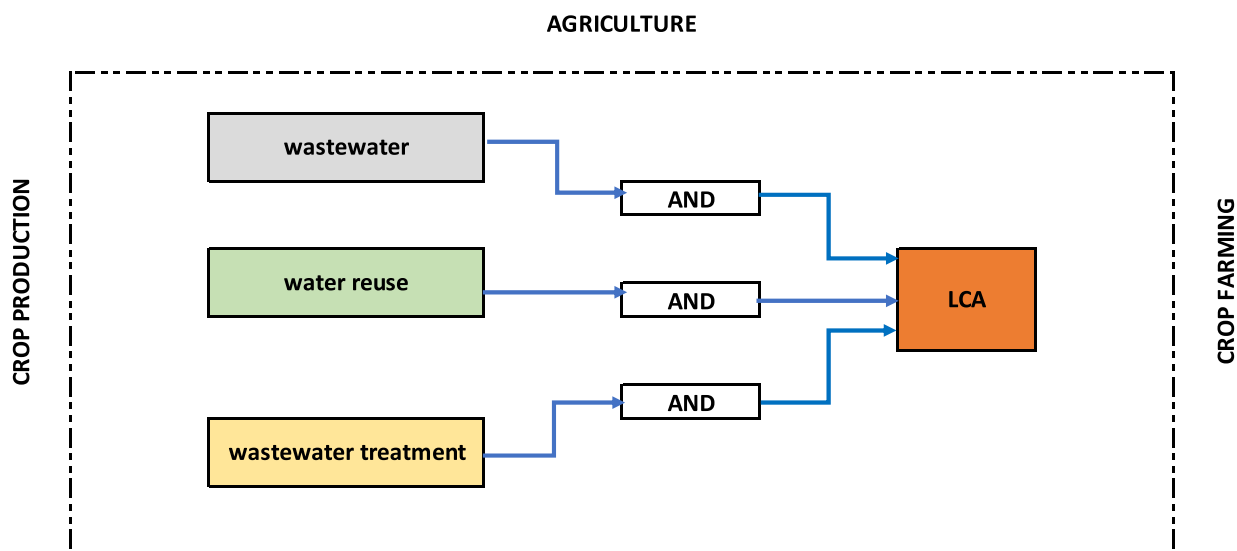


Fig. 2. Keyword combinations used for this SLR development.

recovery in agriculture, though all of them have made remarkable contributions to the literature from the perspective of technology, methodology, regulations, and sustainability.

Under this perspective, the authors wish to fill the aforementioned gaps, through their SLR of a wide range of agricultural wastewater recovery systems with a holistic, integrated, and systematic approach.

This is one key distinctive aspect of the novelty of the paper and of the relevant contribution it can make to the literature upon publication, to explore the relevant circular economy paths in the field of wastewater recovery for agricultural applications.

3. Review of LCAs on wastewater recovery in agriculture: development procedure

In this section, the authors reported the findings from a SLR of the LCA-based literature on wastewater recovery in agriculture, which means that other sectors, including food industries, processing, preparation, distribution, and so on, were not considered.

The authors used the following set of screening criteria, to be able to get to a review sample that was consistent with the aim and scope of this study, and representative of the research area investigated:

1. An initial raw review sample of 157 papers was formed from the search of the aforementioned keywords in Scopus and WoS;
2. Double-count of papers covered by both databases was avoided, by removing the existing duplicates.
3. From such a refined sample, the authors removed the twenty-two review papers previously analysed to highlight the research needs and the novelty of this SLR;
4. Only peer-reviewed articles written in English were considered;
5. Papers published in book chapters and conference proceedings were not reviewed because they are known not to be easily downloadable from databases;
6. The authors carried out an initial screening of the articles by analysing the title and abstract, to better understand the related topics addressed and the adherence to the objectives of this review;
7. The articles meeting the criteria at points 3) and 5) were selected, and the authors analysed in-depth the relative full texts
8. The authors scanned through the reference lists of the articles at point 7), to check whether other articles could have been added to the final review sample, but they found none of those.

Those criteria were followed duly, so that the review sample created

at point 7) was:

- consistent with the aim and scope of this study;
- representative of the literature currently available on the sustainable-agriculture related subject;
- effective in creating a comprehensive overview of LCA applications of sustainable agricultural wastewater recovery into value-added products, including bio-based nutrients, irrigation water, and feed for aquaculture; and
- such to highlight the benefits of applying the circular (bio-)economy principles for the greening of wastewater recovery in agriculture.

In Fig. 3, the authors depicted all the screening steps that, from record identification, led to obtaining the paper sample object of this review paper.

Through application of the aforementioned criteria, out of the 157 initially detected, 27 articles remained in total at the end of the process of identification, screening and evaluation, and so have formed the review sample that is this SLR's focus. For the reader's convenience and for completeness of this review article, they were listed in Table 2.

The twenty-seven manuscripts were published between 2002 and 2022: Fig. 4 shows the percentage distribution per publication year. In particular, from the review of the sample papers, the following wastewater treatment applications were identified:

- recovery of wastewater into irrigation water (26 %);
- extraction of sludge for production of bio-based compounds (33.5 %);
- recovery of nutrient biosolids for soil amendment (40.5 %).

In Table 3, the twenty-seven papers forming the review sample were assigned the related the three thematic areas.

Consistently with the SLR reporting framework, Fig. 5 was incorporated to show the number of yearly publications was associated the research themes addressed. Aside from 2018, an upsurge in interest on the subject can be observed in the period 2016–2022 compared with the previous years.

Most of the review-sample papers were published in 'Science of the Total Environment' (STOTEN) and 'Journal of Cleaner Production' (JCLP) covering a total of 54.54 %, as can be seen in Table 2 and Fig. 6. The authors believe that such a finding confirms the dominating role of those journals in the field of LCA-applications to management and treatment systems of wastes and wastewaters. So, consistently with the specialised

Table 1
Summary of the twenty-two reviews found, which the one presented in this article wishes to differentiate from.

Number	Authors (year of publication)	Aim and scope	Methodological approach	Contribution to the literature
1	Plappally and Lienhard, 2012	Assessment of the energy intensity required for water use and treatment in the municipal and agricultural sector.	In-depth review for elaborating a report surveys of the available literature.	Quantification of energy needed for water production, and wastewater recovery.
2	Cieslik et al., 2015	Critical and technical discussion on legal aspects related to the most allowable concentration of contaminants and critical parameters in sewage sludge management.	Critical review of standards, regulations and analytical methods, related to raw and processed sewage sludge management systems.	Presentation of the most common methods for the sewage sludge management, including land reclamation and adaptation to specific needs.
3	Heimersson et al., 2016	Identification of practices and limitations in the selection and quantification of nitrogen-, phosphorus-, and carbon-containing wastewater flows.	Literature review of 62 studies on wastewater and sludge management operations for classifying and inventorying the alongside flows.	Evidence of connection of LCA results and the inventory data of wastewater and sludge treatment.
4	Faubert et al., 2016	Description of the current and emerging pulp and paper mill sludge management practices alternatives to landfilling. Evidence of the crucial need for GHG emission assessments.	Critical review on pulp and paper mill sludge management practices	Assessment of greenhouse gas emissions.
5	Dennehy et al., 2017	Highlighting the main research gaps in the literature on the effects of dry anaerobic digestion to net GHG emissions.	Review of the currently available literature	Assessment of GHG emissions and mitigation potential of a range of common pig-manure management practices.
6	Morris et al., 2017	Classification of the soil benefits of management method and identification of harmonized climate impacts per kg of food waste	Systematic literature review on 147 LCAs for selecting a subset providing enough data and transparency to facilitate harmonization.	Ranking management methods for harmonized climate impacts based on soil productivity and quality.
7	Qambrani et al., 2017	Analysis of pyrolysis and reuse in agriculture to reduce GHG emissions.	Literature review of studies on quality-biochar production, and applications	Presentation of a wide range of techniques, properties and applications for biochar. Highlights of different pyrolysis conditions and raw materials that influence quantity and quality of biochar.
8	Chang et al., 2018	Reviewing and building upon water quantity, quality, and sustainability.	Literature review of papers published in the year 2018.	A comprehensive overview of the relevant issues of water quantity, quality and sustainability.
9	Sena and Hicks, 2018	Evaluation of the environmental impacts of wastewater treatment operations and struvite extraction from wastewater.	Review of literature LCAs	Presentation of two scenario of struvite extraction: precipitation and source separation.
10	Finnegan et al., 2018	Evaluation of the impact of the cheese production under several conditions of water reuse.	State-of-the-art analysis of 16 LCAs on the environmental impact of cheese production.	Building a Life Cycle Inventory and Life Cycle Impact Assessment of cheese production in USA, Canada and some EU countries.
11	Aleisa and Alshayji, 2019	Assessment of types, quantities of treated and reused water, future plans, challenges, costs and fees for better use of treated effluent.	General review of Kuwait current treatment and reuse practices of domestic wastewater.	Recommendations to improve wastewater treatment, alleviate stress on scarce groundwater resources and provide alternative to desalination process.
12	Collivignarelli et al., 2019	Exploring the application of biosolids on land, as a soil improver/fertiliser for agriculture and for abandoned mining sites	Comprehensive review on 250 papers, reviews, books and conference proceedings	Highlighting environmental aspects related to the possible reuse of biosolids and related technical-engineering and health aspects.
13	Lam et al., 2020	Analysing general insights, methodological practices and providing future outlooks of using LCA to assess wastewater-based nutrient recycling.	Critical review of 65 LCAs related to nutrient recycling from wastewater.	Guiding practitioners to the optimal use of LCA to provide quality environmental information on decision making related to the planning and implementation of wastewater-based nutrient recycling.
14	Garba et al., 2020	Provide a review on different procedures employed in the preparation, characterisation and application of perovskite NPs as adsorbents in wastewater treatment.	Literature review on the processes involved in perovskites preparation and potential applications in wastewater treatment.	In-depth state-of-art on perovskites: properties and applications, different preparation methods, characterisation, current applications as adsorbents.
15	Hao et al., 2020	Comparison between direct incineration and conventional anaerobic digestion (with or without pre-treatment) for sludge management.	Making waves papers for carrying out a comparison.	Direct incineration after sludge drying consumes less energy and has lower costs than conventional anaerobic digestion.
16	Maesele and Roux, 2021	Analysis of the environmental efficiency of wastewater reuse.	Review of 30 LCAs (excluding grey literature) on the eco-efficiency of WW-reuse considering arid and semi-arid areas.	Development of a homogeneous conceptual framework to evaluate the environmental efficiency of wastewater reuse with a standardized reference system for water supply at local level.
17	Jama-Rodzenska et al., 2021	Analysis of wastewater derivatives, treatment processes, pre-treatment for the production of struvite based on the circular economy.	Mini-review on sewage sludge and struvite.	Presentation of operating technologies and installations to obtain high purity, certified fertiliser for use in agriculture.
18	Singh, 2021	Investigation of wastewater for crop irrigation and environmental impact on human and animal health linked to wastewater irrigation and climate.	General review of LCAs focussed on pathogens associated in wastewater reuse.	Detailed data on environmental impacts of wastewater irrigation on soil and plant.
19	Alazaiza et al., 2022	Examination of potential role of algae and reuse as biomass for bioenergy and bioactive compounds for the production of sustainable biofuels.	General review of techno-economic and environmental LCA of biofuels/ bioproducts from microalgae biomass.	Presentation of several opportunities of wastewater reuse in agriculture, petrochemical plants and biofuel production.
20	Wang et al., 2022	Evaluation of environmental impacts of using products recovered from urban water resource reclamation facilities in a sustainable urban agriculture context.	Literature review of LCAs of wastewater resource recovery facilities.	New reflection points for improving the quality of the purified water used, reusing biosolids as fertilisers, soil improvers and additives for building materials.
21	Morin-Crini et al., 2022	Analysis of contamination in wastewater in China, Portugal, Mexico, Colombia, and Brazil.	Review of best practices of water contamination by emerging pollutants.	Description of emerging contaminants present in water resources around the world and especially in China, Portugal, Mexico, Colombia and Brazil (pharmaceuticals, hormones, cosmetics, antibiotic-resistant bacteria and parasites and pesticides).

