Environmental
Science
Water Research & Technology

CRITICAL REVIEW

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Cite this: *Environ. Sci.: Water Res. Technol.*, 2026, **12**, 1342

Valorising co-produced oxygen from green hydrogen systems: circular economy pathways in wastewater treatment

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Received 30th June 2025,
Accepted 26th January 2026

DOI: 10.1039/d5ew00608b

rsc.li/es-water

Population growth, climate change, and urbanisation significantly contribute to environmental stress, particularly through the depletion of finite resources like clean, easily accessible freshwater. In the water industry, the supply chain must become more independent, shifting from the prevailing linear delivery model to a circular economy. This shift can be achieved by adopting advanced treatment methods to ensure high-quality treated water and minimising waste and emissions. A transition to a circular economy can offer an opportunity to address sustainability issues in multiple sectors. For example, the water and energy nexus recognises that these two sectors are inextricably linked. Integrating green hydrogen production and wastewater treatment (WWT) has been identified as a promising strategy as part of the water-energy nexus, which advances the circular economy. When the green hydrogen economy uses treated wastewater as a feedstock, contributing to water reuse, the water industry can further enhance the sustainability of this approach by utilising co-products from hydrogen synthesis, such as high-purity oxygen. This oxygen can then be employed in various stages of WWT, including aeration and producing key reagents such as ozone and hydrogen peroxide, aiming to improve treatment efficiency and reduce emissions. Accordingly, this study examines how such applications can enhance circularity within the water sector. The principal findings were: (i) integrating green hydrogen production with WWT offers promising environmental and economic benefits but requires deeper technical, regulatory, and stakeholder alignment; (ii) optimising co-product oxygen utilisation in aeration and advanced treatment can help enhance WWT performance and economic viability; (iii) future research should prioritise techno-economic assessments, pilot-scale demonstrations, and system-wide integration studies to enable successful implementation of this circular and sustainable approach.

Water impact

Integrating green hydrogen production with wastewater treatment enables circular water reuse while reducing energy demand and emissions. Using treated wastewater as hydrogen feedstock and valorising co-product oxygen for aeration and advanced oxidation can improve treatment efficiency, lower operating costs, and strengthen climate resilience. The approach supports system-wide sustainability, pending targeted pilot trials and regulatory alignment across utilities and communities globally.

1 Introduction

The escalating pressures of population growth, climate change, and urbanisation intensify water stress, necessitating an urgent shift from the current linear delivery model toward a circular economy.[1–5] Establishing circularity through the sustainable reduction of consumption and the enhancement of resource recovery, reuse, and recycling in the water sector can result in decreased raw material use, reduced waste and emissions, and improved energy efficiency.[2,6]

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Implementing a circular economy presents significant challenges.[1,2,7] It necessitates ensuring supply chain independence, minimising waste and emissions, and achieving high-quality water through advanced treatments. Research into energy recovery, minimising environmental impacts, and developing comprehensive net-zero carbon strategies can help address these aspects of the circular economy, but they must be contextualised well.[2,8] The water and energy nexus, particularly the integration of green hydrogen (H_2) production and wastewater treatment (WWT), has been identified as a promising approach to achieving circularity.[8–12]

Green hydrogen is typically defined as hydrogen gas produced using renewable energy sources.[13] Hydrogen has recently attracted substantial attention as a critical energy carrier in pursuing a sustainable and carbon-neutral economy. Hydrogen functions as an energy buffer, has the highest mass-energy density compared to traditional fossil fuels (three times that of gasoline) and assists in the decarbonisation of hard-to-abate industries.[9,14–16] As predicted, green hydrogen has the potential to reduce emissions by nearly a third and supply 24% of the world's energy requirements by 2050.[9] However, some key challenges associated with hydrogen are insufficient research and development, safety and technical challenges, new storage, infrastructure and transportation requirements, market entry barriers, and inadequate public acceptance.

The current methods of green hydrogen production are predominantly limited to water electrolysis, with many others still in the early development stages.[10,14,17] Given the critical concerns about the availability of clean fresh water for hydrogen production, utilising treated wastewater, which is abundant and consistently available, presents an alternative opportunity.[9,10,18] Globally, the annual wastewater volume accounts for 380 000 GL, greatly surpassing the 34 500 GL needed annually to generate the expected 2.3 Gt of hydrogen in a fully developed hydrogen economy.[9,19] Additionally, integrating green hydrogen production with WWT could offer the water sector new pathways to address its prevailing challenges, such as by using co-produced oxygen in treatment processes.

Treating wastewater to a higher quality helps meet effluent standards, reduces environmental impact, and increases the potential for repurposing. Wastewater treatment plants (WWTPs) are responsible for approximately 1.3% of the world's greenhouse gas (GHG) emissions[12] and consume significantly more energy than many other industrial practices.[20] This high energy consumption is a critical issue, particularly in the activated sludge treatment process, which uses around 50–90% of the plant's total electricity demand.[21,22]

Using pure oxygen or oxygen-enriched air has been identified as a potential strategy to reduce greenhouse gas emissions in WWTPs[12] while also achieving higher-quality treated water.[20] Oxygen plays a versatile role in WWT processes, serving either directly or as a feedstock for producing key reagents such as ozone (O_3) and hydrogen peroxide (H_2O_2).[23] Although pure oxygen was introduced as an alternative to air in the activated sludge process (ASP) many decades ago (see Fig. S2),[22,23] current practices for supplying oxygen to WWT processes continue to present challenges.

The prevailing practice for supplying high-purity oxygen to WWT processes primarily involves generating it on-site using traditional methods, such as pressure swing adsorption (PSA) and cryogenic air separation (CAS), or purchasing commercial oxygen gas.[23] The high cost associated with these oxygen supply methods underscores the importance of minimising oxygen waste in the treatment process.[22,23] According to Eckl *et al.*,[24] traditional oxygen production methods are also high in complexity. Given these challenges, identifying an alternative method to supply the required oxygen to WWT processes is urgent, and co-product oxygen from green hydrogen production presents a promising solution. Examples of trials and case studies related to this co-location are available, demonstrating the need to further investigate the potential uses of co-produced oxygen.[9,25]

The integration of co-produced oxygen from green hydrogen production with WWT has shown a promising pathway for supplying oxygen to enhance treatment efficiency, improve oxygen transfer efficiency and process stability, reduce aeration energy demand through lower airflow requirements, and partially offset hydrogen production costs while contributing to broader decarbonisation and resource-efficiency goals. Investigations should compare multiple oxygen utilisation options, evaluate associated trade-offs, and establish a process for selecting the optimal application.[26,27] To date, no comprehensive review has explicitly focused on the utilisation of co-product oxygen from green hydrogen production within WWT systems, with specific emphasis on water-sector circularity. This study, therefore, evaluates this potential and identifies key areas requiring further research to support circular implementation in the water industry.

This study examines opportunities to strengthen circularity in the water sector by utilising co-produced oxygen to enhance supply chain independence, improve treatment performance, and reduce emissions (see Fig. 1). It also consolidates existing knowledge, identifies key gaps, and outlines clear directions for future research. In addition, supplementary information is provided on integrating green hydrogen plants with WWT facilities, including hydrogen generation *via* water electrolysis.

