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REVIEW ARTICLE

Patent-Based Evaluation of Life Cycle and Global Collaboration Trends in Constructed Wetlands, UASB, and Microbial Fuel Cells for Sustainable Wastewater Treatment

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Abstract
This study aims to evaluate the innovation trends and technological maturity, and collaborative dynamics in sustainable wastewater treatment technologies (SWTTs), with a specific focus on Constructed Wetlands (CW), Up-flow Anaerobic Sludge Blankets (UASB), Microbial Fuel Cells (MFC), and their integrated systems. To assess technological progress, a patent analysis was conducted using structured and unstructured data from 467 patents filed between 2001 and 2022, retrieved from the Derwent Innovation Index (DII). Citation metrics were used to determine technological influence, while logistic modeling was applied to estimate diffusion speed, maturity rate, and remaining technology life (ERL). The analysis revealed a 29% annual growth rate in SWTT patenting. China led in the volume of patents and commercialization potential, while the USA demonstrated the highest international collaboration. Keyword analysis reveals that innovation efforts were primarily directed at improving pretreatment technologies and enhancing removal efficiencies of pollutants such as chemical oxygen demand (COD) and ammoniacal nitrogen. Among all the technologies, CW exhibited the fastest diffusion rate (4.97) yet the lowest maturity (74%), reflecting a technology in a rapid growth phase that has not yet reached saturation. The estimated ERL ranged from 8 years for MFC to 14 years for CW, with an overall average of 10 years before market saturation. Beyond descriptive trends, this study provides insight into diffusion-maturity dynamics by highlighting how fast-spreading yet immature technologies (such as CW) may represent future innovation frontiers. In addition, this study integrates patent metrics, diffusion modeling, and collaboration analysis to generate actionable insights for policymakers, investors, and researchers driving sustainable wastewater solutions.

Keywords Constructed wetland · Microbial fuel cell · Up-flow anaerobic sludge blanket · Wastewater treatment · Sustainability · Patent analysis

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Introduction

The rapid pace of population growth, urbanization, and industrial activity has led to a substantial increase in global wastewater generation, placing significant stress on water resources and the environment. According to Sun et al. (2022), anthropogenic activities discharge over 420 billion tons of wastewater into lakes, rivers, and seas each year. With the current rate of discharge, it is globally anticipated that, by 2050, the exponential rise in population, coupled with urbanization and industrialization, will deplete water supplies (Koul et al. 2022). This intensifies the need for wastewater treatment solutions that are not only effective and efficient but also environmentally sustainable (Kathi et al. 2023; Koul et al. 2022; Sonawane et al. 2022). Over

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the years, conventional wastewater treatment technologies, such as activated sludge, nanofiltration, electrolysis, adsorption, advanced oxidation process, and reverse osmosis, have been widely applied across various sectors, including municipal, industrial, and agricultural contexts (Nishat et al. 2023; Vistanty and Crisnaningtyas 2021). While these technologies have successfully reduced contaminant concentrations within allowable limits, they are associated with high installation, operation, and maintenance costs. Many are energy-intensive and produce substantial volumes of sludge, posing additional environmental and operational challenges (Nishat et al. 2023; Senthil Kumar & Saravanan 2018; Singh 2022).

With the global advancement towards sustainable development, there is an increasing advocacy for wastewater treatment technologies that are cost-effective, energy-efficient, and a friendly. These needs are directly aligned with Sustainable Development Goal (SDG) 6 (clean water and sanitation),7 (affordable and clean energy), and 13 (climate action) (Masoud et al. 2022; Obaideen et al. 2022; United Nations 2019b; Yenkie 2019; Molinos-Senante et al. 2014). Consequently, a transition from conventional wastewater treatment methods to more sustainable or "green" technologies is underway. In this context, constructed wetlands (CW), up-flow anaerobic sludge blanket (UASB), microbial fuel cells (MFC), and their integrated systems (CW-MFC and CW-UASB) have emerged as promising alternatives. This study seeks to answer the central research question: How do CW, UASB, MFC, and their integrated configurations compare in terms of technological innovation trends, maturity levels, and remaining innovation life, based on patent analysis and diffusion modeling?

Over the years, these technologies have gained attention for their ability to support sustainable wastewater treatment through resource recovery, bioenergy generation, and low environmental impact (Singh et al. 2018; Zhao et al. 2020). CWs, for instance, use natural processes and plant–microbe interactions for low-cost treatment, while MFCs convert wastewater into electricity using electroactive bacteria (Logan et al. 2006; Das 2017; ElZein et al. 2016; Saravanan et al. 2022; Sonawane et al. 2022; UN-HABITAT 2008; Virdis et al. 2011; Vymazal 2010). Since the recognition of the naturally existing redox condition that exists in CW was parallel to anaerobic and aerobic zones required for MFC operations, in recent years, CWs have turned into energy recovery systems through the integration of CW with MFC (Araneda et al. 2018; Yadav et al. 2012). UASB offer simultaneous treatment and biogas recovery via anaerobic digestion (Ngwenya et al. 2022). Similar to CW-MFC, several studies have also demonstrated the integration of UASB with CW for enhanced treatment efficiency (De la Varga et al. 2013; El-Khateeb and El-Gohary 2003).

In evaluating the technology development of these systems, patent analysis provides a unique advantage over traditional bibliometric methods by revealing market readiness, innovation maturity, and commercialization potential (Mao et al. 2022; OECD 2004; Sun et al. 2022). Unlike scientific publications, patents integrate legal, technical, and economic information that provides insight into technology growth trends, geographical distribution, the identification of potential technologies, research hotspots, technological trends, and the forecasting of technological progress, making them a robust proxy for applied innovation (Ampah et al. 2022; Mao et al. 2022; Sinigaglia et al. 2022).

While innovation in environmental technologies can be measured through various indicators, such as academic publications, R&D expenditure, pilot-scale trials, and commercial deployment, each comes with distinct limitations (Martin 2012; OECD 2004). Academic publications often capture research interest and early-stage development, but may not reflect market readiness or practical application (Godin 2006). Similarly, R&D investments can indicate intent, but do not always result in tangible technological advancement. In contrast, patents offer a more concrete indication of applied innovation and potential for commercialization, particularly when combined with citation trends, assignee analysis, and diffusion modeling (Ernst 2003).

Over the decades, existing studies in this field, as shown in Table 1, have focused on individual technologies or relied heavily on publication data, lacking comparative depth or forecasting analysis. For example, Zhi and Ji (2012) conducted a bibliometric analysis of constructed wetlands using a predictive simulation model over the period 1991 to 2011, but did not integrate patent data. Zhou et al. (2020) took a more integrative approach, combining patent and publication data to assess the development of wetland restoration techniques across countries. However, their analysis remained limited to CWs and did not extend to other SWTTs. In the domain of MFCs, Jiang et al. (2020), used the Web of Science and Derwent Innovation databases to analyze research and patent trends from 1990 to 2018, yet their study did not explore comparative innovation across technologies. Similarly, Mao et al. (2022) focused exclusively on industrial wastewater treatment in their patent analysis from 1973 to 2020, offering limited relevance for broader SWTT applications. Sun et al. (2022) also employed patent data but narrowed their scope to chemical treatment technologies, omitting bio-based or hybrid systems in their review. through patent analysis, without a holistic review of other emergent sustainable technologies to assess the development of chemical treatment technologies for wastewater.

To address this gap, the present study employs a comprehensive patent analysis of CW, UASB, MFC, and their integrated systems. By applying logistic diffusion modeling and

Table 1 Summary of bibliometric and patent-based studies on sustainable wastewater treatment technologies (SWTTs), including CWs, MFCs, UASBs, and their integrated systems

Reference	Study focus and treatment technologies	Method of analysis	Database	Period	No. Publications considered
Zhi and Ji (2012)	A review of research development of **CWs**	Bibliometrics Predictive simulation model	SCI-EXPANDED, Web of Science	1991–2011	3787
Shi et al. (2018)	Evolution of International Scientific Collaboration in **MFCs**	bibliometric methods and social network analysis	WoSCC	1998–2017	20,358
Yu et al. (2021)	Heavy metals and metalloids by **CWs**	Bibliometric analysis	Web of Science and Scopus	1989–2020	619
Colares et al. (2020)	Floating treatment wetlands **[CW]**	Bibliometric analysis	Web of Science Core Collection (WoSCC)	1992–2019	396
Dell'Osbel et al. (2020)	Bibliometric analysis of Phosphorus removal in **CWs**	Bibliometric analysis	WoSCC	1995–2019	2020
Ji et al. (2021)	Mapping the field of **CW-MFC**	Bibliometric analysis	WoSCC	2012–2020	135
Jiang et al. 2020)	Development trends of microbial fuel cell **[MFC]**	Patent Analysis	Derwent Innovation Index	1990–2018	
Collivignarelli et al. (2021)	Trends and recent findings of the microbial community of **UASB**	Meta-analysis of bibliometric data	Scopus	1990–2021	3608
Yu et al. (2023)	Mechanisms of **CW** methane reduction	Bibliometric analysis	WoSCC	1991–2021	108
Patyal et al. (2022)	**CWs** for phosphorus removal in domestic wastewater	Patent Analysis	Relecura patent database	1993–2021	115
Wang et al. (2022)	Microorganisms in **CWs**	Bibliometric analysis	WoSCC	1991–2020	2,764
Xu et al. (2022)	Remediation of microplastics using CWs	Bibliometric analysis	China National Knowledge Infrastructure (CNKI), Wanfang database, WoSCC, and Scopus	1900–2020	79
Xu et al. (2022)	GHGs in CWs	Bibliometrics analysis	WoSCC	2006–2021	332
Marín-Muñiz et al. (2023)	**CWs** with ornamental flowering plants	Bibliometric analysis	Dimensions	2000–2022	92
Wang et al. (2023)	Plant-rhizosphere microorganisms in **CWs**	Bibliometric analysis	WoSCC	1995–2022	231
Li et al. (2024)	Greenhouse gas (GHG) emissions from **CWs**	Bibliometric analysis	WoSCC	2007–2022	286
Miwornunyuie et al. (2024)	R&D status and trend of **CWs**	Bibliometrics Patent analysis. Logistic model (S-curve)	WoSCC Derwent Innovation database (DII)	2001–2022	3,408,192
Qi et al. (2025)	Mitigation and Transformation of GHGs in **CWs**	Bibliometrics	WoSCC	1993–2023	
Sun et al. (2022)	Chemical treatment technologies	Patent analysis	DII database	1970-2021	35,838
Present Study	Sustainable wastewater treatment technologies (CW, MFC, UASB, and their integration)	Patent analysis. Logistic model (S-curve)	WoSCC Derwent Innovation database (DII)	2001–2022	467