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Table 1 (continued)

Number	Authors (year of publication)	Aim and scope	Methodological approach	Contribution to the literature
22	Deng et al., 2023	Analysis of the state-of-the-art microbial electrochemical technologies, microbial fuel cells, microbial electrolysis cells and microbial recycling cells for energy generation and nutrient recovery from wastewater.	Comparative review of LCAs on energy generation, nutrient recovery, and pollutant removal capabilities.	Insights for successful development and implementation of METs for resource recovery from wastewater.

literature, the authors decided to contribute this review paper to STOTEN, as they thought it was in line with the journal's aim and scope, and subject areas, and could contribute to enhancing the journal's literature.

The papers classified in Table 3 were reviewed and built upon in terms of their key objectives and findings, highlighting the multiple contributions those have done to the advancement of the specialised literature and knowledge.

4. Discussions of the sample articles' objectives and findings

4.1. Recovering irrigation water

This section was aimed at reviewing papers that evaluated the recovery of wastewater for crop irrigation, and included seven out of the twenty-seven papers composing the review sample (Table 4).

The first article on this research subject was elaborated by Miller-Robbie et al. (2017), and was aimed at assessing the most relevant impacts of wastewater treatment into water usable for irrigation purposes, in Indian urban agriculture. To that end, they carried out a comparative LCA of 1 l wastewater, between its uncontrolled release into a riverine water body and its treatment with reuse.

Through their study, the authors documented an average reduction of 33 % in GHGs, and up to 99 % for energy demand comparing to the baseline scenario (uncontrolled release).

In another study, Pan et al. (2019) analysed the environmental impacts of 1m³ wastewater recovery for crop irrigation, through a combination of scenarios (i.e. DSE - diverting secondary effluents; RES – retrofitting existing systems, CRF – customizing reclamation water) using LCA. Moreover, through the Monte Carlo simulation, they performed the uncertainty analysis in LCA to observe variations in impacts due to the implementation of several concentrations of wastewater. Results obtained through the LCA underlined that the potential recovery of crop irrigation water resources from wastewater increases by about 30 % when using DSE instead of more sophisticated RES and CRF. Moreover, the authors highlighted that the largest impacts are due to electricity-intensive processes, in terms of fossil fuel consumption and GHG emissions. Wastewater recovery was documented, however, by Pan et al. (2019) as compensating the negative impacts that are due to the consumption of energy and chemicals for contaminant removal: those impacts include mineral depletion, global warming, ozone layer depletion, eco-toxicity and human health risks.

In line with the previous articles' authors, Arzate et al. (2019) documented that reusing treated wastewater for irrigation/fertigation in urban agricultural systems can have a determining effect in enhance environmental sustainability of urban areas. In their valuable work, Arzate et al. (2019) compared several scenarios of tertiary water treatment options based on ozonisation of municipal wastewater and Photo-Fenton, for the removal of micro-pollutants in wastewater. The results highlighted that the reuse of treated wastewater reduces local water scarcity and increases the benefits of quality of the natural ecosystem and human health. Particularly, the environmental impacts related to the ozonisation process contributed to environmental impact reduction, by 37 % compared to the baseline scenario without disinfection treatment. Moreover, in this way, the use of organic membranes in photo-degradation and photocatalysis processes also represents a highly innovative and circular technology since they are reusable after a simple

wash. Particularly, this technology represents a capable of treating wastewater with a dual sustainable process (washable membranes and water treated with solar energy) (Crovella and Paiano, 2023).

Finally, Moretti et al. (2019) performed LCA to determine the environmental sound of water reuse for nectarine orchard irrigation. To that end, they carried out a comparative evaluation between treated municipal wastewater and surface water, by using a unique experimental dataset. Results from the study of Moretti et al. (2019) showed that treated-wastewater used to irrigate nectarine orchards scores better value of eutrophication than that irrigated by surface-water based one. Particularly, the irrigation by surface water determines remarkable impacts on climate change and toxicity, thus affecting the environmental profile of water reuse (Moretti et al., 2019).

Building upon previously-published research, Snehal and Sameer (2020) explored the most relevant environmental and economic issues associated with 1m³ wastewater treatment in India and, for that purpose, used LCA. Two plants were compared by the authors in their study: Decentralised On-Site Integrated Waste Management (DOSIWAM) vs. activated sludge process (ASP). Results underlined that the ASP scenario generates environmental impacts from 30 to 60 % higher than the DOSIWAM mainly due to energy and chemical consumption.

In another study, Canaj et al. (2021) applied LCA to determine the monetary costs and environmental impacts of wastewater recovery into irrigation water. Results showed that the related cost of treatment of wastewater for reuse were higher than those compared to the baseline scenario. Particularly, global warming potential (GWP) influenced costs by 16 % in baseline scenario and 43.4 % in reuse scenario (Canaj et al., 2021). Therefore, the approach applied by Canaj et al. (2021) identified and quantified the environmental and economic trade-offs, previously unobserved in LCAs on agricultural wastewater reuse for irrigation purposes.

Generally, Kalboussi et al. (2022) through their study presented a decision support tool to facilitate the interpretation of the LCA results in the context of wastewater reuse. They evaluated the environmental efficiency of 1 ha vineyard irrigated by water reclamation in an experimental site in France with the aim of applying this decision tool and, comparing three alternative irrigation scenarios, namely UV disinfection, UF filtration, and chlorination (Kalboussi et al., 2022). Those three complex treatment technologies unfortunately increased environmental impacts compared to groundwater reuse or surface irrigation scenarios. In conclusion, the authors found the environmental results obtained for reclaimed water to be strictly dependent upon treatment technology, site of the treatment plant, and quality of the wastewater resources.

4.2. Extraction of sludge for the production of bio-based compounds

Wastewater recovery for production of sludge and biogas has been extensively analysed in the literature sample reviewed in this article.

The first article was conducted by Suh and Rousseaux (2002), and regarded a comparative LCA of five alternative treatment scenarios of

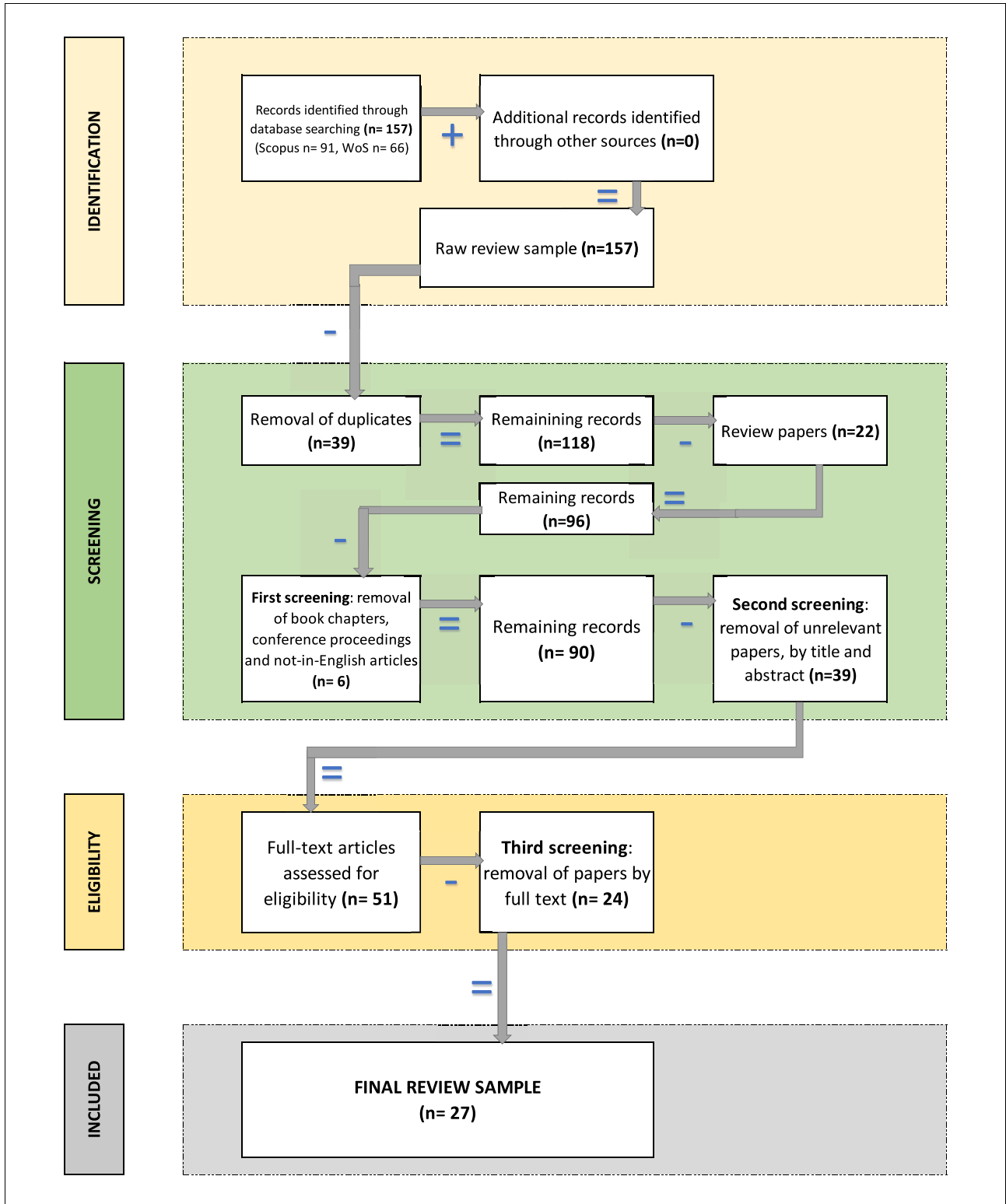


Fig. 3. SLR development steps, using Page et al. (2021).

Table 2
List of the 27 review-sample papers.