2 Methodology

A systematic literature review was conducted following the PRISMA guidelines,[28] as illustrated in Fig. 2. As shown in Table 1, the literature search was conducted using two search streams in the Web of Science (WOS) and Scopus databases. The use of multiple search streams was driven by this study's focus on integrating two distinct sectors: energy and water. Given the novelty of this concept, one stream specifically addresses this integration (stream 1). In contrast, studies focusing solely on the use of pure oxygen or oxygen-enriched air in WWT (stream 2) date back to the 1970s, around the time pure oxygen aeration was first introduced. Studies conducted

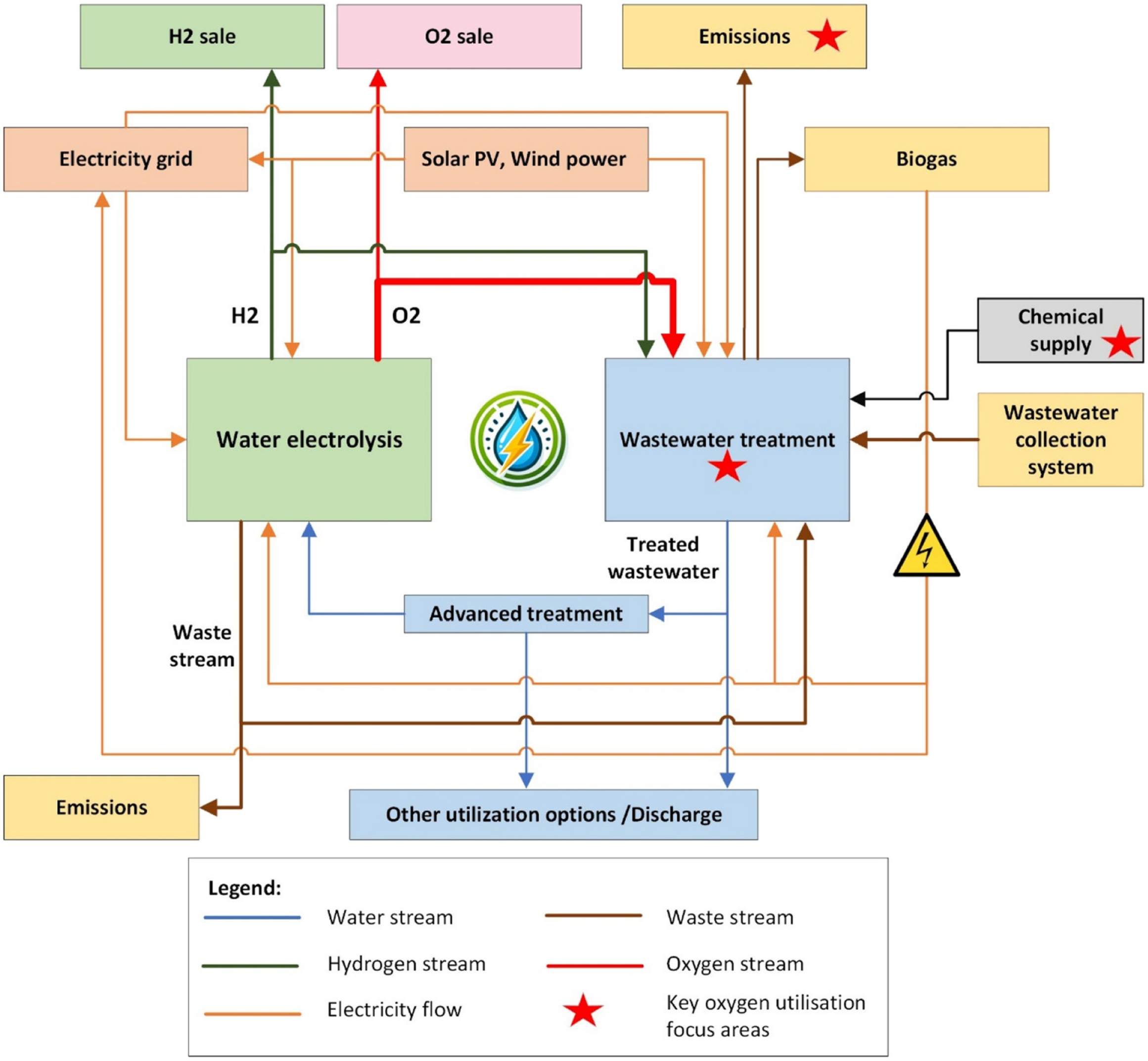


Fig. 1 Integrated hydrogen production and wastewater treatment highlighting key focus areas for co-produced oxygen utilisation towards water-sector circularity.

across multiple countries and regions, encompassing different process configurations and scales, were analysed to assess trends, mechanisms, and technical feasibility.

After identifying 1670 relevant studies from selected databases, duplicates were removed, leaving 1209 studies for title and abstract screening. Of these, 1154 were excluded as out of scope. The remaining 55 studies were assessed for eligibility, and 23 were excluded due to either the focus on biohydrogen production or insufficient information on co-product oxygen utilisation, as this review primarily examines the potential of advanced WWT using co-product oxygen from water electrolysis. Additionally, 92 studies were included in the final review through other methods, such as citation tracking and manual searches, from an initial pool of 131 articles. Under this category, of the initial 131 articles, five could not be retrieved, and the remaining exclusions (34 articles) occurred during eligibility screening because they were out of scope of the article's focus.

For the bibliometric analysis, VOSviewer software (version 1.6.20) was used, and the analysis was conducted separately for the two search streams using temporal clusters to analyse the trends of the studies (Fig. 3). In stream 1, of the 6769 keywords, 58 met the threshold and were categorised into 8 clusters. Keywords such as "green hydrogen", "circular economy", and "optimization" were identified as trending in recent years based on the overlay visualisation. For stream 2, 33 out of 2440 keywords met the threshold and formed 4 clusters, with "waste disposal" and "water purification" as notable trending keywords.

3 Utilising oxygen from green hydrogen production in wastewater treatment

The co-production of oxygen from the green hydrogen production process holds significant potential to address challenges in achieving a circular economy within the wastewater sector by:

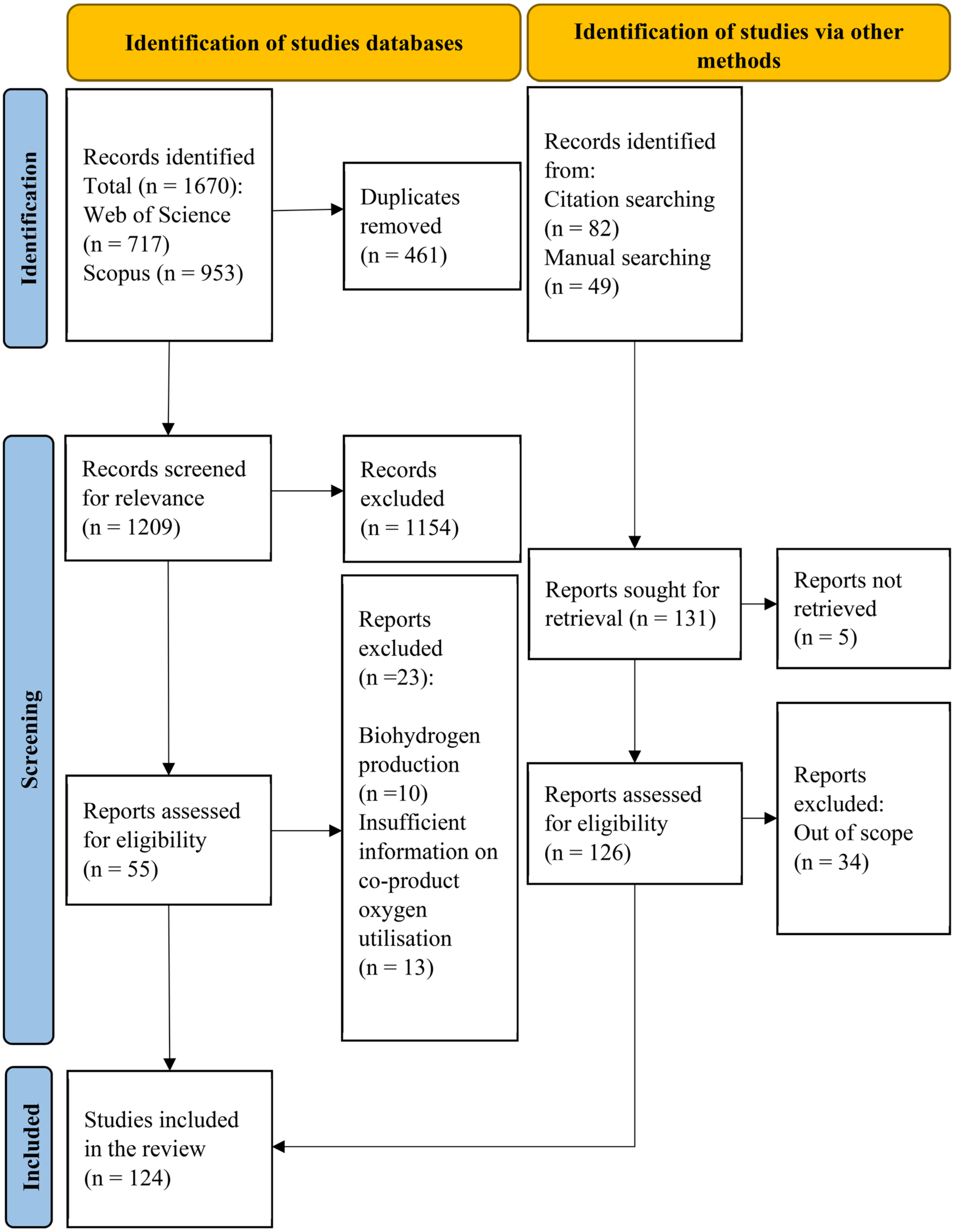


Fig. 2 PRISMA flow diagram.

1. Mitigating supply chain dependencies;
2. Enhancing treatment processes; and
3. Supporting emissions reduction and decarbonisation efforts.

This section explores these opportunities. A summary of studies on utilising oxygen from green hydrogen production in WWT is given in Table 2.

3.1 Addressing supply chain challenges through oxygen co-product utilisation

Developing shorter supply chains and promoting green alternatives through green procurement can significantly enhance supply chain resilience and reduce associated emissions in the water sector.[8] This section explores this

Table 1 Literature review search streams

Search stream	Key words	Conditions	Databases	
			WOS	Scopus
Stream 1	"Hydrogen" AND "wastewater" AND "electrolysis"	Keyword search on title, abstract and keywords Years of publication – 2020 to 2024 Articles and review articles	595	676
Stream 2	"Wastewater" AND ("pure oxygen" OR "oxygen-enriched air")	Keyword search on title, abstract and keywords	122	277
Total			717	953

potential, particularly with regard to chemical supply, energy supply, and sludge management.

Renewable energy-based water electrolysis yields a substantial amount of green oxygen, approximately 8 kg of oxygen per 1 kg of hydrogen.[29,30] Locating water electrolysis-based hydrogen production units onsite or near WWT facilities can provide a direct supply of pure oxygen, which can be used directly in the WWT processes or to produce essential reagents, such as ozone (O_3).[9,20,27,31,32] This has the potential to reduce costs, energy use, transportation requirements, and safety concerns while simplifying operations and maintenance.

According to Woods *et al.*,[9] the globally available wastewater amount exceeds the requirement to produce the projected 2.3 Gt of hydrogen for a mature hydrogen economy. They further emphasised that Australia's annual effluent, which amounts to 1720 GL, could alone produce 0.1 Gt of green hydrogen, a significant amount that is equivalent to expected global demand by 2050.

Assuming the total hydrogen demand for 2050 has been generated as green hydrogen using only water electrolysis, 5 billion tons of pure oxygen can be produced annually.[27] According to Mohammadpour *et al.*,[32] considering 250 L per person per day as the average *per capita* production of wastewater and 300 mg L^{-1} as the typical biochemical oxygen demand (BOD), the required oxygen amount for wastewater oxygenation is about 0.3 m^3 per person per day, which is less than 5% of the oxygen generation by electrolysis considering the hydrogen requirement as 15 m^3 per person per day. This calculation suggests that co-product oxygen from water electrolysis is a potentially useful resource for use in WWT.

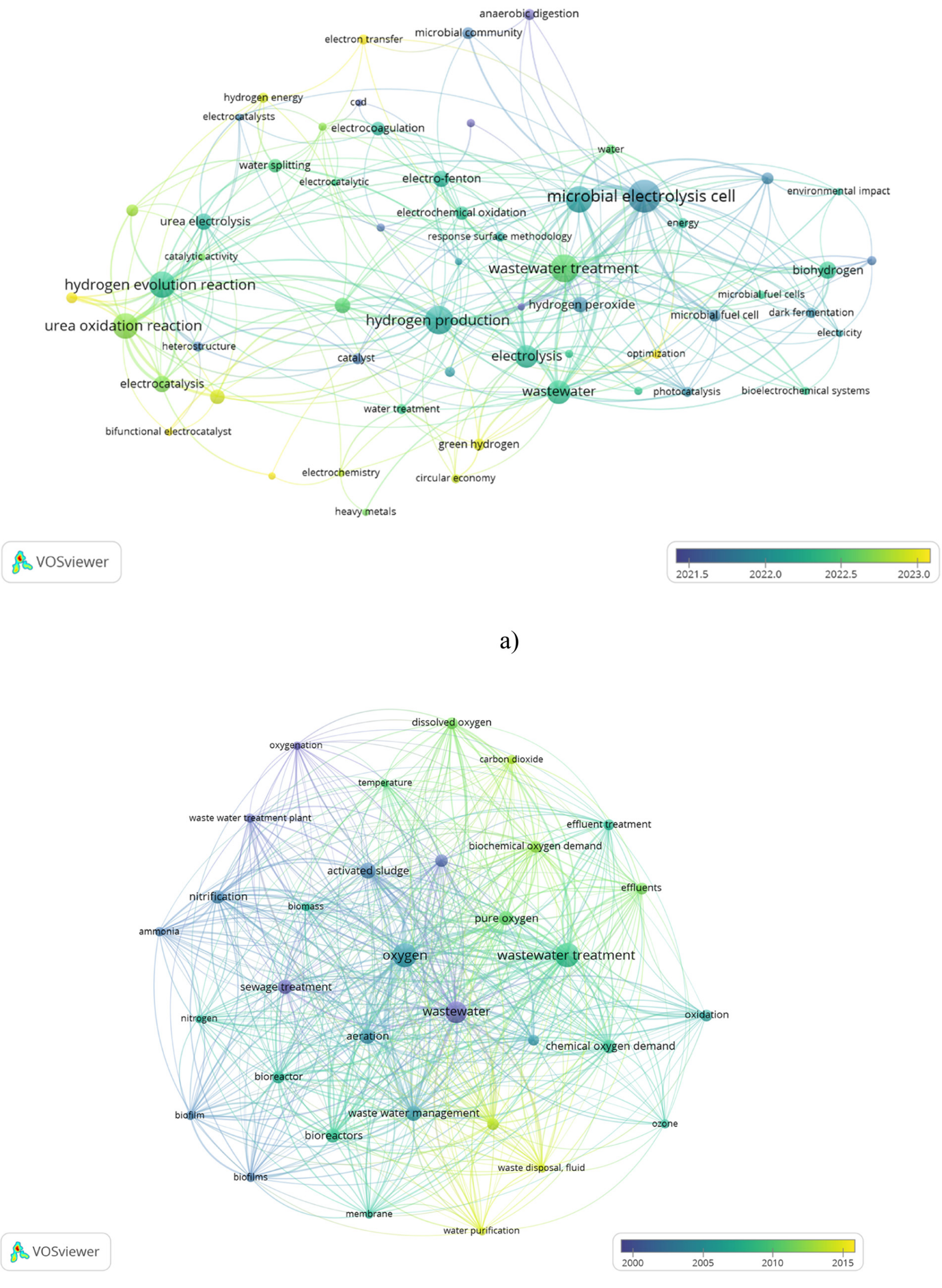
An example calculation was carried out by Liu *et al.*[27] using the International Water Association (IWA) benchmark simulation model 2 (BSM2), determining the alkaline water electrolysis (AWE) capacity requirement to cover the oxygen requirement for aeration and ozone generation (252 kg per hour and 375 kg per hour, respectively) as 4.53 MW, further emphasising the capability of Proton exchange membrane water electrolysis (PEMWE) systems to provide even higher production rate compared to the AWE. For a WWTP having a wastewater flow rate of 20 660 m^3 per day and 50.06 g COD per m^3, the water requirement for an AWE system was calculated at approximately only 0.2% of the total flow,[27] a manageable amount that can be allocated without competing with other treated wastewater demands. Rusmanis *et al.*[12] stated that a 10 MW electrolyser system, operating at 80% capacity, could potentially supply an adequate amount of oxygen for the aeration needs of a WWT facility serving a population equivalent (PE) of 426 400.