estimating remaining life cycles (ERL), the study assesses not only the current innovation trends and geographical spread but also the developmental maturity and future saturation potential for each technology. This broader, comparative, and future-oriented approach provides a more strategic understanding of the innovation landscape in sustainable wastewater treatment. It informs both researchers and policymakers about priority areas for development and investment.

Materials and Methods

A patent review was conducted on the Derwent Innovation Index (DII) platform to retrieve the patent publication scenario for the three sustainable technologies with their two integrated systems. Among several other patent databases, such as the Questel Orbit platform, Korea Intellectual Property Rights Information Service, WIPSON, etc., the DII is recognized as an extensive database that indexes over 50 patent-granting authorities with 39.4 million patent families with regular updates. It is one of the most authoritative and comprehensive databases for patent information, with records related to engineering, sciences, chemistry, electronics, and more. In addition, it also provides patent citations that allow the tracking of technological innovation and its impacts in a particular sector. Hence, it was considered more suitable for this study.

Data Collection

From the 21st of May, 2023, to the 18th of June, 2023, the DII was searched with strict adherence to required search techniques and operators (such as synonyms, Boolean, the appropriate use of quotation marks, parentheses, wild cards, and truncation) following the query recommendations made by Alberts et al. (2009). Figure 1 shows the search query used for each technology to access all related patents. In addition to the search keywords, International Patent Classification (IPC) codes were incorporated into the search query to narrow the scope and reduce pollution, thereby focusing on the current study's specific area of interest. Classification

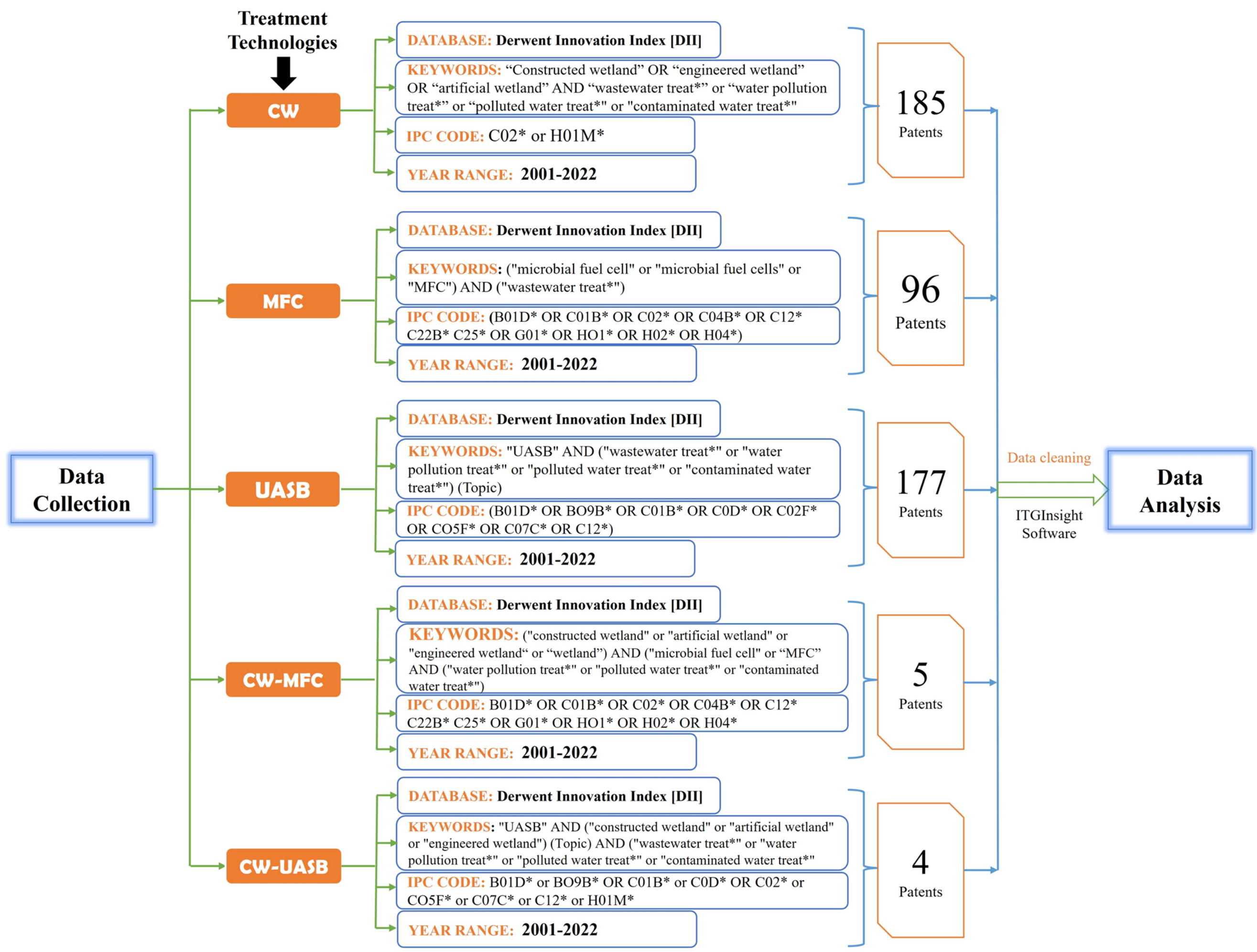


Fig. 1 Workflow for patent retrieval and analysis of sustainable wastewater treatment technologies (CW, MFC, UASB, CW-MFC, and CW-UASB). Patent searches were conducted in the Derwent Innovation Index (DII) database using the field tag "Topic (TS)", which covers Title, Abstract, and Derwent manual codes/keywords. Detailed Boolean queries and field definitions are provided in Supplementary Table S2

codes or systems help patent authorities provide an intellectual structure for the patent database, based on novelty and the knowledge economy. Among the most predominantly used classification codes, such as the European Classification (ECLA), the Japanese File Index and F-Term (FI-F-Term) classification system, the United States Patent Classification (USPC) system, and the Cooperative Patent Classification (CPC) systems, the IPC is the most widely used. They are language-independent symbols that provide a hierarchical system for classifying patents according to their technical application, structural features, or knowledge economy. The specific IPC codes used for each technology are specified, along with a customized timespan for the study (2001–01–01 to 2022–12–31), in Fig. 1, detailed in Supplementary Table S1. The combination of keywords and IPC codes has been proven to be a good strategy from previous studies conducted by Borgstedt et al. (2017), Oltra and Saint-Jean (2009), Ampah et al. (2022), and Sinigaglia et al. (2022a, b).

Data Processing

A total of 185, 96, 177, 5, and 4 patents, respectively, for CW, MFC, UASB, CWMFC, and CW-UASB, were retrieved, downloaded in.txt format, and exported to ITGInsight for data cleaning, refinement, and analysis. Data preparation followed a systematic, multi-stage process to ensure accuracy and reproducibility. First, patent records were screened for completeness by checking for missing inventor names, country data, and other essential metadata, while correcting formatting inconsistencies such as mixed date formats and irregular abbreviation styles. Duplicate entries were then identified, primarily by matching application numbers and standardized patent family IDs, and removed to prevent inflation of results. Additionally, synonyms and name normalization was applied to unify variation in assignee and inventor names (e.g., “Univ Chongqing” and “Chongqing University”), and standardized country names and IPC codes were applied to ensure consistency. Relevance filtering was subsequently performed to exclude patents unrelated to sustainable wastewater treatment, using targeted keyword searches (Fig. 2). Finally, a harmonized, accurate dataset suitable for reliable quantitative and qualitative analysis. This procedure, implemented using ITGInsight (Yuqin et al. 2015) and the sequential cleaning workflow, is illustrated in Supplementary Figure S2.