N.	Publication year	Authors' team	Article title
1	2002	Suh and Rousseaux	An LCA of alternative wastewater sludge treatment scenarios
2	2008	Muñoz et al.	Ranking potential impacts of priority and emerging pollutants in urban wastewater through life cycle impact assessment
3	2009	Hong et al.	Environmental and economic life cycle assessment for sewage sludge treatment processes in Japan
4	2014	Niero et al.	Comparative life cycle assessment of wastewater treatment in Denmark including sensitivity and uncertainty analysis
5	2016	Alvarez-Gaitan et al.	Towards a comprehensive greenhouse gas emissions inventory for biosolids
6	2016	Tomei et al.	Techno-economic and environmental assessment of upgrading alternatives for sludge stabilization in municipal wastewater treatment plants
7	2016	Fang et al.	Life cycle assessment as development and decision support tool for wastewater resource recovery technology
8	2017	Kjerstadius et al.	Carbon footprint of urban source separation for nutrient recovery
9	2017	Miller-Robbie et al.	Wastewater treatment and reuse in urban agriculture: Exploring the food, energy, water, and health nexus in Hyderabad, India
10	2017	Laitinen et al.	Resource efficient wastewater treatment in a developing area—Climate change impacts and economic feasibility
11	2017	Shiu et al.	Water reclamation and sludge recycling scenarios for sustainable resource management in a wastewater treatment plant in Kinmen islands, Taiwan
12	2018	Liu et al.	Diagnosis and evaluation of an early-stage green bio-sorption reactor by life cycle assessment
13	2019	Pan et al.	Characterisation of implementation limits and identification of optimization strategies for sustainable water resource recovery through life cycle impact analysis
14	2019	Arzate et al.	Environmental impacts of an advanced oxidation process as tertiary treatment in a wastewater treatment plant
15	2019	Moretti et al.	Modelling environmental impacts of treated municipal wastewater reuse for tree crops irrigation in the Mediterranean coastal region
16	2019	Do Amaral et al.	Sustainability assessment of sludge and biogas management in wastewater treatment plants using the LCA technique
17	2020	Snehal et al.	Environmental and economic assessment of proposed on-site wastewater management system in multi-storey residential building
18	2020	Ruff-Salís et al.	Can wastewater feed cities? Determining the feasibility and environmental burdens of struvite recovery and reuse for urban regions
19	2020	Wu et al.	Environmental life cycle comparisons of pig farming integrated with anaerobic digestion and algae-based wastewater treatment
20	2021	Aleisa et al.	Recirculating treated sewage sludge for agricultural use: Life cycle assessment for a circular economy
21	2021	Roman and Brennan	Coupling ecological wastewater treatment with the production of livestock feed and irrigation water provides net benefits to human health

Table 2 (continued)

N.	Publication year	Authors' team	Article title
22	2021	Foglia et al.	and the environment: A life cycle assessment Comparative life cycle environmental and economic assessment of anaerobic membrane bioreactor and disinfection for reclaimed water reuse in agricultural irrigation: A case study in Italy
23	2021	Canaj et al.	Life cycle-based evaluation of environmental impacts and external costs of treated wastewater reuse for irrigation: A case study in southern Italy
24	2022	Lima et al.	Resource-oriented sanitation: Identifying appropriate technologies and environmental gains by coupling Santiago software and life cycle assessment in a Brazilian case study
25	2022	Kalboussi et al.	Life cycle assessment as decision support tool for water reuse in agriculture irrigation
26	2022	Lam et al.	Life Cycle Environmental Impacts of Wastewater-Derived Phosphorus Products: An Agricultural End-User Perspective
27	2022	Estévez et al.	How decentralised treatment can contribute to the symbiosis between environmental protection and resource recovery

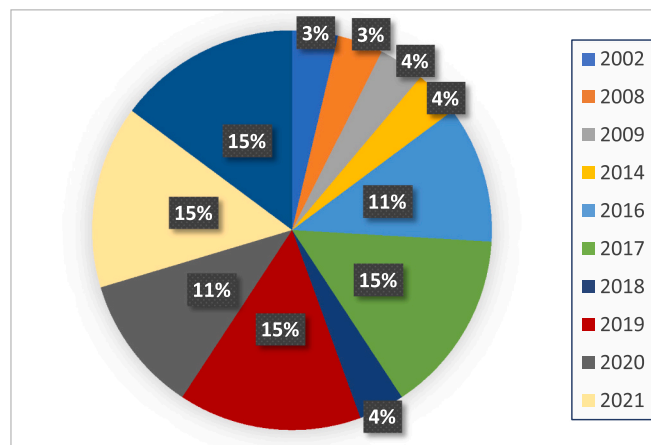


Fig. 4. Percentage distribution of the review-sample papers per publication year.

1ton primary-and-secondary¹sludge mixture (from now on ‘mixed sludge’) in the French context. Results showed that the adoption of anaerobic digestion of sludge for the application on agricultural land looks like the most environmentally friendly approach, recording lower GWP and lower energy consumption.

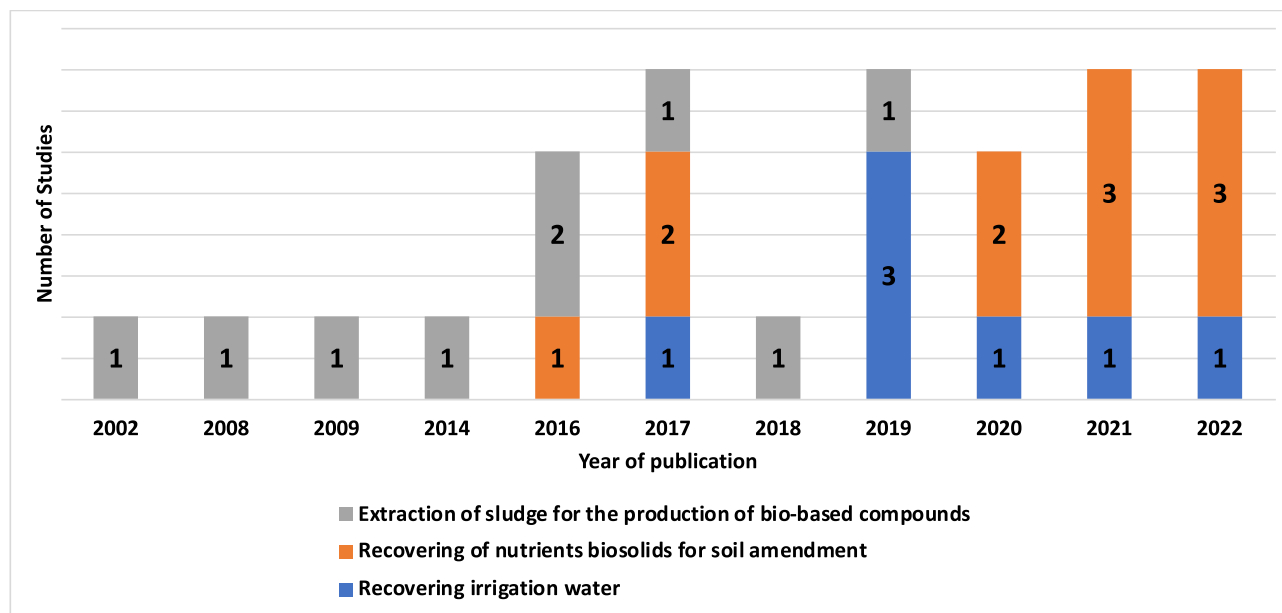
A few years later, Muñoz et al. (2008) used LCA with the aim of assessing ecotoxicity and human toxicity of wastewater. The authors realised a chemicals analysis of 98 polluting wastewaters in a Spanish wastewater treatment plant (WWTP). Nevertheless, Muñoz et al. (2008) highlighted that wastewater discharged into an aquatic recipient or used for agricultural irrigation record a reduction of 42 % of ecotoxicity and

¹ Primary sludge is generated from chemical precipitation, sedimentation, and other primary processes and contains more substances amenable to biodegradation; secondary sludge consists in the activated waste biomass resulting from biological treatments and is composed of biosolids (Sakaveli et al., 2023).

Table 3

List of reviewed papers for the three-research themes (RT).

RT	Description	Number of papers in the thematic area	Associated papers' references
1	Recovering irrigation water	7	Miller-Robbie et al. (2017); Moretti et al. (2019); Pan et al. (2019); Arzate et al. (2019); Snehal and Sameer (2020); Canaj et al. (2021); Kalboussi et al. (2022)
2	Extraction of sludge for the production of bio-based compounds	9	Suh and Rousseaux (2002); Muñoz et al. (2008); Hong et al. (2009); Niero et al. (2014); Alvarez-Gaitan et al. (2016); Tomei et al. (2016); Shiu et al. (2017); Liu et al. (2018); Do Amaral et al. (2019)
3	Recovering of nutrient biosolids for soil amendment	11	Fang et al. (2016); Laitinen et al. (2017); Kjerstadius et al. (2017); Ruff-Salfs et al. (2020); Wu et al. (2020); Aleisa et al. (2021); Foglia et al. (2021); Roman and Brennan (2021); Lam et al. (2022); Lima et al. (2022); Estévez et al. (2022)

**Fig. 5.** Number of papers per publication year and research topic investigated in the agricultural context.

85 % of human toxicity than other civil use. This study was amongst the first ones to analyse the micro-pollutants² present in WWTP, and found that the treated wastewater has a significantly minor environmental impact than other influents. Particularly, the other water sources generate a larger environmental impact due to pharmaceutical products and personnel treatment products which increase their toxicity.

Moreover, [Hong et al. \(2009\)](#) used LCA with the aim of estimating the environmental and economic impacts of 1ton Japanese sewage sludge for agricultural applications focussing on the six scenarios for which the reader is reminded to [Table 4](#). Particularly, the obtained results underlined that the scenarios without anaerobic digestion recorded a GWP that was lesser than those with digestion ([Hong et al., 2009](#)). According to the authors ([Hong et al., 2009](#)), this should be attributed to the machine, construction, fuel and electricity consumption used in digestion scenario.

Furthermore, the composting and drying processes increased the terrestrial acidification (TAD), whilst incineration and dewatered sludge smelting processes contribute to the human carcinogenic toxicity (HCT) impact.

Subsequently, [Niero et al. \(2014\)](#) used LCA with the aim to determine the best environmental performance of 1m³ inlet Danish

² Micro-pollutants represent the different organic compounds contained in various commonly used products such as drugs, detergents, cosmetics, dyes, pesticides. Particularly, this kind of pollutants are the anthropogenic chemicals such as agrochemicals, pharmaceuticals or chemicals related to industrial activity that occur at or below the microgram per liter level ([Verliefde et al., 2007](#)).

wastewater. Particularly, the authors analysed the impacts of the wastewater recovery in agriculture, extracting some fertilising compounds (i.e. nutrients, phosphorus, and nitrogen) from the WWTP-derived sludge. Results underlined that the centralised WWTPs equipped with anaerobic sludge digestion recorded lower impacts of climate change and fossil fuel depletion than those based on aerobic sludge stabilization. Particularly, [Niero et al. \(2014\)](#) underlined that the use of sludge to agriculture soils generate scarcer impacts compared to sludge incineration. Those recovery products are most important for the agricultural industry, as they can be used in replacement of fertilisers from chemical synthesis and so generate significant environmental gains.

Another relevant study in this research content area was done by [Alvarez-Gaitan et al. \(2016\)](#): the authors assessed some of the most popular secondary treatment technologies of wastewater recovery, including conventional activated sludge (CAS), modified Ludzack-Ettinger (MLE), and the BIODENIPHO™ process. Results highlighted that the reuse of biosolids in agriculture compensates for the biogas electricity of the sewage treatment plant (ED) and the carbon capture from land application of the obtained sludge. Thus, the extraction of bio-based compounds from sludge is one valid solution towards decarbonisation ([Alvarez-Gaitan et al., 2016](#)).