A recent case study was conducted on Sweden's ten largest WWTPs to assess green hydrogen-based oxygen utilisation in WWT, focusing on energy gains and oxygen demands.[33] Considering a 10% ozone gas concentration, an ozone dosage of 6–10 mg O_3 per L, and 90% of treated wastewater flow from 50% of these WWTPs, the oxygen demand for producing the required ozone was calculated to be approximately between 15 000–25 000 tons per year, with a corresponding market value around US$22–36.5 million (assuming 1 SEK = 0.10 USD).

Ozone-based oxidation has recently garnered significant attention due to growing concerns about trace constituents in wastewater.[23] Increasing the concentration of ozone is essential for expanding the application in WWT.[34] Enhancing the oxygen concentration in the feed gas stream significantly boosts ozone production yields.[35] The concentration of oxygen in the feed gas critically influences ozone production, generating 0.5–3.0% ozone by weight with air and 8–12% with pure oxygen, approximately two to four times higher than using air alone.[23,36]

High-purity oxygen, the beneficial co-product of green hydrogen production, has a purity of more than 99% oxygen[14] and can possibly be transformed into ozone, providing higher ozone yields.[9,27,33,37] Higher gaseous ozone concentrations in the supply increase liquid mass transfer efficiency, resulting in elevated dissolved ozone levels in water.[38] This leads to lower costs and energy consumption for generating ozone by reducing its demand. However, to maximise ozone concentration, determining the optimal pure oxygen flux is crucial, as ozone levels reach a peak with increasing flux.[35] This can be further optimised by novel technologies, such as using a double dielectric barrier discharge in the process.[34] However, it is important to recognise the limitations of ozone application as well, including the need for strict safety measures such as ozone detectors, adequate ventilation, and use of suitable materials,[39] as well as increased process complexity compared with UV or chlorine disinfection and reduced suitability for wastewaters with high contaminant loads.[36]

The use of hydrogen peroxide (H_2O_2) in WWT is increasing because of its ability to generate on-site, environmental friendliness, and its effectiveness in oxidising contaminants. Multiple studies demonstrated that higher



a)

b)

Fig. 3 Bibliometric analysis a) search stream 1 and b) search stream 2.

Table 2 A summary of studies on utilising oxygen from green hydrogen production in wastewater treatment

Reference	Study aim(s)	Oxygen application in WWT	Key finding(s)
Ramirez *et al.*[61]	To assess the techno-economic feasibility of electrolyser-derived oxygen use in activated sludge treatment	Activated sludge treatment	In 2020, the calculated cost of oxygen production from electrolysers exceeded that of commercial oxygen, but by 2030, with reduced investment and electricity expenses, it became competitive with commercial oxygen under favourable economic conditions
Hönig *et al.*[14]	Assessing the potential to lower the levelized cost of hydrogen through the use of electrolyser-produced oxygen in WWT	Aeration	The use of co-product oxygen in the aeration tank was associated with a positive impact on net present value (NPV) (up to 13%), with substantially higher increases (up to 58%) when photovoltaic (PV) electricity was used alongside grid electricity
Mohammadpour *et al.*[32]	To assess the potential to reduce hydrogen production costs through utilising electrolysis-derived oxygen in WWT and aquaculture	Activated sludge treatment	Simulation suggested up to 30% electrolyser energy savings with oxygen use in wastewater aeration. The oxygen transfer efficiency was higher for oxygen-based fine-bubble aeration, particularly at greater diffuser submergence depths
Donald and Love[26]	To evaluate the potential of electrolysis-derived oxygen to enable energy shifting in WWT processes	Activated sludge treatment	Identified the potential for utilising excess oxygen generated during peak renewable energy supply, which can be stored and used at the WWTP during periods of highest oxygen demand
Gretzschel *et al.*[37]	To assess ozone-based advanced WWT in an electrolysis-integrated WWTP	To produce ozone	Potential water–energy nexus benefits include improved electrolyser efficiency *via* heat and co-product oxygen utilisation, reduced liquid oxygen demand, and enhanced renewable energy integration
Liu *et al.*[27]	To propose a sustainable approach for integrating green hydrogen into the WWT industry	Aeration and to produce ozone	Assessed the potential of applying co-product oxygen for aeration and ozone production, concluding that the green hydrogen-WWT nexus is a viable approach
Rusmanis *et al.*[47]	To assess the role of electrofuels in a circular economy for achieving net-zero objectives	Activated sludge treatment	The use of co-product oxygen from electrolysis for wastewater aeration reduced annual electricity consumption by 3.6% at a 65 000 population-equivalent municipal WWTP, employing a 122 kW electrolyser operated on curtailed on-site electricity
Kabir *et al.*[11]	To explore circular economy opportunities by integrating hydrogen production into the water sector	Aeration	Illustrated the potential to reuse co-product oxygen from water electrolysis in aerobic digestion within the WWT facility, thereby supporting a circular economy
Woods *et al.*[9]	To assess the role of the water sector in enabling a sustainable hydrogen economy	Aeration and to produce ozone	Outlined the potential for utilising co-produced oxygen for aeration and ozone production, highlighting opportunities to reduce hydrogen production costs and the environmental impact of WWTPs
Campana *et al.*[48]	To investigate the techno-economic feasibility of achieving highly renewable energy-dependent WWT systems	Aeration	Utilising co-produced oxygen in the aeration process helped reduce electricity consumption in WWT
Abdelfattah *et al.*[20]	To synthesise available knowledge on the use of pure oxygen in biological WWT, including its performance and sustainability	Aeration	Discussed that the co-produced oxygen could be more than sufficient (only 5% is adequate) for activated sludge aeration, demonstrating the strong potential and sustainability of integrating solar energy-based green hydrogen production with WWT
Schäfer *et al.*[39]	To investigate how WWTPs can contribute to sector coupling	Aeration and to produce ozone	Reviewed ozonation with an emphasis on safety and examined pure-oxygen aeration, where similar or improved treatment performance and theoretical energy savings were possible, despite contradictory findings and limited economic validation at large scale
Kato *et al.*[50]	To evaluate pathways for the effective use of oxygen co-produced during water electrolysis for hydrogen generation	Not specified	Effective utilisation of co-produced oxygen in WWT offers significant potential to enhance energy efficiency and reduce carbon dioxide (CO_2) emissions

Table 2 *(continued)*

Reference	Study aim(s)	Oxygen application in WWT	Key finding(s)
Squadrito *et al.*[78]	To evaluate the financial performance of green hydrogen production with oxygen co-generation across different scales of water electrolysis systems	Not specified	Increasing electrolyser size generally enhances profitability, and self-produced oxygen is economically viable for most system sizes (from 300 kW to 10 MW) at market oxygen prices ≥3 € per kg and hydrogen selling prices of 6–10 € per kg
Eckl *et al.*[24]	To assess the beneficial uses of co-product oxygen from green hydrogen production	Activated sludge treatment	Electrolysis has been highlighted as a promising alternative for affordable and sustainable oxygen production. Further research is encouraged to ensure efficient distribution of the co-product oxygen
Aimale-Troy *et al.*[71]	To assess the impact of dissolved oxygen (DO) variation, induced by the use of co-produced oxygen, on bacterial community structure and oxygen uptake rates in activated sludge systems	Activated sludge treatment	Higher DO levels reduced bacterial diversity and increased oxygen uptake rate, but maintained consistent COD removal
Cameron *et al.*[65]	To conduct a techno-economic assessment of the co-location of WWT and hydrogen production systems	Aeration	Using co-produced oxygen for enriched aeration in aeration basins could offset hydrogen production costs or, in energy terms, recover approximately 0.5–2% of the energy input to hydrogen production
Donald *et al.*[69]	To evaluate the integration of water electrolysis into WWT systems for carbon emission reduction	Activated sludge treatment	The integration of water electrolysis into WWT, with the produced hydrogen used to refuel local buses, represents a feasible and environmentally beneficial pathway for reducing carbon emissions

oxygen purity and higher flow rates create ideal conditions for better H_2O_2 generation.[40–43] These conditions can be further optimised for greater effectiveness by raising the oxygen utilisation efficiency and lowering energy loss.[44] However, similar to ozone generation, it is important to determine the oxygen mass flow rate that corresponds to optimal H_2O_2 generation.[40]