Data Analysis

A total of 467 individual patent publications for the three SWTTs, along with their integrated technologies, were obtained from 2001 to 2022 for structured and unstructured analysis. This study primarily examines the development status and trends of these technologies through a bibliometric analysis of patent activities in the field. The analysis focuses on technology growth trends and social network analysis (SNA) of major contributors in terms of country, authors, and institutional/assignee performance, as well as existing international and local collaborations between countries, authors, and institutions [assignees] in this research area. Additionally, we highlight trends, key issues, and hotspots in SWTTs to guide future research efforts. Analytical tools such as RStudio, OriginLab 2023, and VOS Viewer were employed for data processing, analysis, and visualization of results. RStudio was selected for its robust statistical analysis and data handling capabilities, ideal for complex dataset processing. OriginLab 2023 enabled advanced graphing and curve fitting to produce precise

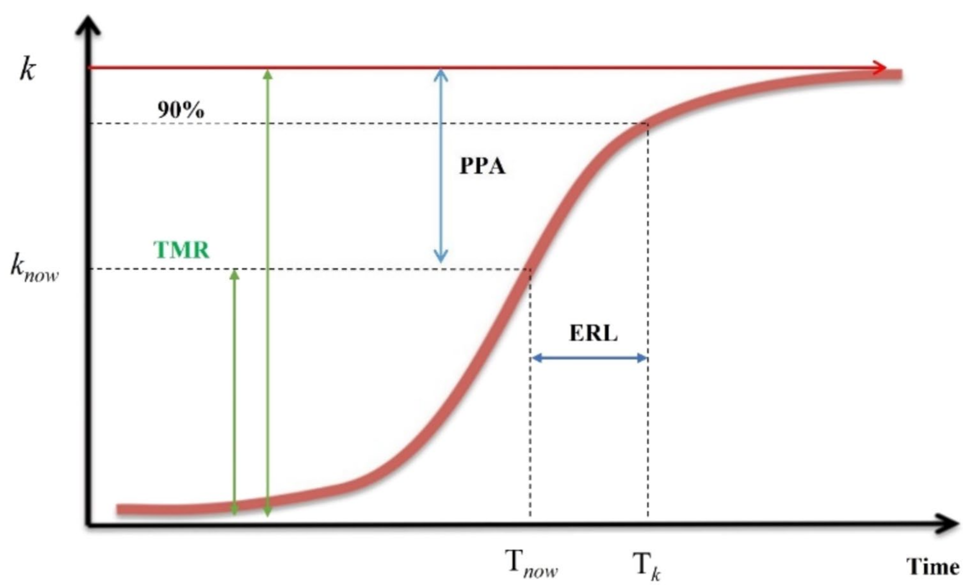


Fig. 2 Illustration of growth curve indices for technological life cycle analysis

visualizations of experimental data. LogLet 4 was explicitly used for S-curve fitting to model growth trends accurately. VOS viewer facilitated bibliometric mapping and network visualization, allowing for detailed analysis of research patterns and collaborations. The equation below was used to calculate the annual growth rate of research publications and patents over the study period.

$$\mathrm{Gr} = [\left(\frac{C_f}{C_i}\right)^{1/_n} - 1] \times 100\% \quad (1)$$

where Gr is the compound annual growth rate (CAGR); Cf and Ci, respectively, represent the initial patent count for the beginning year and total count at the end year; and *n* represents the total number of years for the study period. Additionally, the technological life cycle and assessment of the technologies were examined.

Technology Assessment and Life Cycle Analysis [S-Curve Analysis]

To understand the technological advancements of CW, MFC, and UASB, as well as their integrated systems, we employed S-curve analysis, which is primarily used for technology forecasting, to demonstrate the evolution of an innovation to its technological limit of utility. According to Ampah et al. (2022), every technology goes through four stages in its life cycle: the introduction (emerging) stage, the growth stage, the maturity stage, and the saturation stage. Identifying these stages with regard to these technologies can help understand the dynamic changes that CW, MFC, and UASB have undergone and predict the period at which these technologies will reach their recession periods. Among the various types of growth curve models, such as the fishery-pry model, the Pearl model, and the Gompertz model, following the work of Qi et al. (2023), the logistic model was employed in this study to investigate the growth curve. The logistic model was selected because it provides a symmetrical representation of technology diffusion around the inflection point, where patenting activity accelerates before stabilizing as technological opportunities saturate. This assumption aligns well with the cumulative and policy-driven innovation dynamics of SWTTs, which tend to follow steady, incremental progress rather than disruptive or highly asymmetric diffusion patterns. In contrast, the Gompertz model, which assumes an asymmetric curve with slower early growth and longer saturation tails, is more suitable for consumer-oriented technologies and less representative of infrastructure-related environmental systems. Prior studies have also shown that the logistic model offers interpretability and reliability estimates of technology maturity, expected remaining life, and potential patent applications in environmental and energy sectors (Sinigaglia et al. 2022; Wilson 2012). It is therefore considered theoretically and empirically the most appropriate model for analyzing the innovation trajectory of cw, MFC, and UASB technologies.

The logistic growth model has been widely applied in environmental and clean technology forecasting to identify technological life cycle states and predict saturation points. For example, Park et al. (2013) used S-curve modeling to assess maturity levels of renewable energy technologies, while Yoon and Park (2004) applied patent-based logistic models to forecast cleaner production and energy-efficient innovations. More recently, Chen et al. (2011), applied logistic modeling to assess the development trajectory and patent strategy for hydrogen energy and fuel cell technologies, and Mao et al. (2021) employed similar methods in a bibliometric and patent-based assessment of industrial wastewater treatment technologies, demonstrating the applicability of the logistic model to sustainability-oriented sectors. Building on this precedent, our study applies the logic growth model to patent data for CWs, MFCs, UASBs, and their integrated systems, enabling a comparative assessment of their technological maturity and innovation potential.

The logistic diffusion model applied in this study is based on the assumption that technological innovation follows an S-shaped curve over time, characterized by a slow initial adoption phase, followed by a period of rapid growth, and eventually leveling off as saturation is approached (Griibler 199; Marchetti and Nakicenovic 2015). The model assumes that each technology has a maximum potential for innovation output, which is approximated by a saturation level derived from historical patent data trends. In this study, saturation levels were estimated based on the observed asymptotic trend in cumulative patent applications and by referencing prior studies that identified typical saturation behavior in environmental and energy technologies (Sinigaglia et al. 2022; Wilson 2012). The inflection point and diffusion speed were determined through nonlinear regression fitting using the logistic function. We acknowledge that model results are sensitive to the assumed saturation ceiling; hence, we conducted goodness-of-fit evaluations and sensitivity checks to ensure robustness (Sinigaglia et al. 2022). The Loglet Lab4 program, created by Rockefeller University in 1994, equipped with the logistic curve, was employed for this type of forecasting analysis. The equation below defines the logistic model:

$$P_{(t)} = \frac{k}{1 + \mathrm{e}^{-\alpha(t-\beta)}} \quad (2)$$

where P(t) represents the number of patents at time (t). α means the growth rate of the slope of curve S, whereas β represents the inflection point of growth, which is the turning point of the time spent in the technique. The variable k also represents the saturation level of growth. This assumption is consistent with prior applications of logistic and substitution models in the study of environmental and energy technologies (Griibler 1991; Wilson 2012). This modeling approach not only enables estimation of the current maturity stage of each technology but also provides an indication of its remaining innovation life (ERL), a valuable metric for strategic planning and investment in sustainable wastewater treatment technologies. Hence, three metrics were calculated to describe the pace of patent development of these technologies. The technology maturity rate (TMR), the estimated remaining life (ERL), and the number of prospective patents to appear (PPA).

$$\mathrm{TMR(t)} = \frac{k_{now}}{k} \tag{3}$$

$$\mathrm{ERL} = \mathrm{T}_k - \mathrm{T}_{now} \tag{4}$$

$$\mathrm{PPA} = k - k_{now} \tag{5}$$

TMR represents how closely technology has attained its maximal level of development. It has a range of values between 0 and 1 and could be expressed as a percentage. When TMR is above 50%, it means technology is generally considered to have reached maturity. In the logistic model, K_{now} represents the cumulative number of patents at time t, T_k represents the time (year) at which the cumulative number of patents is expected to reach 99% of the saturation level (K), and T_{now} is the present year. Accordingly, the ERL is expressed as the difference between T_k and $T_{now,}$ representing the time (in years) remaining before the technology reaches saturation. The above equation and methodology are consistent with prior patent-based S-curve analyses (Ampah et al. 2022; Sinigaglia et al. 2022).

Technology Diffusion Speed [TDS]

We further analyzed the rate at which technologies spread. TDS refers to the dissemination of innovation through various channels within a social system. In this study, we measured TDS as the overflow of knowledge by citing patents. According to Song and Aaldering, (2019), the more frequently a patent is cited, the broader the diffusion of the innovation and subsequent citations of related patents. This suggests that highly cited patents are widespread, relevant, and applicable within the field. Therefore, citation serves as a means of spreading technologies and is an important parameter for assessing the speed of technology diffusion. It has been noted that technologies with higher citation rates tend to have greater potential for commercialization than those with lower citation rates. These parameters are crucial for guiding R&D investments based on the market potential of the technology (OECD, 2009). TDS can be calculated as:

$$TDS = \frac{x}{y} \tag{6}$$

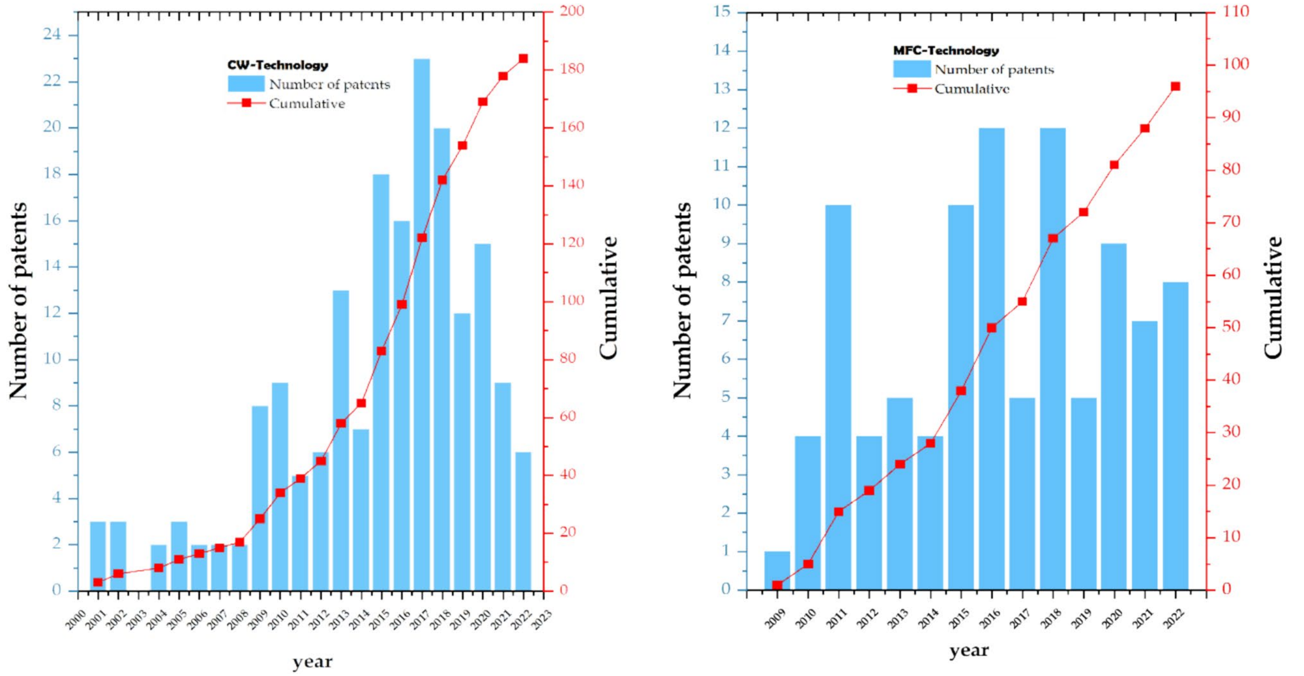
where x is the number of future citations and y is the number of patents considered for diffusion.

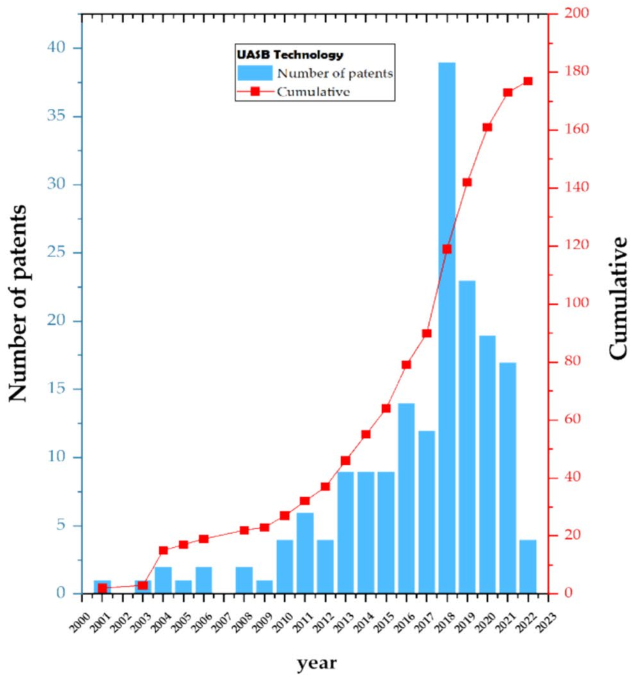
Results and Discussion

Patents Trends and Growth Patterns for Key Sustainable Treatment Technologies

The records of CW, MFC, and UASB technologies, along with their integrated systems (CW-MFC and CW-UASB), are identified as key sustainable technologies for wastewater treatment. They revealed a total of 467 patents during the study period: 185, 96, 177, 5, and 4 patents were obtained respectively for CW, MFC, UASB, CW-MFC, and CW-UASB. The calculation of the annual growth rate indicates an average rate of 29% per year from 2001 to 2022 for all technologies. Although the specified period for the study spans from 2001 to 2022, Fig. 3 shows missing records for CW (2003) and UASB (2002 and 2007). While this could initially suggest a lack of innovation activity. Such missing data points are often artifacts of the patenting and indexing process rather than true absences. As highlighted by Andersen and Andersen (2017), inconsistencies in patent terminology, delays in publication or indexing, and evolving classification systems may result in apparent data gaps. Similarly, Narin et al. (1998), Khudzari et al. (2018), and Singh et al. (2021) emphasized that patent databases can suffer from temporal lags, particularly for emerging or less established technologies. To reduce the impact of such anomalies, patent trends were interpreted over broader time intervals rather than relying on single-year data points. This strategy aligns with van Eck and Waltman (2014), who suggest that smoothing yearly fluctuations can enhance the robustness of bibliometric and patent trend analysis. Therefore, while missing years are acknowledged, they are unlikely to skew the overall trajectory and interpretation of technological development significantly.

Additionally, records for MFC, CW-MFC, and CW-UASB began in 2009, 2014, and 2015, unlike CW and UASB, which displayed records from earlier years. This suggests that innovative developments in MFC, CW-MFC, and CW-UASB are relatively recent compared to those of CW and UASB. The results also highlight the most productive years for each technology. The highest growth peaks





CW-MFC		CW-UASB	
Year	Patents	Year	Patents
2014	1	2015	1
2018	3	2016	1
		2017	1
		2018	1
		2022	1

Fig. 3 Annual and cumulative numbers of patents for key SWTTs. Note: The red line represents the cumulative number of patents each year

for CW were noted in the years 2017 (23), 2018 (20), 2015 (18), 2020 (15), and 2016 (16). UASB shows peaks in 2018 (39), 2019 (23), 2020 (19), 2021 (17), and 2016 (14), while the most productive years for MFC were also marked in the years 2018 (12), 2016 (12), 2015 (10), and 2020 (9). It can be inferred that the overall productive period for all three sustainable technologies occurred in the past seven years, from 2015 to 2021. This steady growth over the last seven years aligns directly with the period following the enactment of the global sustainable development goals (SDGs) in 2015, which include four of its primary goals focused on clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), sustainable cities and communities (SDG 11), and climate action (SDG 13). These goals emphasize the need for exploring green and sustainable technologies. This global objective may have contributed to the relatively high patent activities in the past seven years, as innovative efforts toward sustainable development.

In addition, out of a total of 467 patents on these key SWTTs, it was evident that patents on CW recorded the highest (185 patents), accounting for 39.6%. In contrast, UASB, MFC, CW-MFC, and CW-UASB accounted for 37.9%, 20.6%, 1.1%, and 0.9%, respectively, as shown in Fig. 4. A considerable extent of patenting activities for a technology is often interpreted as an indication of innovative efforts toward its development (Sinigaglia et al. 2022). The substantial records of CW patents suggest comparatively higher levels of innovation-oriented activity than MFC and UASB. The development of CWs can be attributed to their green features and potential as sustainable technologies. Yenkie (2019), emphasized the importance of integrating the three E's (efficient design, economic viability, and environmental sustainability) in wastewater treatment and compared CWs and MFCs with other technologies. Their review identifies CW as a cost-effective technology for water purification, noting that MFC, as a sustainable technology, may be limited for commercial use due to the high cost of design components used in its configuration. Similarly, Swarnakar et al. (2022) compared CW with UASB, trickling filter, and activated sludge process, concluding that CWs require less infrastructure, investment, raw materials, energy consumption, operational staff, and maintenance, while producing fewer odors and by-products. This positions CWs as low-footprint systems that fit the 3 E's framework more effectively than MFCs and UASBs (Yenkie 2019).

Global policy frameworks have also reinforced CW adoption. The Ramsar Convention (2018) highlighted wetlands, both natural and artificial, as central to achieving four overarching goals and 19 specific targets in their fourth strategic plan (2016–2024), directly aligning with the United Nations Sustainable Development Goals (UN SDGs). In particular, CWs have been linked with contributions to SDG 6 (clean water and sanitation), SDG 13 (climate action), SDG 11 (sustainable cities and communities), and SDG 15 (life on land). The potential wetlands [natural and artificial] hold as a green technology towards the achievement of the sustainable development goals as set by the UN Agenda 2030 might have contributed to this extent of growth in the patent in recent times (Seifollahi-aghmiuni et al. 2019; United Nations 2019a). While patents filed after 2015 in our dataset did not explicitly reference terms such as 'sustainability,' 'SDG,' or 'climate adaptation,' their growth trajectory aligns with global bibliometric studies, which show that patenting activity in environmental technologies has increasingly been associated with SDG-related policy drivers (Hajikhani and Suominen 2022; WIPO 2024a). This suggests that international frameworks like the UN SDGs may have indirectly reinforced innovation growth in CW and related technologies.