Moreover, [Tomei et al. \(2016\)](#) used LCA to quantify the environmental, economic and technical impacts ([Table 4](#)) of three different sludge treatment plants, highlighting results of two digestion units and the following two scenarios per each plant:

- the first scenario was based upon the most favourable conditions with costs minimized and incomes maximized;

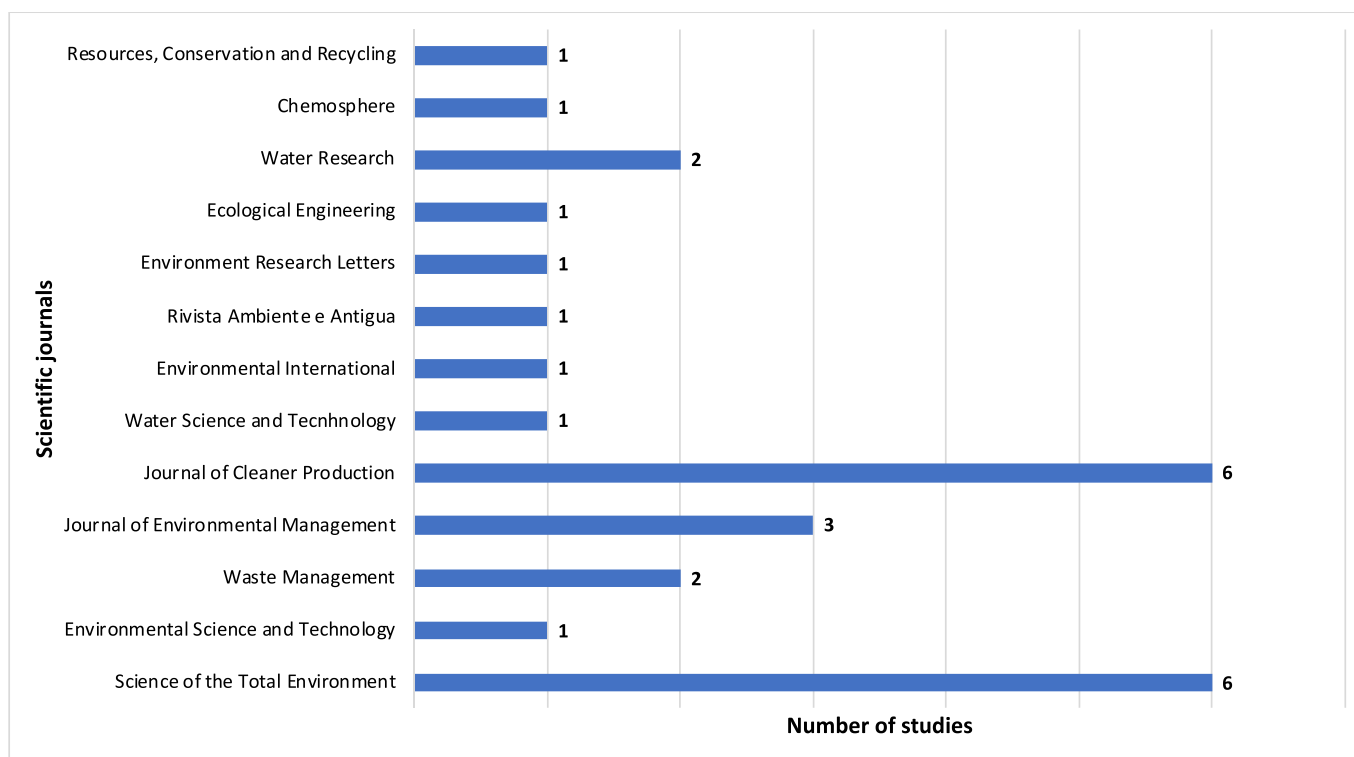


Fig. 6. Scientific journals consulted for the development of the review.

- the second, conversely, on worst conditions with all costs maximized and incomes minimized.

The obtained results emphasised that the agricultural use of sludge generates positive effects related to its application on the soil and, in fact, is increasingly being used in sustainable conservative and organic agriculture. This is mainly because treated-sludge application contrasts the progressive loss of organic matter and nutrients in the soil.

The field of extracting valuable compounds from the wastewater-treatment derived sludge was explored also by [Shiu et al. \(2017\)](#): in their study, the authors applied LCA to the treatment of 1m³ wastewater in Taiwan. The outcomes documented significant environmental benefits from reusing recovered wastewater for agricultural applications. In particular, the extraction of sludge-derived compounds and their reuse for land farming applications recorded a 27.8 % reduction in eutrophication potential, and a 157 % GWP reduction. Moreover, generating energy from waste sludge incineration allowed for neutralising the environmental impacts such as global warming and marine aquatic ecotoxicity due to the incineration of recycled sludge ([Table 5](#)).

Likewise, the [Liu et al. \(2018\)](#) paper has been evaluated some environmental impacts of 1 m³ of Chinese purified wastewater in 5 scenarios ([Table 4](#)) using LCA. Particularly, the five scenarios were set-up as follows:

- scenario I focussed on oxidation ditch model;
- scenario II on end-of-life alum sludge;
- in scenario III, end-of-life alum sludge was an input;
- in scenario IV, alum sludge was reused for agricultural application; and
- scenario V included the avoided landfilling process.

Results emphasised that the agricultural application as an alternative to other end-of-life alum sludge landfill treatment plants is more sustainable and avoids about 23–82 % of sulphur dioxide and carbon dioxide.

Lastly, [Do Amaral et al. \(2019\)](#) assessed the sustainability of four scenarios for which the reader is reminded to [Table 4](#) for the treatment and final destination of biological sludge and biogas in a medium-sized Brazilian WWTP using LCA. Results highlighted that Scenario 1, characterised by biogas used for drying sludge for application in agriculture, is the best scenario with low environmental impacts of Terrestrial Acidification and Ozone Layer Depletion. Scenario 2, based on sludge sanitization using a rotary dryer, is the second best, with a better index than scenario 1 due to the higher Nitrogen content and Phosphorus in the ash of biological sludge. Scenario 3 (similar to scenario 2, but with the ashes going to landfill) recorded lower than the other scenarios due to the social dimension due to not using the agronomic potential of biological sludge.

4.3. Recovering of nutrient biosolids for soil amendment

It is proven in the literature that applications of recovered wastewater include not only irrigation but, also, the production of fertilisers and the recovery of nutrients, as well as the extraction of value-added compounds from the WWT-derived sludge valorisation. Undoubtedly, the treated wastewater and the nutrients that are contained in it cannot be used for groundwater recharge, but only for irrigation, fertilisation and fertigation: thus, they satisfy goals and principles of the circular bioeconomy ([Maaß and Grundmann, 2016](#)).

Particularly, this kind of reuse reduces GWP up to 15 % and marine eutrophication impacts up to 9 % compared to conventional treatments, as highlighted by [Fang et al. \(2016\)](#). Those results were obtained by [Fang et al. \(2016\)](#) through application of LCA to the treatment of 1m³ wastewater in Denmark to identify environmental hotspots of – and the improvements that can be made in – the existing technologies.

Such a research field was explored further by [Laitinen et al. \(2017\)](#) in Mexico applied LCA to a Constructed Wetland (CW) treating 1000m³ wastewater influent to be recovered into irrigation water. The CW system was combined with an anaerobic digestion plant, for the treatment of the resulting sludge, thereby producing digestate usable as soil

Table 4
Key methodological aspects of the reviewed LCAs.

Reference	Research area	Methodology	FU	Description of the system investigated	Purpose of wastewater treatment	Impact assessment method (IAM)	Impact categories	Data quality	Local cluster	Cluster analysis
Suh and Rousseaux (2002)	France	LCA (ISO, 1997, 1998, 2000)	1 ton of mixed sludge in dry basis	From thermal energy recovered by incineration/anaerobic digestion to waste liquids and gases of sludge treatment plants	Extraction of sludge for the production of bio-based compounds	SETAC/CML	Environmental impacts (resources depletion, climate change, human toxicity, fresh water aquatic, marine aquatic and terrestrial ecotoxicity, acidification, eutrophication, and photo-oxidant formation)	1) Average data from literature, 2) Real site data and simulation	Not applicable	Five scenarios: 1) Silo storage, incineration, transport and landfill, 2) Lime stabilization, transport and landfill, 3) Lime stabilization, transport, silo storage and land application, 4) Composting, transport, silo storage and land application, 5) Anaerobic digestion, transport, silo storage and land application
Muñoz et al. (2008)	Spain	Chemical analysis-combined LCA of 98 wastewaters pollutants	Not specified because not is a complete LCA, but a chemical analysis	WWTP discharged the treated effluent to the sea	Extraction of sludge for the production of bio-based compounds	EDIP97 and USES-LCA	Impact on freshwater ecosystems, terrestrial ecosystems, and human health, of discharging wastewater to a river or reusing it in agricultural fields.	1) Technical data from estimation program interface suite, 2) Real site data of influent and effluent sample collected each	Almería (Southern Spain)	Two scenarios: 1) Discharging wastewater to aquatic recipient, 2) Using it for crop
Hong et al. (2009)	Japan	LCA and LCC	1 ton of dry solids	From heavy metal, dioxin emissions, energy consumption and recovery, transport to infrastructure of different sludge treatment	Extraction of sludge for the production of bio-based compounds	USES LCA model	Environmental impact, including machinery, construction, electric installation, energy acquisition, operation, transport and waste disposal stages	Combined cost and LCI databases	Not applicable	Six scenarios into three end-of-life treatments without digestion: 1) Dewatering, 2) Composting, 3) Drying, 4) Incineration, 5) Incinerated ash melting, 6) Dewatered and sludge melting and into two different applications: a) With digestion, b) Without digestion
Niero et al. (2014)	Denmark	LCA	1 m ³ of inlet wastewater	From operational stage, to buildings/equipment infrastructure/dismantling	Extraction of sludge for the production of bio-based compounds	ReCiPe LCIA method International Reference Life Cycle Data System Handbook	Climate change, fossil depletion, human toxicity, terrestrial, freshwater and marine ecotoxicity, freshwater eutrophication and marine eutrophication	DEPA National database	Danish WWTP Plant	Six scenarios: a) Sludge end-of-life treatment in the actual scenarios (plant type 1, 2, 3, 4), b) Alternative scenarios (plant type 3B, 4B)
Alvarez-Gaitan et al. (2016)	Australia	LCA	1 ton dried sludge	From electricity to diesel consumption	Extraction of sludge for the production of bio-based compounds	IPCC 2006	Impacts of secondary treatment technology	BioWin® models and Ecoinvent	Australian New South Wales	Three plants: 1) Conventional activated sludge (CAS), (continued on next page)

Table 4 (continued)