This indicates that the co-produced oxygen from green hydrogen production can be effectively utilised in the H_2O_2 synthesis process. Given the lack of studies to comprehensively assess the feasibility of utilising green hydrogen-based oxygen for H_2O_2 generation, further research is needed in this area. Using the right electrocatalysts as the anode, water oxidation can generate H_2O_2 instead of oxygen, demonstrating high efficiency and lower costs,[45,46] and this on-site generation of H_2O_2 at hydrogen production and WWT facilities could reduce storage demands and risks.[10]

Co-locating green hydrogen production facilities at WWTPs can enhance energy management by using generated hydrogen as an energy source and co-produced oxygen for reducing energy demands and improving treatment efficiency. While employing produced hydrogen for refuelling vehicles,[14,37] biomethanation[12,27,47] or as an alternative energy supply method in WWTPs,[48] utilising co-produced oxygen can facilitate significantly higher efficiency gains. Compressing and storing green hydrogen-based oxygen produced during peak renewable energy availability and supplying it during peak oxygen demand has proven to be a feasible energy-shifting approach.[26]

Multiple studies have demonstrated that introducing oxygen as an alternative to air in the activated sludge process has the ability to lower energy costs.[12,22,49] This reduction can be up to fivefold due to the increased oxygen concentration in the supply.[32] Using co-product oxygen helps lower the electricity consumption associated with oxygen production by conventional air-separation technologies, such as pressure swing adsorption and cryogenic air separation.[50]

Combining sustainable hydrogen production with WWT into a cohesive process has been proven to synchronise the renewable energy supply with the daily oxygen requirement.[26] Donald and Love[26] proposed a novel energy-shifting technique that enables the storage of compressed oxygen as an ‘oxygen battery’ during peak electricity availability, allowing its utilisation when the WWTP reaches its maximum oxygen demand. A power-to-gas project in Germany showed a 13% increase in its net present value (NPV) by utilising co-produced oxygen in the aeration tank, which could be further improved up to 58% by adding solar photovoltaic (PV) to the system.[14] Deriving benefits from generated oxygen showed a reduction in the levelized cost of hydrogen (LCOH) compared to traditional air-based aeration in this study.

Producing ozone from pure oxygen can significantly lower operating costs and boost efficiency compared to air-based ozone generation.[27] Pure oxygen-based ozone generation results in lower energy consumption compared to air-based systems, particularly by eliminating the requirement of conditioning the feed gas in the preparation stage (saving 4.4–6.6 kWh kg^{-1} O_3) and by reducing energy consumption in the ozone generation stage by around 40% in average.[23]

Reviewing previous literature, Risch *et al.*[51] similarly summarised that altering the feed gas to pure oxygen in an ozone generation system could reduce energy demand by 25%, with the negligible energy requirement for the air preparation. Gretzschel *et al.*[37] conducted a detailed analysis showing that the cost of liquid oxygen can be reduced by utilising the co-product oxygen generated during electrolysis for ozone production.

Effective management of sludge from WWT is crucial due to its composition and potential environmental impacts, making the reduction of sludge production highly beneficial. Using oxygen in the activated sludge treatment process can reduce sludge production, lowering sludge disposal costs.[20,22] Specifically, employing pure oxygen for aeration achieves complete oxidation, and with higher dissolved oxygen (DO) concentrations, the presence of filamentous bacteria becomes limited, thereby reducing sludge bulking and biomass foaming, resulting in denser and better-settling sludge.[22,33]

3.2 Enhancing wastewater treatment processes

Evaluating the potential of high-purity oxygen in WWT processes to meet advanced treatment requirements, including improved effluent quality, enhanced efficiency, increased system capacity, and reduced emissions, can significantly aid in assuring economic efficiency and circularity. There are a limited number of studies that have assessed leveraging co-produced oxygen from green hydrogen synthesis (in WWT colocations), and they indicate mixed outcomes and results.[26]

Pure oxygen can be directly utilised at various stages of WWT, specifically: 1) in wastewater collection systems to control odour, 2) in secondary WWT (in activated sludge process and membrane aeration bioreactor (MABR) process), 3) for post-aeration, 4) for sludge treatment, and 5) for water recovery processes (see Fig. 4).[23] Utilising pure oxygen in the activated sludge process has garnered significant attention due to its potential to enhance the treatment process.[20,22] The use of oxygen for odour control in wastewater collection systems, secondary WWT, and other high-purity oxygen applications is discussed in detail below.

a) Odour control in wastewater collection systems. Controlling odours from wastewater systems can be achieved *via* two strategies: 1) avoiding odorous gas production and 2) controlling the emission of produced odorous gases.[52] This topic's main focus is on preventing odorous gas production, whereas the next topic discusses controlling the emission of odorous compounds.

Injection of pure oxygen at critical points in a wastewater collection system has proven effective in facilitating aerobic conditions to limit the release of odours by controlling hydrogen sulfide (H_2S) levels.[23,52] The limited oxygen solubility in wastewater with air injection can be addressed by introducing pure oxygen, which has a fivefold higher concentration (reaching higher DO levels around 5–7 mg L^{-1}).[52,53] Talaiekhozani *et al.*[52] further highlight the expense associated with pure oxygen utilisation as a significant barrier to its application. However, the cost of oxygen production associated with traditional methods could potentially be mitigated by utilising co-produced oxygen from green hydrogen production, suggesting and opportunity for further study.

b) Secondary wastewater treatment. Aerobic WWT is crucial for decomposing organic pollutants, facilitating effective nutrient removal, enhancing overall treatment efficiency, and producing environmentally safer effluents. Aeration-based secondary treatment, considered the highest source of energy consumption in a WWT facility, accounting for 50% to 70% of the total energy consumption[39,54] and even as high as 90%.[22,26] Consequently, supplemental high-purity oxygen addition may theoretically reduce aeration-related energy demand and operating costs through improved oxygen transfer efficiency, although additional operational energy requirements, such as additional mixing, extra

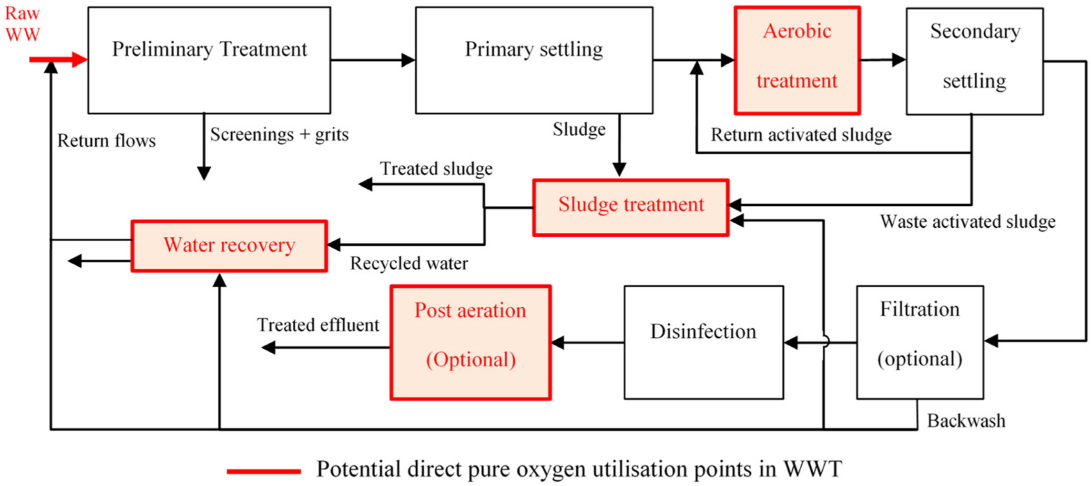


Fig. 4 Schematic developed by the authors highlighting WWT process units with potential direct oxygen utilisation, informed by standard wastewater engineering practice as described in Metcalf & Eddy.[23]

infrastructure costs, and safety measures to reduce fire risks, need to be evaluated. The approach is also potentially more sustainable and efficient if the oxygen is sourced as a co-product from green hydrogen production.