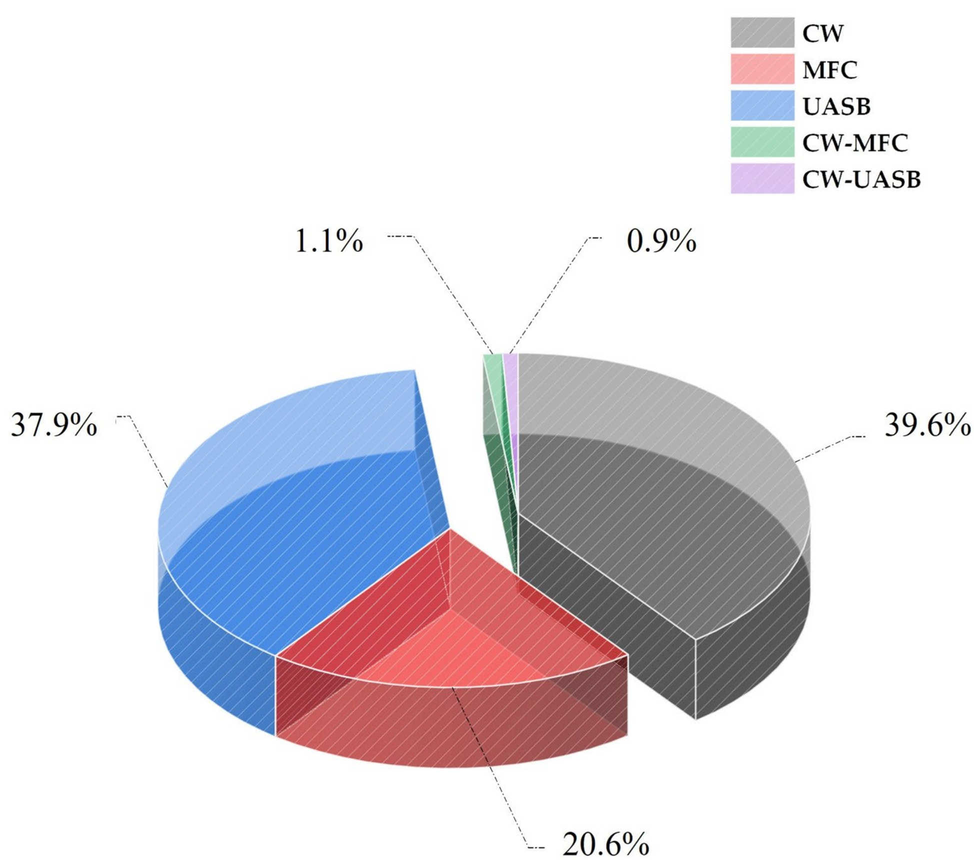


Fig. 4 Contribution of treatment technologies to sustainable development

Wu et al. (2015) and Masoud et al. (2022) showed in their publication several benefits of using CW over other treatment technologies [activated sludge, membrane, etc.]. Masoud et al. (2022) asserted that CWs act as a green multipurpose solution for water management and wastewater treatment, and have been effectively proven through several worldwide applications to possess multiple environmental and economic advantages, such as climate change adaptation and mitigation benefits. In addition, as part of their central role as water treatment plants, they have been recognized to serve several other purposes, such as habitat creation sites, urban wildlife refuges, recreational or educational facilities, landscape engineering, and ecological areas. Hence, the multi-faceted benefits provided by CW technology are owed to its growing development over the years.

Country Performance

Countries or regions with a comparatively large number of published patents are often the primary technology holders that have demonstrated high innovative proficiency in the field. In this study, we extracted and analyzed the performance and contributions of countries in the area of SWTT, focusing on CW, MFC, and UASB, as well as their integrated systems, from 2001 to 2022. Of the 195 countries in the world, a total of 21 countries (10.8%) were observed to hold relevant patents over the last 21 years, indicating that these key SWTTs have not achieved significant global dominance. The geographical distribution of the most dominant patenting countries/regions in the field of SWTT is shown below in Fig. 5.

China led the field over the past two decades with 381 patent applications, accounting for 81.56% of total patents for SWTTs. The US follows with 29 patents (6.2%). Among the top 15 countries or regions, besides China and the US, three other Asian countries are listed: South Korea (22), Japan (13), and India (9). Additionally, 18 patents were filed through the World Intellectual Property Organization (WIPO) and 10 through the European Patent Office (EPO). Factors influencing patent activity include research and development (R&D) capability, funding availability, and the existence of clear and active domestic and international policies for the adoption and development of sustainable wastewater treatment technologies (Ampah et al. 2022; Mao et al. 2022; Sun et al. 2022a, b). For example, in 2016 and 2021, China's 13th and 14th Five-Year Plans established robust policies to promote an optimal combination of innovative systems that address the country's strategic needs through the allocation of scientific and technological resources (The Chinese State Council 2020, 2021). These policies, along with available funding and resources, may encourage national and institutional focus in this area to support innovative activities in SWTTs. Besides such policies, factors like population growth and industrialization increase a country's burden to find innovative and sustainable solutions for

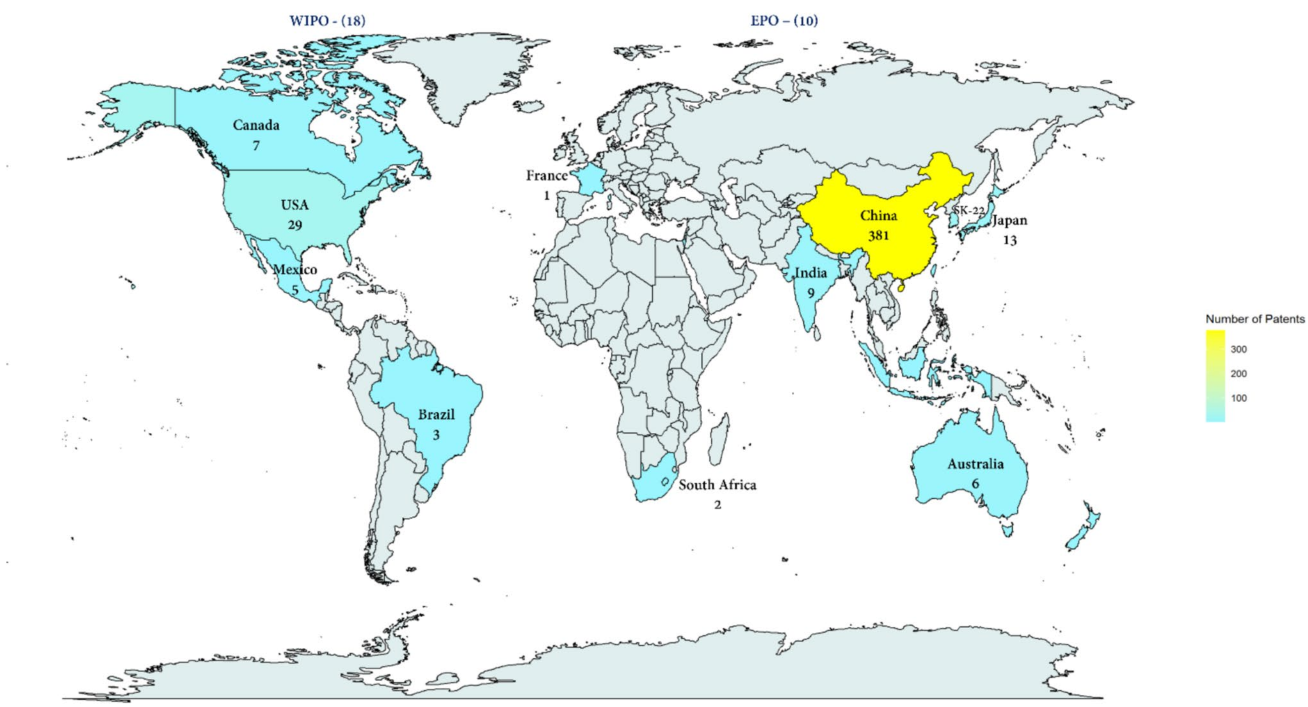


Fig. 5 The geographical distribution map of patent publications on key SWTT from 2001 to 2022 [top 14 countries]. Note: Patent counts for "China" include filings from mainland China, Hong Kong, and Taiwan, which the authors aggregated for consistency with prior bibliometric studies

wastewater management. A study by Shi et al. (2020) examining the relationship between economic efficiency and wastewater efficiency using Data Envelopment Analysis (DEA) found that regions with high GDP have higher efficiency in wastewater treatment and treatment technologies compared to less economically developed regions. Additionally, a recent study by Khan et al. (2022) on environmental technology and wastewater treatment: strategies for achieving environmental sustainability also indicated that a country's gross domestic product (GDP), trade, population, and industrialization are positively and significantly correlated with their concern for wastewater treatment (Zapata-Mendoza et al. 2022). These findings align with our results, as the top 12 most productive countries with high patent records for sustainable wastewater treatment are all within the top 15 countries by GDP according to the World Development Indicators (WDI)(The World Bank 2022). This also explains the lower patent records for SWTT in less developed regions like Africa. The results of this study are also consistent with the findings of Liao et al. (2021) regarding the factors influencing wastewater treatment and reuse in major Asian countries.