Reference	Research area	Methodology	FU	Description of the system investigated	Purpose of wastewater treatment	Impact assessment method (IAM)	Impact categories	Data quality	Local cluster	Cluster analysis
Tomei et al. (2016)	Italy	LCA	Treatment to the required level of the WW and sludge during one day for a plant of the capacity: 70,000 PE	Gate-to-gate, without considering emissions relating to alternative activities	Extraction of sludge for the production of bio-based compounds	ISO 14040-14044:2006	Environmental impacts (GWP, AP, EP) for freshwater, marine and terrestrial systems	Literature and Gabi inventory	Rome North WWTP	2) Modified Ludzack-Ettinger (MLE), 3) Biodenipho™ process Two scenarios: 1) Most favourable conditions with costs minimized and incomes maximized, 2) Worst conditions with all costs maximized and incomes minimized And two digestion units: a) Process efficiency for VS, b) Nitrogen removal Three scenarios: 1) Status quo zero recovery and reuse, 2) Agricultural fertigation, 3) Aquifer recharge Two scenarios: 1) Constructed wetland (CW) 2) Conventional activated sludge process (ASP)
Fang et al. (2016)	Southeast of Copenhagen (Denmark)	LCA based on EASETECH	1m ³ of influent wastewater	From the influent of the WWTP to final end use	Recovering of nutrients biosolids for soil amendment	LCIA and Life Cycle Data System	Environmental impacts of wastewater resource recovery and reuse in agricultural crop	Operating reports for existing processes, databases, and model results	Lynetten – WWT Plant	1) Status quo zero recovery and reuse, 2) Agricultural fertigation, 3) Aquifer recharge Two scenarios: 1) Constructed wetland (CW) 2) Conventional activated sludge process (ASP)
Laitinen et al. (2017)	Messico	LCT and LCA (ISO 14040, ISO 14044)	1000 m ³ of influent wastewater	From raw sewage to the obtained output	Recovering of nutrients biosolids for soil amendment	ISO 14040 and 14044	Climate change impact of WWT	Ecoinvent Database, Literature and National Report	City of Matamoros	1) Constructed wetland (CW) 2) Conventional activated sludge process (ASP)
Shiu et al. (2017)	Taiwan	LCA	1 m ³ of treated water	From WWTP operational stage to waste recycling	Extraction of sludge for the production of bio-based compounds	CML 2 baseline 2000 (V2.05) method	Environmental impact	Ecoinvent v3.1	Kinmen islands	Two scenarios: 1) Water reclamation 2) Sludge recycling
Kjerstadius et al. (2017)	Southern Sweden	LCA and CF	1 capita yearly load of food waste, blackwater and greywater	From infrastructure to sludge in agriculture/soil	Recovering of nutrients biosolids for soil amendment	LCIA and ReCiPe	GWP emissions to water or air	LCI based on ILCD Handbook	Sample urban area in Southern Sweden	Two scenarios: 1) Conventional system in a sanitation system for food waste and wastewater, 2) Second system as source separation system
Miller-Robbie et al. (2017)	India	LCA	1 l of combined wastewater by treatment and reuse	From cradle-to-gate, that includes the WWTP effluent to be reused for irrigation	Recovering irrigation water	DAYCENT model by Colorado State University	Energy and GHG emissions	Ecobalance 2006 - Life Cycle Inventory Database	City of Hyderabad	Two scenarios: a) Irrigation water/ treated effluent and untreated surface, b) Untreated water (influent to WWTP) and water treated

(continued on next page)

Table 4 (continued)

Reference	Research area	Methodology	FU	Description of the system investigated	Purpose of wastewater treatment	Impact assessment method (IAM)	Impact categories	Data quality	Local cluster	Cluster analysis
Liu et al. (2018)	China	LCA (ISO 14040-44)	1m ³ of purified wastewater over 20 years	Gate-to-gate (excluded direct domestic carbon dioxide emission included methane and nitrous oxide)	Extraction of sludge for the production of bio-based compounds	E-balance, CML2002 LCIA at Midpoint level	Fossil depletion potential (FDP), acidification potential (AP), eutrophication potential (EP) and global warming potential (GWP), emission of CO ₂ , NO _x , and SO ₂	Literature data	Chinese WWTP with ditch oxidation process	Five scenarios: 1) Oxidation ditch model, 2) End-of-life alum sludge, 3) Sludge as an input, 4) Reuse for agricultural application, 5) Without landfilling
Moretti et al. (2019)	Mediterranean coastal region	LCA (ISO 14044:2006)	1 kg of nectarines orchards	Cradle-to-farm gates for nectarine orchards irrigation using treated municipal water and surface water, including impacts generated by the avoided freshwater withdrawals and discharging into the sea	Recovering irrigation water	International Reference Life-Cycle Data System (ILCD)	Environmental impacts	Ecoinvent v3 and three years of the experimental trial (2012–2014)	Commercial nectarine grown up in Trinitapoli, Apulia region (Southern Italy) -	Three scenarios: 1) Baseline, 2) Irrigation using TMW, 3) Irrigation surface water
Do Amaral et al. (2019)	South Brazil	LCA and LCC, S – LCA and LCSA	1 m ³ of domestic effluent	Gate-to-gate considering treatment of civil wastewater, including the treatment stages and final destination	Extraction of sludge for production of bio-based compounds	SimaPro 8.4, ReCiPe 2016 Midpoint, dashboard of sustainability (DoS)	Environmental, social and economic impacts, GWP, stratospheric ozone layer depletion, ozone formation, terrestrial ecosystems, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity and human non-carcinogenic toxicity	Literature, UNEP, SETAC, rotary dryer installed	South Brazilian WWTP	Four scenarios: 1) Baseline with biogas use to dry sludge, 2) Sludge burning for drying, 3) Sludge burning for sanitation, 4) Ashes to landfills
Pan et al. (2019)	Semi-arid and arid regions	LCA and Montecarlo simulation	1 m ³ of wastewater treated and reused for irrigating crops	Gate-to-gate, considering municipal WWT, excluding fertiliser production	Recovering irrigation water	Hierarchist ReCiPe 2016 mid-point based method, ver. 1.1	Environmental and human health impacts (water use, resource scarcity, eutrophication, toxicity, acidification, GWP, ozone depletion, human health risks)	USES-LCA	Not applicable	Three scenarios: 1) Diverting secondary effluents, 2) Retrofitting existing systems, 3) Customizing reclamation
Arzate et al. (2019)	Spain	LCA	1 m ³ of secondary effluent	Gate-to-gate, including materials for infrastructure of tertiary treatment	Recovering irrigation water	ReCiPe 2016 Midpoint and Endpoint, USEtox	Water depletion, energy, infrastructure, chemicals, micro-pollutants,	LCI, Literature, Ecoinvent and SimaPro	Almeria	Three scenarios: 1) Baseline (without tertiary treatment + groundwater supply for agricultural proposes, 2) Ozonation + sand filtration, 3) Photo-Fenton + sand filtration
Snehal and Sameer (2020)	India	LCA and LCC	1 m ³ of treated wastewater	Cradle-to-gate, considering extraction, production, processing of materials, operational	Recovering irrigation water	Impact 2002+, midpoint and endpoint categories	GWP, energy consumption and chemical dosing	SimaPro, Ecoinvent 3 database	Indian metro-cities	Three scenarios: 1) Baseline 2) DOSIWA, 3) ASP systems

(continued on next page)

Table 4 (continued)

Reference	Research area	Methodology	FU	Description of the system investigated	Purpose of wastewater treatment	Impact assessment method (IAM)	Impact categories	Data quality	Local cluster	Cluster analysis
Ruff-Salís et al. (2020)	Spain	LCA	1 m ³ of wastewater	equipment, chemicals and energy Gate-to-gate, Including the accounting of direct emissions in air and heavy metals to soil	Recovering of nutrients biosolids for soil amendment	ISO 14040:2016 ReCiPe (H) 2016 method	Environmental impacts (GWP, freshwater eutrophication, marine eutrophication and ecotoxicity and cumulative energy demand)	Literature, SimaPro 9.0, Ecoinvent 3.5 database	Area Metropolitan of Barcelona (AMB)	Four scenarios 1) BaU (Business-as-Usual), 2) REM-NUT, Ostara, 3) AirPrex in Besòs 4) AirPrex in Llobregat
Wu et al. (2020)	Spain	LCA	1000 kg live weight of pig at the farm gate	From pig feed production to wastewater treatment of pig fattening farms	Recovering of nutrients biosolids for soil amendment	ReCiPe (version 1.13)	18 midpoint impacts categories and 3 endpoint impacts categories of impact	SimaPro and Agri-footprint	Galicia (Northwest Spain)	Four scenarios: 1) Manure management systems, 2) Integrated anaerobic mono-digester and the outside storage, 3) Nonconventional MMS scenario with an integrated anaerobic mono-digester and AWWT process 4) Integrated anaerobic co-digester and AWWT process
Roman and Brennan (2021)	USA	LCA	1 of ML wastewater treated	From WWT to final use of the obtained treated water	Recovering of nutrient biosolids for soil amendment	Impact 2002+	Human health, ecosystem quality, climate change and resources 15 midpoints categories	SimaPro 9.0 and Ecoinvent 3.6 databases	Pennsylvania State University campus	A scenario of Eco-Machine™ waste water treatment plant Four scenarios of sensitivity analysis: a) Propane heated greenhouse, b) Natural gas heated greenhouse, c) Nonheated greenhouse, d) No heat and no greenhouse
Foglia et al. (2021)	Italy	LCA Umberto LCA + v10.0	1 m ³ of treated wastewater	Pre-primary-anaerobic treatments, disinfection and filtration	Recovering of nutrients biosolids for soil amendment	ReCiPe 2008 Midpoint (H) V1.13 no LT	Environmental impact	Ecoinvent databases	Peschiera Borromeo (MI)	Four scenarios: 1) Baseline scenario, 2) Enhanced UV disinfection, 3) Chemical disinfection, 4) Biological treatment
Canaj et al. (2021)	Southern Italy	LCA, LCIA, openLCA 1.10.2	1 m ³ of water	From treated secondary effluent, to discharge of treated effluent to the sea or the reuse in agriculture	Recovering irrigation water	ISO 14040 – 14044, ReCiPe 2016 midpoint and endpoint categories	Environmental and financial impacts	Literature, local operator and Consorzio per la Bonifica della Capitanata (CBC)	Apulia region (Trinitapoli-Foggia)	Two scenarios: 1) Baseline, 2) Reuse
Aleisa et al. (2021)	Kuwait	LCA (ISO 14044)	1 ton of NPK nutrients	From cradle-to-cradle, including primary treatment process	Recovering of nutrients biosolids for	ReCiPe 2016 at midpoint	4 midpoints of impacts of categories: Climate change, fossil fuel depletion, metal	Simapro v.8.03	Not applicable	Three scenarios: 1) Landfilling, 2) Incineration,

(continued on next page)

Table 4 (continued)