The addition of pure oxygen as opposed to air results in increased oxygen transfer rates even at low gas flow rates, leading to higher DO concentrations in wastewater.[22,32,33] Studies have shown up to a tenfold rise in DO levels within the digesters,[55] and up to seven times the DO provided from air-based aeration in a study on salt-tolerant sludge with 1% to 3.5% salinity in wastewater.[56] This increase has been calculated as a 20% improvement in the oxygen mass transfer coefficient when utilising oxygen from water electrolysis to replace atmospheric air.[26] Besides the aeration system, the α-factor, which indicates the impact of wastewater quality on oxygen transfer, showed a higher value with pure oxygen-based aeration in a membrane bioreactor system.[57]

According to Metcalf & Eddy,[23] diffused-air systems, mechanical aeration or aeration systems specially designed for high-purity oxygen supply, such as the Speece Cone,[26] can facilitate pure-oxygen-based aeration. However, when green hydrogen-based oxygen is directly utilised for aeration, with its high pressure exceeding 500 kPa (compared to only 80 kPa provided by current air blowers), it can result in additional costs for air blower retrofitting.[9]

Fine bubbles or microbubbles are recommended for efficient oxygen transfer due to their enhanced contact area, prolonged stagnation period, reduced bubble ascent rate, better mass transfer coefficient values and potential for further shrinkage leading to higher gas retention.[20,22,32,58] Further, this can aid in minimising membrane fouling.[20] Focusing on the utilisation of oxygen from water electrolysers, Mohammadpour *et al.*[32] identified 2.5 mm as the critical bubble diameter (the bubble rising speed remains nearly constant despite increasing the diameter above 2.5 mm), showing a 12% increase in the ratio between oxygen transfer rates of oxygen and air compared to the corresponding value calculated considering the higher driving force by pure oxygen. The resulting higher DO levels (a minimum of 1.1 mg O_2 per L is recommended for aeration) can significantly reduce the risks of filamentous bacteria growth, foam formation, and sludge bulking.[22,33] Other than using fine bubbles, early detection can assist in minimising nocardioform foaming, allowing for timely interventions to be taken.[23]

Enhanced DO concentrations with pure oxygen-based aeration boost enzyme activities, improving microorganism proliferation, specific oxygen uptake rates and pollutant removal efficiency.[20,22,58,59] Introducing pure oxygen for aeration lowers the diversity and richness of the microbial community and changes its structure, but results in a more stable microbial community that can endure varying food-to-microorganism (F/M) ratios, leading to exceptional performance.[20,58,60] Conversely, Skouteris *et al.*[22] highlighted that when the F/M ratio is low, there is a higher chance of filament growth and weak flocculation, while a high F/M ratio can result in dispersed growth in pure oxygen-based systems.

Increased microbial activities due to pure oxygen aeration can rapidly decrease the DO concentration in the secondary settling tanks, resulting in poor settling and low effluent quality levels.[22] However, it is important to note that pure oxygen allows more organic materials to decompose,[33] lowering the effects of the aforementioned negative impacts. Further research is recommended to comprehensively understand the effects of various aeration methods on microbial activities and WWT performance.[22]

Pure oxygen-based aeration is recommended for effectively treating wastewater with high concentrations of pollutants (*e.g.* organics, micropollutants and phenolic compounds) and salinity due to its ability to maintain good aerobic conditions even with low oxygen flow rates.[20,22] However, it is crucial to determine changes in performance related to variations in mixed liquor suspended solids (MLSS) concentrations under different hydraulic retention time (HRT) values.[22] Increased flows can interrupt operations by depleting MLSS.[23] As pure oxygen-based systems tend to produce a discharge with elevated refractory characteristics, it is advised to utilise this application with higher F/M values.[22]

By reviewing previous studies Zhang *et al.*[56] and Zhuang, Han, & Shan,[59] Liu *et al.*[27] describe the potential of increasing chemical oxygen demand (COD) removal efficiency by 10% in activated sludge treatment and around 38% in moving bed biofilm reactors (MBBR) with pure oxygen-based aeration, further highlighting a 60% increase in the ammonia removal efficiency. Similarly, Abdelfattah *et al.*[20] explain the positive impact of aeration with pure oxygen on enhancing organic removal, nitrification and denitrification; however, some previous publications suggest that pure oxygen for aeration can adversely affect nitrification and denitrification processes.

Having an enclosed and/or deep reactor can lead to carbon dioxide (CO_2) gas accumulation, which lowers the pH in wastewater, affecting enzyme reactions, the dominance of specific bacterial species, and the characteristics of the organisms, thereby limiting the nitrification (at pH $<$ 6.6) except acclimation has occurred already.[22,23,39,61] Metcalf & Eddy[23] and Skouteris *et al.*[22] further emphasise that the lower sludge retention time (SRT) and HRT associated with high-purity oxygen-activated sludge treatment (typically 1.5 h to 2.5 h) can limit nitrification at higher temperatures. However, these studies also explain that increasing the buffer capacity in wastewater, enhancing the degree of venting in the reactor chamber, alternating aeration with pure oxygen and air,[62] introducing novel treatment processes such as pure oxygen-fed MBBR systems for further nitrification[63] and providing longer SRT and HRT values (not excessively long as $>$20 days) can mitigate the adverse impacts of low pH. Seeding aged sludge can help overcome issues with low retention times, enhancing nitrification.[22]

Higher dissolved oxygen levels in high-purity oxygen-based systems can adversely affect denitrification by suppressing the production and function of nitrous oxide (N_2O) reductase, resulting in elevated N_2O emissions.[23,64] Information on N_2O emission will be further explained in this paper under section 3.3. However, increased DO levels do not similarly impact all denitrifying bacteria, and proper DO monitoring can help mitigate the effect of elevated DO levels.[23] Duan *et al.*[64] list the general strategies for N_2O mitigation, such as process optimisation by ensuring extended SRT values and modifying the return-activated sludge system, as well as aeration control by lowering the DO set point, reducing aeration rate, implementing intermittent aeration, shortening aeration period, and avoiding over-aeration. Future research can study the applicability of these strategies with high-purity oxygen-based aeration systems.

Focusing on utilising oxygen from electrolysis in an activated sludge process, Donald and Love[26] determined that equipment size could be reduced by four times by substituting high-purity oxygen for air. Moreover, co-product oxygen can increase WWT plant capacity in an emergency by having concentrated oxygen as a backup to deal with unexpected and challenging situations such as climatic incidents or social events.[65] Future designs should consider the potential reduction in equipment sizes by applying high-purity oxygen for aerobic systems, which can also allow existing WWTPs to enhance their capacities using existing infrastructure.[10] Further, in terms of operation, high-purity oxygen leads to a relatively less complex operation and easier DO control, easing the implementation.[23]

c) Other high-purity oxygen applications. High-purity oxygen can be utilised for sludge treatment, recycling water from the WWT process, and post-aeration. According to Metcalf & Eddy,[23] high-purity oxygen-based aerobic sludge digestion is most commonly carried out in closed tanks with mechanical aerators, particularly in cold weather conditions. Although thermophilic digestion is more effective with air supply (requires additional heat), low flow requirements (around 20%), better mesophilic digestion, minimised foaming, and improved nitrification can be obtained *via* oxygen supply.[66] With higher costs associated with oxygen production using conventional methods, high-purity oxygen-based sludge digestion is considered cost-effective only when the plant runs a high-purity oxygen-based activated sludge treatment process as well.[23] Consequently, exploring the potential of green hydrogen-based oxygen is significant in assessing the possibility of overcoming challenges with existing high-purity oxygen supply methods.