Moreover, patenting activities for each sub-technology varied from one region/country to another. Figure 6. Provides details of patenting activities of the top 10 countries for each technology (CW, MFC, and UASB). The results show that China has been the most active country in patenting all three technologies, as well as their integrated systems. China shows 157 CW patents, accounting for 84.41% of the 185 patents within the study period. In MFC, 66 patents (68.75%), and in UASB, 166 patents (91.71%) were filed in China. Similarly, in the integrated systems (CW-MFC and CW-UASB), China and the USA were the only countries with patenting activities for CW-MFC, 4 and 1 patents, respectively. However, with regard to CW-UASB, the only country with a patent application was China (4 patents). This generally reveals China's dominance in exploring innovative efforts toward sustainable wastewater treatment technologies. Following China on the list as the second most dominant country was the US, with 17 patents (9.14%) for CW, 14 patents (14.58%) for MFC, and one patent (20%) for CW-MFC, except for UASB, where the US placed 6th, losing its 2nd position to Japan with five patents (2.76%). South Korea ranked as the 3rd most productive country for all three technologies, with 9, 10, and 4 patents, respectively, for CW, MFC, and UASB. Other countries, among the top 10 for each technology, are shown in Fig. 6 below. The results of each country with respect to each technology are consistent with the overall sustainability output map as shown in Fig. 5, which reveals that since 2001–2022, China has become the most dominant country in the field, followed by the US and South Korea.

International Collaborations

The essence of global patent collaboration mainly involves identifying major technology holders in a field and investigating the collaborative relationships that exist between countries and core jurisdictions (Rassenfosse 2013a, b). International collaboration is becoming an increasingly significant area of innovation studies, as it helps foster growth in the technological field (Ampah et al. 2022; Mao et al. 2021). In a study by Kerr and Kerr (2018), to understand the prevalence and traits of collaborative patents, they revealed that patents created collaboratively by global research teams reduce underperformance, produce better discoveries, and are highly cited within and outside of the firm than patents developed entirely by local scientists. Hence, as part of this study, the international collaboration across the top 10 most productive countries/jurisdictions in SWTT patent publications was analyzed by SNA as shown in Fig. 7. Each country is represented by a node with a specific color; the node's size, with its calibrations on the resulting chord diagram, represents the number of patent publications for each country. The direction and size of the arrow from one node to another indicate an existing collaboration between regions, with the direction indicating one node as the initiator and the other as the recipient. Additionally, the arrow thickness indicates the number of collaborations between the two regions. According to their node sizes, aside from WIPO, which holds 100 patents, the USA ranks first as the country with the highest number of patents (94), followed collaboratively by other jurisdictions, in the order of China, Canada, Australia, and Japan. The most frequent bilateral collaboration occurred between the USA and China, resulting in 12 jointly filed patents, followed by the USA and Canada, with 11 shared patents (Fig. 7b). While China shows multiple international collaborations (Fig. 6), its collaborative intensity remains proportionally lower relative to its overall patenting output. For instance, when normalized as the ratio of internationally collaborative patents to total national patents, the U.S. demonstrates a stronger collaborative orientation. In contrast, China's large volume of patents is primarily domestically concentrated. This suggests that although China participates in international networks, its innovation strategy in wastewater treatment remains predominantly inward-focused. This limited cross-border engagement from China can be attributed to several factors. First, China's innovation ecosystem has historically focused on domestic innovation, supported by national funding and policy incentives that promote self-reliance in key technological sectors (CEPR 2023; Chang et al. 2025; WIPO 2024b). Language and legal barriers, including differences in intellectual property regimes, may hinder smooth international patent filings. Moreover, geopolitical and trade

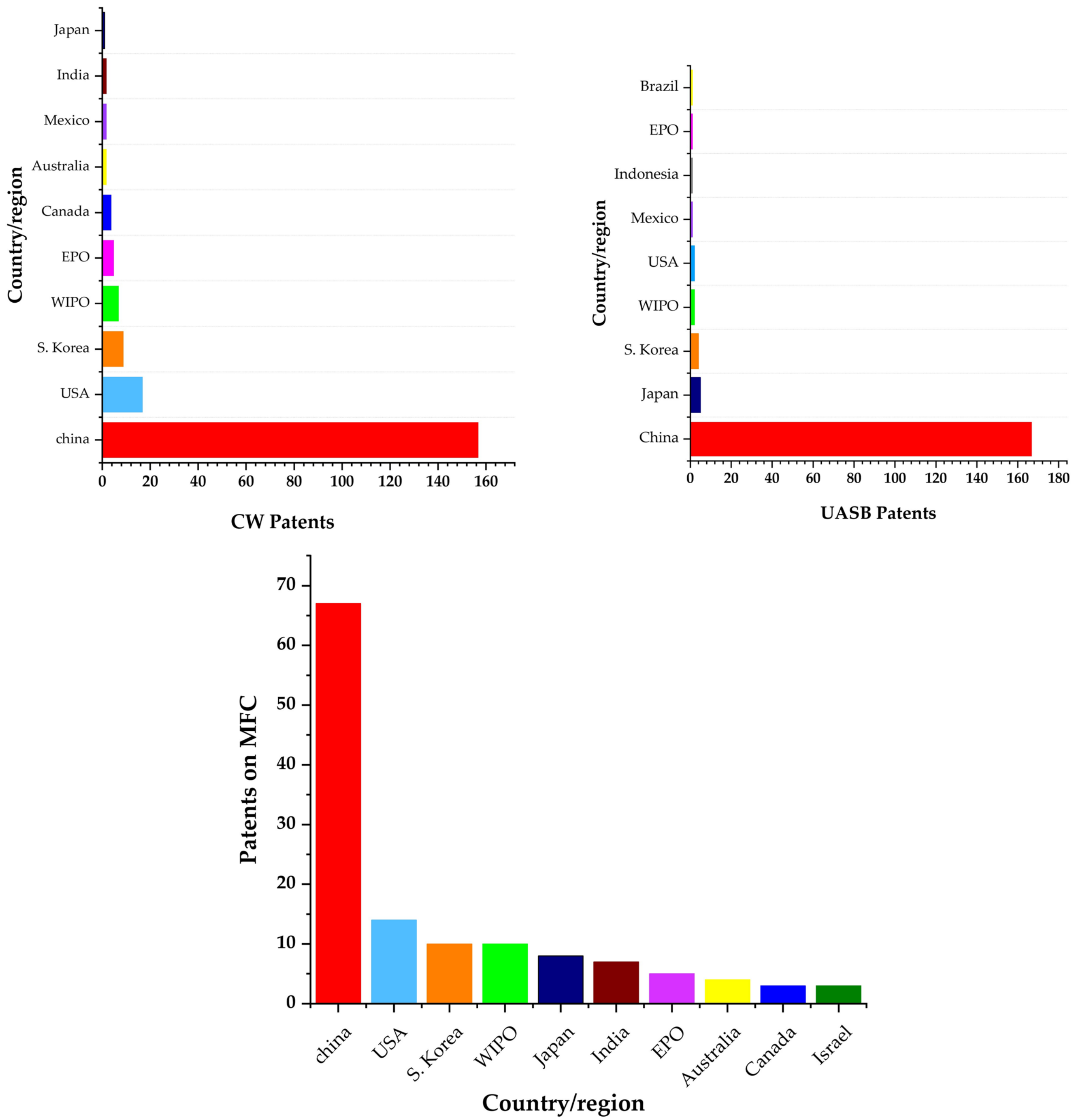


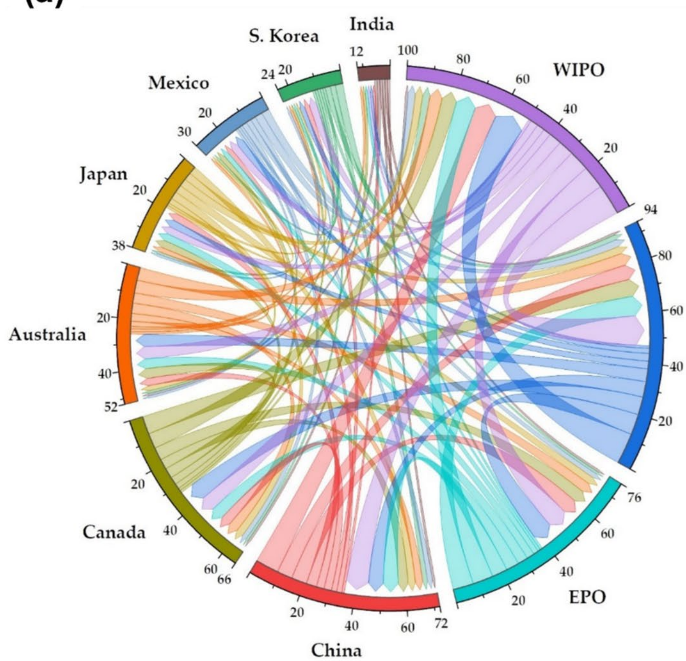
Fig. 6 The total patent application of top patenting countries toward SWTTs

tensions, particularly with Western countries, have made institutions more cautious about joint development due to concerns about technology transfer and national security (Cao et al. 2024; USPTO 2023a, b). These factors suggest that while international collaboration plays a significant role in knowledge exchange and technology diffusion, its patterns are influenced not only by innovation capacity but also by national strategy, policy, and geopolitical positioning.