Reference	Research area	Methodology	FU	Description of the system investigated	Purpose of wastewater treatment	Impact assessment method (IAM)	Impact categories	Data quality	Local cluster	Cluster analysis
Kalboussi et al. (2022)	France	LCA (ISO 14040)	1 ha of vineyard	removing large floating particles and coarse solids From gate-to-gate, which means from wastewater to crop irrigation	soil amendment Recovering irrigation water	ILCD (2011)	depletion, human toxicity and particulate matter formation 8 midpoint of impact categories: Climate change, ozone depletion, human toxicity that regroup human carcinogenic toxicity and human non-carcinogenic toxicity, ionizing radiation, acidification, freshwater eutrophication, marine eutrophication, freshwater ecotoxicity	Experimental measurements and modelling datasets Ecoinvent, v3.6	Murviel-Les-Montpellier experimental site (Hérault)	3) Fertilisers application Three scenarios: 1) Reclaimed water and reuse, 2) Irrigation with river water, 3) Groundwater irrigation
Lam et al. (2022)	U.S. context	LCA	1 kg of crops (maize, rice, wheat)	From crop production system to WWTP including phosphorus recovery	Recovering of nutrients biosolids for soil amendment	TRACI 2.1 (U.S. E.P.A.)	4 impact categories: GWP, eutrophication potential, ecotoxicity potential, and acidification potential	Ecoinvent database	Not applicable	Six recovery phosphorus pathways from wastewater: a) For struvite extraction, b) For Ca-P extraction, c) Incineration and Rhenania Phosphate extraction, d) With CEPT and incineration and Rhenania Phosphate extraction, e) Incineration and single superphosphate, f) With CEPT and single superphosphate
Estévez et al. (2022)	Spain	LCA	1 m ² of urban garden	From cradle-to-gate, considering input (potable water, energy production, chemicals production)	Recovering of nutrients biosolids for soil amendment	ReCiPe 2016: Hierarchist Midpoint and Hierarchist Endpoint	Set of impact categories at midpoint Level and 3 indicators Human health, ecosystem quality and resource scarcity	Inventory data	Not applicable	A baseline scenario divided into two subsystems: a) Wastewater management and fertiliser production, b) Gardening activities.
Lima et al. (2022)	West-central Brazil	Santiago SW and LCA (ISO 14040)	173 m ³ /year of wastewater	All inputs and outputs for materials, nutrients, water and energy	Recovering of nutrients biosolids for soil amendment	Recipe 2016	Emissions to water, soil and air, associated with nitrogen, phosphorus, heavy metals and carbon emissions	Primary input data from the Los Angeles WWTP, Characteristics of separated flow streams based on literature	Campo-grande	9 scenarios: 1) Baseline and 8 Santiago scenarios divided into four groups: a) Dry onsite storage; b) Onsite septic tank, c) Offsite solid fertiliser, d) Onsite

amendment and green electricity to be input to the grid. Through their LCA, in line with [Ingrao et al. \(2020\)](#), the authors documented CW as showing to be particularly efficient in warm climate areas, and as generating GHG-emission savings compared to conventional treatment processes. According to the authors, and again in line with [Ingrao et al. \(2020\)](#), CWs are economic method due to its energy saving and production.

In another study, [Kjerstadius et al. \(2017\)](#) carried out a single-issue LCA with the twofold aim of:

- identifying the carbon footprint (CF) of two sanitation systems, that have potentials for nutrient recovery in agriculture;
- determining which parts of the management chain are effective in decreasing climate impact.

Through their study, the authors documented in fact that source separation decreases the CF of urban sanitation management and, at the same time, leads to a 25 % increase in nutrient recovery from urban areas to agriculture.

As the previous literature studies that have been reviewed in this article, results from this study could be beneficial to municipal water utilities and policy makers for the design of city infrastructure and farming practices, with a long-term perspective.

In another study, [Wu et al. \(2020\)](#) performed a comparative LCA of four scenarios of pig manure management systems (MMS) considering different combinations of outside storage, anaerobic mono-/co-digester, and algae-based wastewater treatment: further details can be found in [Table 4](#) of this article. The outcomes emphasised that algae-based pig farming system makes it possible to reduce nitrogen-based pollutants that have negative effects to human health and climate change.

Similar to [Kjerstadius et al. \(2017\)](#), [Ruff-Salís et al. \(2020\)](#) proposed the recovery of phosphorus from wastewater considering the struvite extraction from treatment of enormous volumes of wastewater from urban wastewater treatment plant.

Thus, [Ruff-Salís et al. \(2020\)](#) assessed the technical and environmental practicability of recovering and reusing struvite to fertilise agricultural fields in an urban region, focussing on in the two biggest WWTPs of the Metropolitan Area of Barcelona. Particularly, these plants located in Besòs and El Prat de Llobregat treated respectively the 45 % and 34 % of wastewater produced in Barcelona. Then, the authors examined the potential phosphorus recovery and environmental impacts resulting from the integration of three recovery technologies, called REM-NUT®, Ostara® and AirPrex® in the Besòs and El Prat de Llobregat wastewater treatment plants. Specifically:

- in REM-NUT® process based on ion-exchange-based the phosphorus was recovered from the secondary treated effluent ([Petruzzelli et al., 2004](#); [Ruff-Salís et al., 2020](#));
- in the Ostara® process a specific reactor and chemical products are used to stimulate the precipitation of struvite from the digestate ([Egle et al., 2015](#); [Amann et al., 2018](#); [Ruff-Salís et al., 2020](#));
- lastly, in AirPrex® recovers phosphorus from digested sewage sludge before sludge dehydration ([CNP, 2017](#); [Ruff-Salís et al., 2020](#)).

Results showed that amongst the three recovery technologies, REM-NUT® recorded the higher impacts due to the use of chemicals, mainly the magnesium chloride (MgCl₂) to preserve the stoichiometric precipitation ratios. Moreover, amongst the two wastewater treatment plants, Besòs plant generated greater impacts than El Prat Llobregat comparing, due to the higher volume of wastewater treated by Besòs (equal of 125 million m³), compared to those treated by El Prat Llobregat plant (equal of 94 million m³). Finally, the authors affirmed that the integration of these new technologies will slightly increase impacts on GWP and on energy demand.

Another similar study was carried out by [Aleisa et al. \(2021\)](#), evaluate the environmental impacts of nutrients recovered from treated

sewage sludge and applied to agricultural land to grow fodder. The authors use LCA approach and investigated an agricultural soil located in Kuwait that use treated sewage sludge for forage cultivation. Results showed that the use of treated Sewadge Sludge to integrate fertilisers in agriculture can be the best solution to avoid increasing all impact categories ([Aleisa et al., 2021](#)).

Also, [Foglia et al. \(2021\)](#) explored the environmental and economic impacts related to wastewater treatment plant located in the province of Milan, Italy and compared some scenarios to encourage the reuse of recovered water for agriculture. The authors proposed some methods of treatment and recovery:

- alternative disinfection methods with enhanced ultraviolet rays and peracetic acid;
- replacement of conventional activated sludge (CAS) with a carpet of reflux anaerobic sludge (UASB) for treatment;
- the use of the anaerobic biological membrane bioreactor (AnMBR) as a tertiary treatment.

Results highlighted that the impact categories are mainly influenced by previously used fertilisers, whose application is responsible cause direct emissions into water and soil (e.g. nutrients and heavy metals). Moreover, the use of life cycle approach in these kinds of analysis can successfully encourage the decision-making process when considering possible scenarios in WWTPs for water reuse in agriculture. Lastly, outcomes revealed that the combination of anaerobic with ultrafiltration chamber in the secondary wastewater treatment methods reduces the environmental impact of the final effluents compared to the disinfection processes when the reclaimed water is intended for reuse in agriculture.

[Lam et al. \(2022\)](#) used LCA to estimate the environmental impacts of substituting conventional, phosphate rock-based fertilisers in agricultural production systems. Therefore, authors explored the opportunity of recovering phosphorus from wastewater (essential for food production in agro-industry) based on six recovery pathways for which the reader is reminded to [Table 4](#). Results showed that replacement of recovered phosphorus in U.S. maize, rice, and wheat production reduces GWP, eutrophication, ecotoxicity and acidification of agricultural production.

Likewise, [Lima et al. \(2022\)](#) combined two approaches, LCA and Santiago³ for comparing alternative scenarios in WWTPs in west-central Brazil. Particularly, the authors used Santiago tool for developing resource-recovery efficient scenarios; instead LCA assessed the environmental impacts and specify recommendations on coupling the tools for improved decision-making ([Lima et al., 2022](#)).

[Lima et al. \(2022\)](#) hypothesised nine scenarios:

- baseline where existing WWTP compost for the up flow anaerobic sludge blanket reactor without post-treatment;
- dry storage on-site with urine diversion (UDDT) and on-site storage and processing;
- dry storage on-site with separation of feces and urine at source, in on-site storage chambers;
- on-site septic tank and sewage collected in an on-site septic tank;
- on-site septic tank and effluents from the septic tank flow into a sewer free of solids and sludge transported for further treatment;
- offsite solid fertilisers: the septic tank effluent, after flowing into a solid-free sewer, is discharged into a wetland with horizontal underground flow to irrigate eucalyptus plantations with the treated effluent;
- offsite solid fertilisers: sludge is transferred with truck for successive treatment;

³ Santiago is the acronym of SANitation system Alternative GeneratOr, a free tool used for urban planning based on a set of standards ([Lima et al., 2022](#)).

Table 5

Summary of the reviewed LCAs' selected results as referred of the FU of the given study. For details on the multiple system scenarios, some results are referred to, the reader is reminded to [Table 4](#).