Although recovering recycled water from sludge using high-purity oxygen is not widely popular, it is applicable because it facilitates a higher oxygen uptake rate.[23] Additionally, maintaining the recommended DO levels *via* post-aeration in the treated effluent is significant; similar to aeration-based treatment, high-purity oxygen appears to be a potential application here.

3.3 Enhancing emission reduction and decarbonisation in wastewater treatment

Renewable energy-based hydrogen, considered an ideal zero-emission fuel, can also be used to produce certain chemicals and for process heat applications.[67] However, expanding the hydrogen industry to achieve net-zero emission goals must also align with the United Nations Sustainable Development Goals, including actions to mitigate climate change and ensure sustainable water management.[26,68]

Even though oxygen gas itself does not have a global warming potential, it can affect other processes positively and negatively, making environmental impacts.[33] It has been proven that integrating WWT facilities with green hydrogen production can reduce carbon emissions through direct and indirect use of the products from water electrolysis, especially by using the co-produced oxygen.[69–71]

Wastewater treatment plants are responsible for 1.3% of the world's GHG emissions.[12] The scope 1 emissions, primarily the N_2O and methane (CH_4) gases emitted directly from the wastewater and sludge treatment processes, appear to be reducible by applying co-product oxygen in the treatment processes. The oxygen supply from the green hydrogen production can save GHG emissions by eliminating the need for conventional air separation methods,[23] saving approximately 70 tCO_2-e/a with a 400 gCO_2-e per kWh grey electricity supply for producing 600 t/a oxygen.[37] Furthermore, Donald *et al.*[69] analysed emissions from an integrated hydrogen production and WWT facility, concluding that this integration is a preferable option with environmental benefits, also considering co-product oxygen utilisation for aerobic WWT.

Limited oxygen transfer with air-based aeration can lead to considerable odour (*e.g.* H_2S) and GHG (*e.g.* CH_4) emissions.[32] It has been identified that pure oxygen-based aeration systems have lower emissions compared to air-based aeration systems,[20] whereas Rusmanis *et al.*[12] calculated this reduction as a 40% amount. Pure oxygen-based activated sludge treatment results in lower sludge production, reduced odour, and decreased emissions of volatile organic compounds (VOCs).[22,33]

Nitrous oxide (N_2O) is considered a highly potent greenhouse gas, with an impact 300 times greater than that of CO_2, and it significantly contributes to ozone layer depletion.[23,72] In WWT, N_2O is generated during biological nitritation by ammonia-oxidising bacteria (AOB) and during biological denitrification by heterotrophic bacteria.[23] The primary contributor to N_2O emissions has been identified as aeration zones, which have AOB activities, rather than denitrification zones driven by heterotrophic bacteria because of the immediate N_2O stripping occurring under aerated conditions.[73]

According to Metcalf & Eddy,[23] AOB-led N_2O production can occur under both lower and higher DO concentrations, contingent on the gene expression level for nitrite reductase (nirK) and nitric oxide reductase (norB). Lee *et al.*[74] similarly highlight that low DO levels (<1.5 mg L^{-1}) can increase the production of N_2O. However, as summarised in the same study, at DO levels >3.5 mg L^{-1}, N_2O production can be partially inhibited due to the increased rate of NH_4^+ oxidation. Because of that, increasing DO levels can potentially reduce N_2O production by nitrifier denitrification.[74] This finding supports using pure oxygen-based aeration to enhance nitrification, as explained by Abdelfattah *et al.*[20] and Skouteris *et al.*,[22] who analysed the use of pure oxygen for aeration. However, it is significant to note that elevated ammonium (NH_4^+) and DO concentrations during nitrifying bacteria recovery from anoxic conditions can also drive significant N_2O production by AOB.[75]

In the heterotrophic denitrification stage, higher DO concentrations, especially when transitioning from anaerobic to aerobic conditions, hinder the production and function of N_2O reductase, resulting in N_2O emissions from the system.[23,64,74] However, it is highlighted that not all denitrifying bacteria are similarly affected by changes in DO concentrations and DO monitoring can help mitigate the effect of elevated DO levels.[23] Duan *et al.*[64] outline general strategies to mitigate N_2O emissions, such as process optimisation by extending SRT values and adjusting the return-activated sludge system, as well as controlling aeration by lowering DO set points, reducing aeration rates, using intermittent aeration, shortening aeration times, and avoiding excessive aeration. Future research can study the applicability of these strategies with high-purity oxygen-based aeration systems. Treatment technologies like membrane-aerated biofilm reactors (MABR) may help reduce direct emissions like N_2O.[70]

Organic matter decomposition under anoxic and anaerobic conditions releases CH_4 gas, which is considered a GHG when uncaptured and emitted into the atmosphere.[76] This CH_4 can be captured and utilised as a renewable energy source (biogas), and its combustion results in less harmful CO_2 emissions than direct CH_4 emissions, thereby decreasing the carbon footprint. Biomethanation can be encouraged by integrating green hydrogen production with WWTPs, thereby eliminating CH_4 emissions from WWT processes.[12,27,47]

As explained in section 3.1, co-located hydrogen hubs enhance independence from the supply chain and reduce energy demands, significantly reducing scope 2 and scope 3 emissions associated with WWT facilities. This co-location provides benefits in the operational activities of WWT, such as transitioning it into a net-zero emission process by encouraging more use of renewable energy to supply the required energy for the treatment process.[26] Further, it has been identified that using decentralised systems to supply energy for green hydrogen and oxygen synthesis seems promising for reducing GHG emissions.[14,77] Utilising produced hydrogen gas as a fuel in the WWT can potentially reduce the associated GHG emissions, which showed an 89% reduction in the case analysed by Gretzschel *et al.*[37] comparing four hydrogen-fueled buses with diesel buses. Moreover, as this co-location can encourage biomethanation, generated biogas can be used as an electricity source, thereby reducing GHG emissions.[37,47]

4 Conclusions & future research needs

Integrating green hydrogen production with WWT shows potential and promise, indicating a range of opportunities for innovative research and applications. This integration requires a better understanding of water security and energy, addressing policies for improved implementation, and developing enhanced strategies.[9] Further analysis of the feasibility of using treated wastewater for electrolysis is also required.[26]

Enhancing the efficiency of the water electrolysis processes can significantly reduce energy consumption and associated costs, thereby amplifying the benefits of this integrated approach. It is recommended to assess different power-to-gas technologies[27] and pay significant attention to energy sources and modes of operation when designing a new project, as these factors primarily determine the efficiency of the water electrolysis process.[37] It is further recommended that more theoretical and experimental studies be conducted on immature electrolysis technologies, such as solid oxide electrolysis cells (SOECs), ideally by running small-scale pilot projects for experimental studies first before making larger investments.[79]

Implementing this novel concept can be challenging, as it requires gaining confidence, convincing industry stakeholders, and establishing interconnections between the two different sectors: energy and water. An extensive evaluation of the trade-offs between power-to-X pathways and water resource recovery facilities can significantly aid in gaining confidence from operators and stakeholders.[26,27] Interdisciplinary expertise will be needed to gain the required technical knowledge for coupling two sectors.[39] Schäfer *et al.*[39] further highlight that the challenges associated with this concept include the lack of experience in the interconnection between sectors, difficulties in promoting and convincing stakeholders for such a large investment, and the significant dedication required to navigate the regulatory environment.