Patent Assignee's Productivity and Target Markets

Table 2 presents the top 10 most productive patent assignees or affiliations for the key SWTTs presented in this study. Out of a total of 185 patents filed for CW technology, the following key players were identified as assignees: companies (49.5%), universities and institutes (30.7%), and individual researchers (19.8%). This indicates that companies are the most productive players in CW-technology development

(a)



(b)

Rank	Collaboration Pair	Number of Shared Patents
1	World Intellectual Property Organization (WIPO) – United States of America	12
2	China, People's Republic of – WIPO	9
3	European Patent Office (EPO) – United States of America	8
4	European Patent Office (EPO) – WIPO	8
5	Canada – United States of America	7
6	China, People's Republic of – United States of America	6
7	China, People's Republic of – European Patent Office (EPO)	6
8	United States of America – Canada	7 (same as #5, symmetric)
9	China, Hong Kong S.A.R. – China, People's Republic of	4
10	United States of America – China, Hong Kong S.A.R.	4

Fig. 7 International patent collaboration on SWTT among the top 10 countries/jurisdictions. **a** Chord diagram showing collaborations among the top 10 most productive countries/jurisdictions, where node size represents the total number of patents and arrow thickness represents the number of collaborations between regions. **b** Table listing the top ten collaboration pairs and their corresponding number of shared patents for clarity

and commercial applications for sustainable wastewater treatment. Moreover, results for the top 10 CW-technology patent assignees show that, except for Novozymes Biologicals Inc., a US-based company, all remaining nine (9) assignees are Chinese companies and institutions, further emphasizing the dominance of China in the development of the field. Positioned first with the highest number of patents from 2001–2022 are two (2) academic institutions from China (Univ of Chongqing and Univ Guizhou Nationalities) and one US-based company (Novozymes Biologicals Inc) with 4 patents each. Generally, there is a primary distinction between company patents and university patents. While university patents are more cited than company patents, they are unable to monetize their technology, unlike companies, except that they transfer their patents to companies. This kind of transfer increases practical productivity and commercial application of the technology and ensures that the developments in CW technology are largely promoted (Baldini et al. 2007; Henderson et al. 2015; Mao et al. 2022; Schmid and Fajebe 2019). One of the most notable patents filed by the University of Chongqing was to design a wastewater treatment system configured with a grit chamber, contact-type oxidation pond, constructed wetland pool, and sedimentation basin separated by transverse walls (Patent No. CN201501819-U) (Fang et al. 2010). The installation of their system effectively utilizes ditches as a landscape that harmonizes with the surrounding environment, continuously purifying sewage at the site. The non-academic institution with the highest number of patents, Novozymes Biologicals Inc., a US-based company, also ranked first in CW-technology development, focusing on the microbial component of CW-technology. The novelty of one of their earliest innovation was to install a CW with a microbial composition comprising a specific microbial strain selected from *Aeromonas enteropelogenes*, *Enterobacter pyrinus*, *Klebsiella pneumoniae*, *Pantoea agglomerans*, *Proteus penneri*, *Pseudomonas geniculata*, *Pseudomonas monteilii*, and *Pseudomonas plecoglossicida* for efficient removal of COD and halides, decolorization of effluent water (Patent No. WO2006069035-A2) (Dewitt et al. 2006). These significant contributions have significantly advanced the field. Additionally, it is worth noting that the diverse engagement of universities, individuals, and companies (both government and private) in CW-technology development fosters collaboration and partnership among these entities, which is essential for the technology's growth. In addition, it facilitates the translation of scientific discoveries into industrial applications by strengthening collaborative ties between science and industry (Zuniga 2011).

MFC assignees show a total of 116 assignees for the study period, with the following key players as assignees: universities (44.8%), individual researchers/entrepreneurs

Table 2 Top (10) assignees in key sustainable wastewater treatment technologies

Technology	Rank	Assignee (Full Name)	Patents Deposited, n (%)	Country
CW	1	University of Chongqing (UYCQ-C)	4 (2.2)	China
	2	Guizhou University for Nationalities (UGMZ-C)	4 (2.2)	China
	3	Novozymes Biologicals Inc. (NOVO-C)	4 (2.2)	USA
	4	Shandong University (USHA-C)	3 (1.6)	China
	5	Flowers, D. A. (Flow-Individual)	3 (1.6)	China
	6	Shanxi Xinkelian Environmental Technology Co., Ltd. (SHAN-Non-Standard)	3 (1.6)	China
	7	Nanchang University (NANU-C)	3 (1.6)	China
	8	Fuyang Hongxiang Technology Services Co., Ltd. (FUYA-Non-Standard)	2 (1.1)	China
	9	Zhang, Y. (ZHAN-Individual)	2 (1.1)	China
	10	He, X. (HEXX-Individual)	2 (1.1)	China
MFC	1	Dalian University of Technology (UYDA-C)	4 (4.2)	China
	2	Aquacycl LLC (Aqua-Non-Standard)	3 (3.1)	USA
	3	Gwangju Institute of Science and Technology (GWAN-C)	2 (2.1)	South Korea
	4	Southeast University (UYSE-C)	2 (2.1)	China
	5	Zhejiang University (UYZH-C)	2 (2.1)	China
	6	Pusan National University Industry Cooperation Foundation (UYPU-C)	2 (2.1)	South Korea
	7	Chinese Academy of Sciences, Urban Environment Institute (CUBN-C)	2 (2.1)	China
	8	Peking University (UYPK-C)	2 (2.1)	China
	9	Kyung Hee University Industry Cooperation Foundation (UYKY-C)	2 (2.1)	South Korea
	10	Nantong University (UYNT-C)	2 (1.7)	China
UASB	1	Henan Hengan Environmental Technology Co., Ltd. (HENA-Non-Standard)	8 (4.5)	China
	2	Suzhou Suwote Environmental Technology Co., Ltd. (SUZH-Non-Standard)	4 (2.3)	China
	3	Hunan Dachen Environmental Protection Co., Ltd. (HUNA-Non-Standard)	4 (2.3)	China
	4	Jiangsu Nanjing Huaxing Environmental Technology Co., Ltd. (UYJI-Non-Standard)	2 (1.1)	China
	5	Qingdao University of Technology (UQDT-C)	2 (1.1)	China
	6	Sun, X. (SUNX-Individual)	2 (1.1)	China
	7	Zhengzhou University of Light Industry (UZHL-C)	2 (1.1)	China
	8	Tianjin University of Science and Technology (UYTC-C)	2 (1.1)	China
	9	Global Quality Certification Service (GLOB-Non-Standard)	2 (1.1)	China
	10	Guizhou Qinghe Ecological Technology Co., Ltd. (GUIZ-Non-Standard)	2 (1.1)	China
CW-MFC	1	Southeast University (UYSE-C)	1 (–)	China
	2	Huaibei Normal University (UHUB-C)	1 (–)	China
	3	Nuleaf Tech Inc. (NULE-Non-Standard)	1 (–)	USA
	4	Jiangxi University of Science and Technology (UYJL-C)	1 (–)	China
	5	China Institute of Water Resources & Hydropower Research (IWHR-C)	1 (–)	China
CW-UASB	1	Zhejiang Qingtiandi Environmental Engineering Co., Ltd. (ZHEJ-Non-Standard)	1 (–)	China
	2	Guizhou University for Nationalities (UGMZ-C)	1 (–)	China
	3	Harbin Jinda Environmental Engineering Co., Ltd. (HARB-Non-Standard)	1 (–)	China
	4	Henan Hengan Environmental Technology Co., Ltd. (HENA-Non-Standard)	1 (–)	China

CW = Constructed Wetland; MFC = Microbial Fuel Cell; UASB = Upflow Anaerobic Sludge Blanket; CW-MFC = Constructed Wetland coupled with Microbial Fuel Cell; CW-UASB = Constructed Wetland coupled with Upflow Anaerobic Sludge Blanket. "-C" = University or research institute; "Non-Standard" = Company name listed in non-standardized format in patent database; "Individual" = Patent assignee registered as an individual inventor. Percentages indicate proportion of total patents in the respective technology group

(31%), and companies (24.1%). Unlike CW, universities were the most productive players at the forefront of MFC technology, with companies recording the least number of assignees. This is also reflected in the list of the top 10 assignees in the field; nine (9) academic institutions (6 Chinese universities and 3 South Korean universities) and 1 US-based company (Aquacycl LLC) as the only company among the top 10 assignees. The disproportionate number of companies as assignees as compared to universities may be due to possible limitations in the commercial application of the MFC technology as compared to CW and UASB (Li et al. 2014). Nevertheless, similar to CW, it was observed that the majority of the assignees were from China (6), followed by three assignees from South Korea and 1-assignees from the US. Ranked in first position with the most significant number of deposited patents in MFC-technology development is the Dalian University of Technology, with four patent applications.

UASB technology has a total of 176 patent assignees, with companies being the most productive contributors in the field (80.7%), followed by universities (13.1%) and individual researchers (5.7%). Similar to CW, it was evident that most contributions were submitted by companies (including government companies) engaged in R&D for the commercialization of UASB technology for sustainable wastewater treatment. As shown in Table 2 (the top 10 most influential assignees in the field from 2001–2022), there were 6-Chinese companies, 3 Chinese universities, and 1 Chinese researcher. This indicates that the field was mainly dominated by China. Ranked first on the list was Henan Hengan Environmental Technology Co., with 8 patents, which contribute about 4.5% of the total number of patents related to UASB. Followed by Suzhou Suwote Environmental Technology and Hunan Dachen Environmental Protection, with 4 patents each. One of the earlier patents filed by the Henan Hengan Environmental Technology Co. was their invention with patent No. CN106673372-A, which provided a cost-effective and simple method for the treatment of traditional Chinese medicinal wastewater using a 3-phase separator UASB reactor, including processes of filtering wastewater through a grid, oxidizing the liquid phase, precipitating the oxidized solution, the addition of supernatant (polyacrylamide) to decolorize, and flocculating the solution (Chen et al. 2017). Very recently, they also filed an innovative idea using UASB to treat gelatin wastewater generated by various glue-making processes. The advantage of their utility model is to provide a sustainable solution with easy operation, good in effect, low operational cost with remarkable social and economic benefits (Patent No. CN106673372-A) (M. Zhang et al. 2022).