Reference	FU	GWP (kg CO ₂ eq)	TAD (kg SO ₂ eq.)	AAC (H+moles eq./kg)	FET (kg P eq.)	MET (kg N eq.)	TEC (kg 1,4-DCB eq.)	FEC (Kg 1,4- DCB eq.)	MEC (Kg 1,4- DCB eq.)	ME (Kg Cu eq.)	HCT (Kg 1,4- DCB eq.)	HNCT (Kg 1,4- DCB eq.)	OLD (kg CFC-11 eq/kg)	WC (m ³)	ED (MJ/kg)	LU (m ² eq.)
Suh and Rousseaux (2002)	1 ton of the mixed sludge in dry basis	Range: 10-100%	x	Range: 50-100%	Range: 100-220%	x	Range: 100-200%	Range: 100-885%	Range: 60-140%	X	Range 5-100%	x	x	x	x	Range: 100-180%
Munoz et al. (2008)	Not specified because not is a complete LCA.	x	x	x	Scenario: a) Influent: 4.0E-02 b) Effluent: 1.0E-02	Scenario: a) Influent: 1.2E-02 b) Effluent: 3.0E-03	Scenario: a) Influent: 3.5E-04 b) Effluent: 2.0E-04	x	x	x	Scenario a) Influent: 4.0E-03 b) Effluent: 2.0E-03	x	x	x	x	x
Hong et al. (2009)	1 ton of dry solids	Scenario a) With digestion 723.4 - 1.3E03 b) Without digestion 625.4 - 698.8	x	Scenario a) With digestion: 0.20 - 088 b) Without acidification: -0.06-1.50	x	x	x	x	x	x	Scenario a) With digestion: 38.1 - 90.2 b) Without digestion: 71.1-166.9	x	x	x	x	Scenario a) With digestion: 1.56E-03 - 0.29 b) Without digestion: 71.1-175.3
Niero et al. (2014)	1 m ³ of inlet wastewater	Range: 9.98E-02 - 2.13E-01	x	x	Range: -1.63E-04 - +8.88E-05	Range: 6.24 E-03 - +3.28 E-03	Range: 5.04E-05 - +1.57E-03	Range: 1.85E-03 - + 1.38E-03	Range: 6.6E-04 - + 1.71E-03	x	Range: 7.59E-0 - + 4.67E-02	x	x	x	Range: 6.64E-02 - + 6.64E-02	x
Alvarez-Gaitan et al. (2016)	1 tonne of dry biosolids	Range: 1.9 - + 14.3	x	x	x	x	x	x	x	x	x	x	x	x	Range: 1092 - + 2517	x
Tomei et al. (2016)	treatment to the required level of the wastewater and sludge during one day for a plant of the capacity 70,000 PE	Scenario: a) Sludge incineration: 0.85 - +0.90 b) Use of sludge: 0.80 - 1.10	x	Scenario: a) Sludge incineration: 0.72 - +0.88 b) Use of sludge: 0.74 - 1.30	Scenario: a) Sludge incineration : 0.84 - +1.00 b) Use of sludge: 0.80-1.00	Scenario: a) Sludge incineration: 1.00- +1.00 b) Use of sludge: - + 1.00	Scenario a) Sludge incineration: 0.64 - 0.82 b) Use of sludge: 0.25 - + 1.25	x	x	x	x	x	x	x	x	x
Fang et al. (2016)	1m ³ of influent wastewater	Scenario a) 0.05% b) 0.05 % c) 0.06 %	x	Scenario a) 0.0025% b) 0.020 % c) 0.025%	x	-x	Scenario a) 0.0025% b) 0.020% c) 0.025%	Scenario a) 1.10% b) 1.00% c) 1.00%	x	x	Scenario a) 0.010% b) 0.020% c) 0.010%	x	x	x	x	x
Laitinen et al. (2017)	1000 m ³ of influent wastewater	Scenario a) CW: 130 b) ASP: 406	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Shiu et al. (2017)	1 m ³ of treated water	Range: 3.24E+01 - +1.88E+01	x	x	x	Range: 6.56E+04 - +82E+04	Range: 3.38E-01 - +1.62E+00	Range: 1.48E+01 - +1.23E+01	x	x	Range: 1.05E+01 - +7.70E+01	x	Range: 5.90E-06 - +1.01E-04	x	x	x
Kjerstadius et al. (2017)	1 capita yearly load	Scenario: a) -10 b) -37	x	x	x	x	x	x	x	x	x	x	x	x	x	x

	of food waste															
Miller-Robbie et al. (2017)	1 litre for the combination of wastewater treatment and reuse in agriculture	Scenario: a) uncontrolled release: 5.50 b) release to stream: 4.80 c) effluent reuse in existing farms: 4.80 d) effluent reuse in surrounding land: 2.00	x	x	x	x	x	x	x	x	x	x	x	x	Value: -99%	x
Liu et al. (2018)	1 m ³ of purified wastewater over 20 years	Scenario a) 1.11 b) 8.56E-01 c) 1.51 d) 8.48E-01 e) 1.94E-01	Scenario a) 5.57E-03 b) 4.41E-03 c) 4.62E-03 d) S4: 4.38E-03 e) 4.17E-03	x	Scenario a) 9.61E-03 b) 8.97E-03 c) 1.28E-02 d) 8.96E-03 e) 5.10E-03	x	x	x	x	x	x	x	x	x	Range: 9 - +59%	x
Moretti et al. (2019)	1 kg of nectarines	Scenario: a) 9.3E-01 b) 2.29E-01 c) 2.18E-02	Scenario: a)x b) 7.17E-03 c) 5.02E-03	x	Scenario a)x b) 1.47E-03 c) 2.51E-03	Scenario: a) x b) -6.41E-03 c) 6.55E-04	x	Scenario: a) 2.86E-02 b) 1.04E+00 c) 1.22E-01	x	x	Scenario: a) 1.63E-09 b) 3.02E-08 c) 7.84E-09	x	x	Scenario: a) 9.2E-01 b)x c)x	x	x
Do Amaral et al. (2019)	1 m ³ of effluent	Scenario: a) 0.7864 b) 0.4409 c) 0.4325 d) 0.4598	Scenario: a) 0.0033 b) 0.0007 c) 0.0059 d) 0.0048	x	Scenario: a) 0.0033 b) 0.0007 c) 0.0059 d) 0.0048	x	Scenario: a) 5.3E-05 b) 1.44E-05 c) 2.47E-07 d) 3.69E-06	Scenario: a) 9.65E-05 b) 1.62E-05 c) 4.06E-06 d) 1.12E-05	x	x	Scenario: a) 14.3482 b) 0.102905 c) 0.0642 d) 0.0715	Scenario: a) 7.94E-08 b) 3.88E-08 c) 3.43E-08 d) 3.09E-08	x	x	x	x
Pan et al. (2019)	1m ³ of wastewater	Scenario a) DSE: 4 b) RES: 4.25 c) CRF: 7	Scenario a) DSE: 9.0 b) RES: 8.5 c) CRF: 15	x	Scenario a) DSE: 10 b) RES: 0.4 c) CRF: 0.7	Scenario a) DSE: 0.5 b) RES: 0.4 c) CRF: 0.3	Value: 1.16	Value: x	x	Value: 0.142	Value: 1.4	Value: 1.4	Scenario a) DSE: 2.5 b) RES: 2.4 c) CRF: 2.3	Value: 0.17	x	Scenario a) DSE: 0.025 b) RES: 0.25 c) CRF: 0.175
Arzate et al. (2019)	1m ³ of secondary effluent	Scenario a) 4.0E-1 b) 2.5E-1 c) 9E-1 d) 8E-1 e) 3E-1 f) 8E-1	Value: 1.73E-03	x	Scenario a) 5.0E+0 b) 4.0E+0 c) 7E+0 d) 6E+0 e) 3.75E+0 f) 6.0E+0	Value: 1.04E-04	Value: 3.74E-05	Value: 6.67E-03	x	x	Scenario a) 1.6E-7 b) 2.5E-8 c) 9.0E-8 d) 8.0E-8 e) 3.0E-8 f) 8.0E-8	Scenario a) 2.3E-7 b) 6.0E-8 c) 2.75E-7 d) 8.0E-8 e) 6.0E-8 f) 2.75E-7	Value: 4.02E-08	Scenario a) 1.01E+00 b) -1.0E+0 c) -1.0E+0 d) -1.0E+0 e) -1.0E+0 f) -1.0E+0	x	Scenario a) 5.5E-5 b) 3E-5 c) 11E-5 d) 10E-5 e) 3E-5 f) 10E-5
Snehal and Sameer (2020)	1 m ³ of treated wastewater	Scenario a) ASP 1017 b) DOSIWAM -0.126	Scenario a) ASP 1.66E-02 b) DOSIWAM 7.89E-03	Scenario a) ASP 4.52E-03 b) DOSIWAM 1.37E-03	Scenario a) ASP 0.0124 b) DOSIWAM 0.0783	x	Scenario a) ASP 22.67 b) DOSIWAM 6.22	Scenario a) ASP 5.762 b) DOSIWAM 23.24		Scenario a) ASP 1.57E-02 b) DOSIWAM 1.36E-02	Scenario a) ASP 7.33E-03 b) DOSIWAM 4.78E-03	Scenario a) ASP 2.27E-02 b) DOSIWAM 5.88E-03	Scenario a) ASP 5.31E-08 b) DOSIWAM 1.11E-08	x	x	x

Ruff-Salis et al. (2020)	1 m ³ of wastewater	Range 2 areas: a) Besós: 3.80E-01 b) Llobregat: 4.23E-01	x	x	Range 2 areas: a) Besós: 2.40E-03 b) Llobregat: 2.54E-03	Range 2 areas: a) Besós: 1.98E-03 b) Llobregat: 2.58E-03	Range 2 areas: a) Besós: 1.28E-00 b) Llobregat: 3.5E+00	x	x	x	x	x	x	x	x	x
Wu et al. (2020)	1000 kg live weight of pig at the farm gate	Range: 55 - +100%	Range: 72 - +100%	x	Range: 60 - +100%	Range: 55 - +100%	Range: 55 - +100%	Range: 95 - +100%	Range: 95 - +100%	x	Range: -100 - -10%	x	Range: -100 - +5%	Range: -25 - +100	x	Range: 18 - +100%
Aleisa et al. (2021)	1 ton of N-P-K nutrients	Scenario: a)landfilling 190% b)incineration 15% c)fertiliser complement -100%	x	x	x	x	x	x	x	x	Scenario: a)landfilling 160% b)incineration -40% c)fertiliser complement -60%	x	x	x	x	Scenario: a)landfilling -103% b)incineration 100% c)fertiliser complement -90%
Roman and Brennan (2021)	1 ML of wastewater treated	Value: 959	Value: 23.0	Value: 8.46	Value: 0.31	x	x	Value: 20,400	Value: 193,000	Value: -38.1	Value: -1.77	Value: -90.9	Value: 0.001	x	Value: 85,600	Value: -44.1
Foglia et al. (2021)	1 m ³ of treated wastewater	Range: 70 - +100%	x	x	Range: 80 - +100%	x	Range: 75 - +100%	x	x	x	Range: 83 - +100%	x	Range: 68 - +100%	Range: 1 - +100%	x	x
Canaj et al. (2021)	1 m ³ of water	Scenario: a) Baseline: 0.41 b) Reuse: 0.21	Scenario: a) Baseline: 1.97E-03 b) Reuse: 2.04E-03	x	Scenario: a) Baseline: 9.55E-04 b) Reuse: 1.14E-03	Scenario: a) Baseline: 2.73E-02 b) Reuse: 3.18E-03	Scenario: a) Baseline: 0.22 b) Reuse: 0.63	Scenario: a) Baseline: 1.21E-03 b) Reuse: 7.58E-03	x	x	Scenario: a) Baseline: 388E-03 b) Reuse: 8.71E-03	Scenario: a) Baseline: 3.29E-02 b) Reuse: 1.60E-01	x	Scenario: a) Baseline: 0.38 b) Reuse: 0.18	x	x
Lima et al. (2022)	173 m ³ /year of wastewater reused	Scenario: a) Baseline: 3.5E+03 b) Others: -0.87E+03	Scenario: a) Baseline: 14.4 b) Others: 3.7	x	Scenario: a) Baseline: 5.37 b) Others: 0.151	Scenario: a) Baseline: 27.9 b) Others: 0.176	Scenario: a) Baseline: 8.70 b) Others: 2.687	Scenario: a) Baseline: 0.0895 b) Others: 20.94	x	x	Scenario: a) Baseline: 0.0879 b) Others: -16.4	Scenario: a) Baseline: 2.77 b) Others: 708.12	x	Scenario: a) Baseline: 0.0390 b) Others: 16.61	x	x
Kalboussi et al. (2022)	1 ha of vineyards	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Lam et al. (2022)	1 kg of crops (maize, rice, wheat)	Range: -5E-03; -9E-03 Range (%) Maize: -2.61 -4.17 Rice: -7.61; +0.89 Wheat: -6.59; +7.84	Range: -4E-02; -7E-02 Range (%) Maize: - 4.73; +2.50 Rice: -2.60; +1.52 Wheat: - 4.40; +17.94	x	Range (%) Maize: - 97.13; +5.40 Rice: - 29.94; +1.65 Wheat: - 65.11; +5.05	Range (%) Maize: - 24.83; +22.90 Rice: -7.61; +4.90 Wheat: - 23.23; +32.23	x	x	x	x	x	x	x	x	x	x
Estévez et al. (2022)	1 m ² of urban garden	Scenario	Scenario	x	Scenario	Scenario	Scenario	Scenario	Scenario	x	x	x	Scenario	x	x	Scenario
		a)Centralised scenario 100% b)Decentralised Baseline Scenario (DBS) 35%	a)Centralised scenario 100% b)Decentralised Baseline Scenario (DBS) 55%		a)Centralised scenario 100% b)Decentralised Baseline Scenario (DBS) 35%	a)Centralised scenario 100% b)Decentralised Baseline Scenario (DBS) 42%	a)Centralised scenario 100% b)Decentralised Baseline Scenario (DBS) 30%	a)Centralised scenario 100% b)Decentralised Baseline Scenario (DBS) 35%	a)Centralised scenario 100% b)Decentralised Baseline Scenario (DBS) 35%				a)Centralised scenario 100% b)Decentralised Baseline Scenario (DBS) 82%			b)Decentralised Baseline Scenario (DBS) 25%

- on-site biogas production with effluent transport:
- on-site biogas production: sludge from on-site black-water treatment transferred to a biogas reactor for producing heat and electricity for the use within the system.