More projects should focus on harnessing co-products from hydrogen production to enhance economic efficiency.[37,80] It is recommended to carry out comprehensive studies that incorporate all potential avenues, such as the utilisation of generated oxygen in WWT, biogas production, heat recovery, and variations in the renewable energy supply.[20,26,47,61] Plant-wide simulations,[26] studies on full-scale systems[20] and life cycle assessments[79] are advised for extended analysis. The optimal configuration that aligns with the system's objectives needs to be determined.[26]

Understanding the optimal process setup and size of renewable equipment is crucial for this integration, an aspect that many studies have not focused on.[26] Designing components for this integration involves high complexity. The current research on identifying the appropriate devices for high-purity oxygen-based activated sludge processes is limited.[26] Future research is needed in areas such as sizing aeration tanks, blowers, and compressors, temporarily storing produced oxygen for aeration, hydrogen storage and utilisation, assuring a reliable renewable energy supply, and conducting further calculation-based analysis and techno-economic assessments.[12]

Linking existing systems with new components that can significantly impact operations will be challenging. Proper coordination and management of utilisation paths are needed to avoid complications in data management and competition between resources.[39] When utilising co-product oxygen, it is crucial to understand its storage requirements, associated costs, and operational details.[33] Future studies can also consider high-purity oxygen liquefaction for storage.[26]

Gretzschel *et al.*[37] highlighted the potential additional energy consumption by using the co-product oxygen for advanced treatment, and this needs to be further analysed. More research should focus on renewable energy sources, such as wind energy, by examining the balance between demand and production.[47] Detailed studies can consider changes in electricity prices, the operations of electrolysers based on demand-side management, variations in inventory costs, and performance changes throughout the plant's lifetime.[61]

Co-location-focused future projects and pilots are recommended further.[65] According to Freund *et al.*,[70] the success of co-location depends on two main factors: 1) the possibility of upgrading and replacing infrastructure in WWTPs and 2) cost-efficient renewable energy production. Future studies need to assess the financial feasibility of minor upgrades or early refurbishments to WWTPs, especially those that are not yet scheduled for replacement.[61,70] Furthermore, Freund *et al.*[70] emphasise the significance of increasing on-site renewable energy generation, particularly through waste-to-energy and solar technologies and the use of power purchase agreements (PPAs). It also highlights the benefits of flexible electrolyser operation strategies, such as advanced electrolysers that can adjust according to market conditions and generate additional revenue by operating similarly to batteries. More importantly, the current hydrogen production has focused mostly on co-locating near hydrogen exporting facilities, but more studies are needed to consider access to water and locating closer to water resources.[9]

More future research is encouraged to assess the possible oxygen applications associated with WWT. Currently, many pure oxygen-based systems are at the bench or pilot scales, making full-scale results questionable.[22] It is recommended to experimentally investigate the consequences of utilising oxygen from water electrolysis further.[61,65] Even though it has been proven that the compressed and stored oxygen from the green hydrogen synthesis can shift the energy demand, allowing the utilisation of renewable energy, it is recommended that the additional impacts on the operation of the WWT facility and the overall cost-effectiveness be examined in greater detail.[26] Further, the same study mentions that a comprehensive analysis of the separate energy requirements for the oxygen supply and mixing in the activated sludge basin can help determine the mixing energy of high-purity oxygen applications compared to the air supply. Moreover, it is necessary to assess closed-activated sludge systems and their additional effects, such as the impact on nitrification due to CO_2 accumulation and the resulting reduction in pH.[61]

Cameron *et al.*[65] emphasised the importance of a comprehensive analysis to examine the impact of enriching aeration gas with oxygen from green hydrogen production to identify its benefits and showcase viable business models. It will be highly beneficial to develop generalised models that can aid in assessing the impacts of applications related to co-product oxygen utilisation, such as the impact of different oxygen concentrations on aeration.[65] Gretzschel *et al.*[37] mention that further studies are needed to develop additional business cases and evaluate the adaptability of their results, where oxygen from the hydrogen plant is harnessed as a feedstock for generating ozone.

More research is encouraged to assess the performance of moving bed biofilm reactor (MBBR) processes with pure oxygen utilisation, particularly focusing on nitrification at lower temperatures ($<$10 °C) with oxygen.[33] Here, laboratory and pilot scale studies are recommended to identify the relationship between temperature, nitrification, and oxygen. Furthermore, evaluating the performance of membrane bioreactors (MBRs) under pure oxygen utilisation is also identified as a promising direction for future research.[61]

The capability of treating high-strength wastewater, such as industrial wastewater, with pure oxygen-based systems can be examined further.[61] Evaluating environmental impacts using life cycle assessments should be done while considering alternatives to conventional activated sludge processes, such as granular activated sludge processes or microalgae-based systems.[48]

The integration of green hydrogen production with WWT presents substantial potential as a sustainable approach, with co-product oxygen serving as a valuable input to enhance WWT processes. The principal findings of this review demonstrate that this sector integration offers significant prospects for environmental and economic benefits; however, realising this potential will require enhanced technical optimisation, regulatory coherence, and stakeholder coordination. Specifically, the strategic application of co-produced oxygen for aeration enhancement and/or advanced treatment methodologies can improve treatment efficiency and bolster overall process sustainability. To support practical implementation, future research should focus on robust techno-economic assessments, pilot- and demonstration-scale studies, and integrated system-level evaluations that capture operational, environmental, and institutional dimensions of this circular and sustainable approach.

Author contributions

Amaya Kahaduwa: conceptualisation, data curation, formal analysis, investigation, methodology, resources, software, visualisation, writing – original draft; Brandon Winfrey: conceptualization, methodology, supervision, writing – review & editing; Thomas J. Hughes: conceptualization, methodology, supervision, writing – review & editing; Mike Tebyetekerwa: conceptualisation, resources, writing – review & editing; Xiwang Zhang: conceptualisation, resources, writing – review & editing; Mark C. M. van Loosdrecht: conceptualisation, supervision, writing – review & editing; Linda Blackall: conceptualisation, supervision, writing – review & editing; Michael Burch: conceptualisation, writing – review & editing; Michael Thomas: conceptualisation, writing – review & editing; Deepak Surendhra Mallya: conceptualisation, writing – review & editing; Li Gao: conceptualisation, writing – review & editing; Ortal Raikhlin: conceptualisation, writing – review & editing; Arash Zamyadi: conceptualisation, funding acquisition, methodology, project administration, resources, supervision, validation, writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

Nomenclature

AEMWE	Anion exchange membrane water electrolysis
AWE	Alkaline water electrolysis
BOD	Biochemical oxygen demand
CH_4	Methane
Cl^-	Chloride ion
COD	Chemical oxygen demand
DO	Dissolved oxygen
Fe^{3+}	Ferric ion
F/M	Food-to-microorganism ratio
GHG	Greenhouse gas
H_2	Hydrogen
H_2O_2	Hydrogen peroxide
HRT	Hydraulic retention time
MLSS	Mixed liquor suspended solids
N_2O	Nitrous oxide
NPV	Net present value
O_2	Oxygen
O_3	Ozone
PEMWE	Proton exchange membrane water electrolysis
PV	Photovoltaic
SOEC	Solid oxide electrolysis cell
SRT	Sludge retention time
WW	Wastewater
WWT	Wastewater treatment
WWTP	Wastewater treatment plant

Data availability

This study was carried out using publicly available data from literature cited in the main text and the supplementary document.

Supplementary information (SI) is available. See DOI: https://doi.org/10.1039/d5ew00608b.

Acknowledgements

This work was supported by the Monash Graduate Scholarship (MGS) from Monash University, Australia, and Barwon Water facilitated *via* Water Research Australia. We acknowledge the support provided by Monash University, Australia, along with industry support from Water Research Australia Nancy Millis Memorial Award, Dr. Nicholas D. Crosbie from Melbourne Water, and Barwon Water experts for their valuable contributions to this study. During the preparation of this work the author(s) used ChatGPT in order to improve the clarity and readability of this text. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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