Results showed that through LCA none of the eight scenarios obtained good environmental performance compared with the baseline scenario. Instead, through the Santiago tool the best environmental performance was recorded by the separation at the source of human urine and feces for storage and application as a fertiliser. Therefore, this outcome recommends that source separation should be considered and evaluated by practitioners (Lima et al., 2022).

In the same year, Estévez et al. (2022) estimate the environmental and economic impacts of a hybrid-decentralised configuration of a wastewater treatment plant used to efficiently manage wastewater and resource recovery. Particularly, this decentralised wastewater plant mitigates the pressure on central plants that could exceed treatment capacity, reducing wastewater pumping and related costs (Capodaglio, 2017; Estévez et al., 2022). Results displayed the efficiency of this decentralised treatment plant in valorising digestate flows as sources of nutrients for horticultural or ornamental crops located near the plant. Furthermore, this decentralised treatment plant respects the Circular Economy since it allows the use of purified water and biofertilisers in safe and environmentally friendly conditions. Moreover, the authors concluded that this technology tested mitigated the impacts of urban areas from a sustainable perspective.

Additionally, in terms of wastewater recovery for animal food production there has not been much interest in published studies unlike the reuse of water for irrigation and fertilisers. Principally, the US study by Roman and Brennan (2021) was the only one that explored the wastewater recover for the production of feed, addressing a series of LCAs on different operating scenarios of the pilot-scale 1000-gallon-per-day through Eco-Machine™.⁴ Particularly, through this wastewater treatment plant which does not require a GHG or additional heating, is consumed about a third of the energy, water has been recovered for irrigation and duckweed biomass for aquaculture. Additionally, this system produces half the GHG compared to traditional wastewater treatment systems. In terms of environmental impacts, this plant contributed to reducing some midpoint categories as shown in Table 5. Moreover, the solar array, especially during the summer months, provide more electricity than the Eco-Machine™ consumes, and the additional electricity is directed to the university grid. Conversely, wastewater treatment is responsible for the largest beneficial impact for others midpoint categories.

5. Discussion of the final remarks from the sample-article review

Studies were found to be relevant and on target with the objectives of this review paper, as they provided the authors with the opportunity of describing and clarifying the most important methodological and technical aspects associated with LCA applications of wastewater recovery in the agricultural sector.

Through their review, the authors could highlight that recovering wastewater into irrigation water, biosolids usable as soil amendments, and energy is a practice that contributes to making agricultural production more resource efficient, and more environmentally and economically sustainable. This should be attributed mainly to the fact that waste water recovery avoids conventional disposal, and the resulting environmental impacts like eutrophication and eco-toxicity. Studies like Kalboussi et al. (2022) highlighted, however, that the

environmental impact of reclaimed water directly depends on the type of tertiary treatment, the technology and the location of the treatment plant in relation to the field and other water sources.

In addition to this, it is essential to comply with local and national regulations on the reuse of treated municipal wastewater for irrigation purposes, and to constantly monitor the microbiological quality of the treated effluents. Doing so will make it possible to avoid soil and water contaminations phenomena, and penalty applications (Moretti et al., 2019).

The review highlighted that sludge from wastewater treatment should be valorised and recovered in a sustainable manner, instead of being disposed of in sanitary land, thus avoiding a 33–36 % increase in GHG emissions (Liu et al., 2018). In particular, the reuse of struvite can meet the fertiliser needs of peri-urban agriculture, thus upgrading WWT facilities to further support sustainability in local food production and consumption in cities (Ruff-Salís et al., 2020).

Moreover, to interestingly emerge is that advanced strategies for fossil energy savings can be crucial for enhancing the environmental sustainability level of WWT plants. Under this perspective, it would be desirable that those strategies provided the combined approach of making changes in the process technology to reduce energy consumption (if feasible), and using renewable energy sources.

Tools like LCA are, however, desirable to be applied to determine the recovery systems and the improvement strategies that perform best in energy and environmental terms. To that end, this review article highlighted the importance of:

- creating a system model that is as close as possible to the real one, from compiling a reliable set of primary and secondary data; and
- giving due attention to the selection of the most relevant impact indicators, so as to avoid generating unreliable results that do not fully express the environmental profile of the system investigated.

The authors of most of the articles reviewed carried out, in fact, holistic assessments, with a multi-indicator approach, that provided an exhaustive overview of the overall environmental burdens and gains coming from the systems investigated. It should be observed, however, only one of the review-sample articles, that is Canaj et al.'s (2021), carried out a monetisation of the pre-determined life cycle environmental impacts, so as to weigh, aggregate, and compare results.

So, given the lack in the subject literature, it would be desirable, however, to expand the assessment to the economic and societal dimensions of sustainability, considering that water treatment and reuse are intended to meet human needs for water and other value-added bio-materials, thereby being beneficial from a monetary and ethical point-of-view. This would lead to sustainability assessments in an integrated holistic approach, that allow for best identifying and quantifying trade-offs, both between life cycle stages and between different sustainability dimensions.

GWP resulted to be the most quantified environmental impact indicator, but different values were obtained depending upon the wastewater recovery process considered. By way of example, the following ones were extrapolated by the authors:

- with regard to sludge extraction for bio-based compound production, the integration with an aerobic digestion plant contributes to increasing GWP up to a value range of 723.4–1.3E03 kg CO₂-eq (Hong et al., 2009);
- in the case of recovery of nutrient biosolids for soil amendment, the authors noticed GHG-emission gains for the system explored by Kjerstadius et al. (2017), that are between –10 and –37 kg CO₂-eq, with the highest value recorded for the source-separation based scenario;
- lastly, in the case of wastewater recovery into irrigation water, a 0.21 kg CO₂-eq were determined by Canaj et al. (2021), per 1 m³ of water analysed.

⁴ Eco-Machine™ utilises a series of tanks containing a variety of microorganisms, macro-invertebrates, and plants to treat wastewater and recover nutrients, all with no chemical input (Roman and Brennan, 2021).

However, differences in the values reported in Table 5, for all the life categories considered by the twenty-seven papers' authors, were found to be due to differences in the treatment plant investigated, and to methodological issues associated with LCA applications. Their comparability were found by this SLR's authors to be not always doable and reliable, which puts emphasis upon the need for harmonization of LCAs and of the way results are presented, to make them understood and easy to review and build upon.

6. Conclusions, limitations and practical and policy implications

LCA has been extensively used for assessing the multiple environmental impacts associated with the production of a wide range of agricultural commodities. Particularly, the increased scarcity of water for agricultural irrigation in semi-arid and arid regions has resulted in a growing interest in water reuse practices, in order to contribute to reducing those impacts in the context of a sustainable, equitable circular economy.

Under this perspective, this SLR allowed to highlight that the optimal wastewater treatment represents the trade-off between environmental risks, good quality biofertilisers, available irrigation water, and economic efficiency.

Moreover, the regulation on wastewater recovery and sewage sludge can drive stakeholders, including producers, users and practitioners, and policy makers, towards the implementation, assessment and promotion of more sustainable, less-energy intensive, more resource-efficient wastewater recovery installations. From this point of view, this SLR's authors came to the conclusion that design, operational, and management conditions influence the efficiency of wastewater and waste management systems and, so, their effectiveness in contributing to environmental pollution mitigation. Under this perspective, based upon the findings obtained, this SLR can stimulate public administrations at national and local scales in their planning and funding activities towards implementing circular economy paths based upon wastewater recovery for a sustainable, resilient agriculture.

Another problem concerns the presented data in the papers: particularly, normalised data in some papers, percentage values and punctual data cannot be compared easily and this is a parameter of significant uncertainty that was found in this SLR. Actually, the authors encountered some difficulties in extrapolating information and results from a number of the reviewed papers, mainly due to their absence or to the form they were presented (i.e. as percentage and mean values, or in histograms without point indication of the value).

Moreover, human health implications were accounted for with a midpoint approach, based only on the toxic effects of chemicals, without considering the other impacts such as for e.g. eutrophication, oxidation.

However, insights into the life cycle impacts and potential trade-offs of those emerging practices are still limited by the paucity of systematic evaluations of different water reuse implementations as emerged by the limited papers published. This is why this SLR's authors believe that further investigations comparing the influence of different crops on the quality and amount of wastewater generated and the treatment needed would be desirable for advancement of research and enhancement of inventory and impact datasets in the field.

Abbreviations

AAC	Aquatic acidification
BSL	Baseline scenario
ED	Energy demand
FEC	Freshwater ecotoxicity
FET	Freshwater eutrophication
FU	Functional unit
GWP	Global warming potential
HCT	Human carcinogenic toxicity

HNCT	Human non-carcinogenic toxicity
LCA	Life Cycle Assessment
LCIA	Life cycle impact assessment
LU	Land use
ME	Mineral extraction
MEC	Marine ecotoxicity
MECs	Microbial electrolysis cells
MET	Marine eutrophication
MFCs	Microbial fuel cells
MRCs	Microbial recycling cells
NPK	Nitrogen, phosphorus, and potassium
OLD	Ozone layer depletion
PM10	Particulate matter
S _x	Scenario x
TAD	Terrestrial acidification
TEC	Terrestrial ecotoxicity
TWW	Treated wastewater
UV	Ultraviolet
WC	Water consumption
WRRF	Water resource reclamation facility
WWTP	Waste water treatment plant

CRediT authorship contribution statement

Tiziana Crovella: Conceptualization, Data curation, Formal analysis, Investigation, Resources, Software, Writing – original draft, Visualization, Methodology. **Annarita Paiano:** Conceptualization, Funding acquisition, Project administration, Supervision, Validation. **Pietro Paolo Falciglia:** Writing – review & editing, Validation. **Giovanni Lagioia:** Writing – review & editing. **Carlo Ingrao:** Conceptualization, Formal analysis, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Prof. Annarita Paiano reports financial support was provided by Government of Italy Ministry of Education, University and Research.

Data availability

No data was used for the research described in the article.

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