Regarding the integrated systems (CW-MFC and CW-UASB), the number of patents deposited is relatively low compared to the research work. However, Henan Hengan Environmental Technology Co., as part of their exploration for sustainable technologies for wastewater treatment, is one of the few assignees (companies and institutions) that have exploited the integration of CW and UASB (CW-UASB) as a coupling device for enhanced wastewater treatment. In their innovation with Patent No. CN208964758-U used the coupling device for dry dehumidification, aquaculture wastewater treatment, and biogas generation (Chen et al. 2019). Hengan Environmental Technology Co. is a major contributor to the exploration and commercialization of key sustainable technologies for wastewater treatment, accounting for 1.78% of the total patents in this field.

The typology of patent assignee across sustainable wastewater treatment technologies reveals important insights into their innovation and commercialization pathways. Overall, academic and public research institutions dominate early-stage patent activity, particularly in emerging or integrated technologies such as CW-MFC and CW-UASB. While institutions are vital drivers of foundational research, they often face systematic barriers to commercialization, including limited funding for scale-up, weaker ties to industry, and an emphasis on academic outputs over market deployment (Markman et al. 2008; OECD 2019a, b). In contrast, corporate assignees, though fewer in number, are more capable of translating innovations into marketable solutions, often supported by established production, distribution, and regulatory infrastructure (Arora et al. 2016). Furthermore, the presence of individual inventors and smaller non-standard assignees suggests grassroots innovation, particularly in regions like China, where inventor-level filings may reflect experimental adaptation of existing technologies. However, such patents may face challenges in enforcement, financing, and scaling unless they are integrated into a broader institutional ecosystem. These patterns underscore the importance of fostering multi-actor innovation systems where collaboration between academia, industry, and government can accelerate the development, transfer, and commercialization of sustainable wastewater technologies (Arora et al. 2016; Markman et al. 2008; OECD 2019a, b).

In addition to understanding the patent productivity level of assignees and its implications on commercialization pathway for SWTTs, we further explored the target market of the top 6 assignees using correlation analysis as shown in Fig. 8. The results of the analysis show that China is the world's largest target market for all these companies/institutions with respect to the key SWTT. However, the results are also not surprising because China has become the world's industrial powerhouse (Wen et al. 2016). Hence, wastewater treatment pressure induced by industrial activities is no longer negligible in the region (Savenije et al. 2014; Senthil Kumar and Saravanan 2018). In a study conducted by Li et al. (2019), the authors investigated and quantified China's industrial water pressure based on water footprint and dynamic structure decomposition analysis (SDA). Their results unambiguously demonstrated that industrial activities, via large-scale exports and urban consumption, are two major drivers of water contamination. Hence, it is obvious that the growing environmental concern caused by industrialization has induced the exploration of technology development of SWTT, such as CW, MFC, UASB, and their integrated systems (CW-MFC and CW-UASB) by both

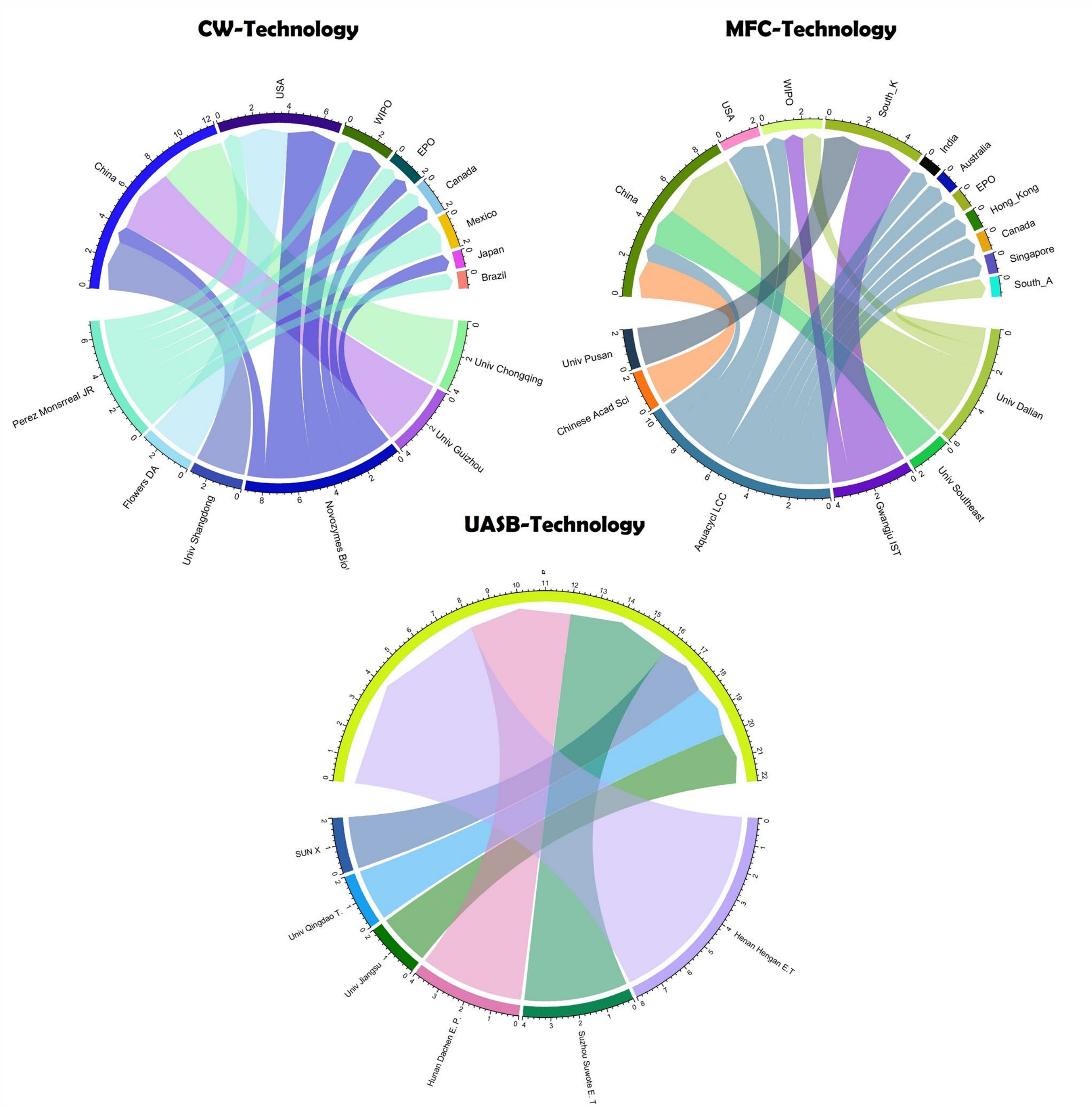


Fig. 8 Top 6 assignees in SWTTs and their major target markets for each technology

local and foreign companies and institutions as dominant contributors towards the alleviation of China's water pressure. Therefore, the recognition of China as the primary target market for local and foreign companies/institutions, as illustrated in Fig. 8 below, is primarily due to the market opportunity created by a growing environmental need. In addition, it is worth noting that among the top 6 assignees, Novozymes Biologicals Inc. and Aquacycl LLC, US-based companies, were the only companies that exploited a wider international market for CW and MFC, compared to the other assignees (except Perez Monsrreal Jr.), with a focus on the local market niche. This demonstrates their keenness to promote global sustainability through the international commercialization of SWTT.

Comparative Trend

Technology Life Cycle and Assessment

The life cycle of the key sustainable wastewater treatment technologies (CW, MFC, and UASB) together with their integrated systems (CW-MFC and CW-UASB) is discussed in this section. As outlined earlier in Sect. "Technology Assessment and Life Cycle Analysis [S-Curve Analysis]", the S-curve (logistic growth curve) analysis was employed to evaluate the technological evolution and forecast development trajectories of these systems, thereby supporting informed decision-making by researchers and practitioners. According to Ampah et al. (2022), every technology typically progresses through 4 main phases: the embryonic (introduction) stage, the growth stage, the maturity stage, and the saturation phase, during which development of the technology slows or ceases(Mann 1999; Song and Aaldering 2019). The resulting logistic curves are illustrated in Fig. 9, depicting the technological pathway of each technology. Although some years (e.g., 2003) exhibited no recorded patent activity, the S-curve modeling conducted in Loglet Lab 4 is based on cumulative data, which minimizes the impact of isolated data gaps. To ensure robustness, a sensitivity check by re-estimating the model with interpolated and omitted values for the missing years was performed. The resulting variation in key life-cycle parameters, including saturation levels and inflection points, remained ± 3%, indicating that the missing data do not significantly distort the diffusion trends or forecasting outcomes.

The results show that the embryonic phase for CW, MFC, and UASB ended in 2006, 2010, and 2012, respectively. The growth phase, defined as the period between the introduction and the midpoint (the 50th percentile) occurred between 2006 and 2016 for CW, 2010 and 2017 for MFC, and 2012 and 2018 for UASB. This indicates that, comparatively, CW had the most extended growth period, spanning approximately 11 years. Due to the culmination year of the growth phase, the result also indicates that CW, MFC, and UASB have already attained maturity.. In contrast, the integrated systems CW-MFC and CW-UASB had only 5 and 4 patent records, respectively, making them unsuitable for logistic modeling. Hence, they were excluded from the S-curve analysis, indicating that they remain at an early developmental stage with limited commercialization.

For the standalone technologies, the logistic growth curve indicates that CW is projected to reach 90% and 99% saturation by 2026 and 2036, respectively. MFC and UASB

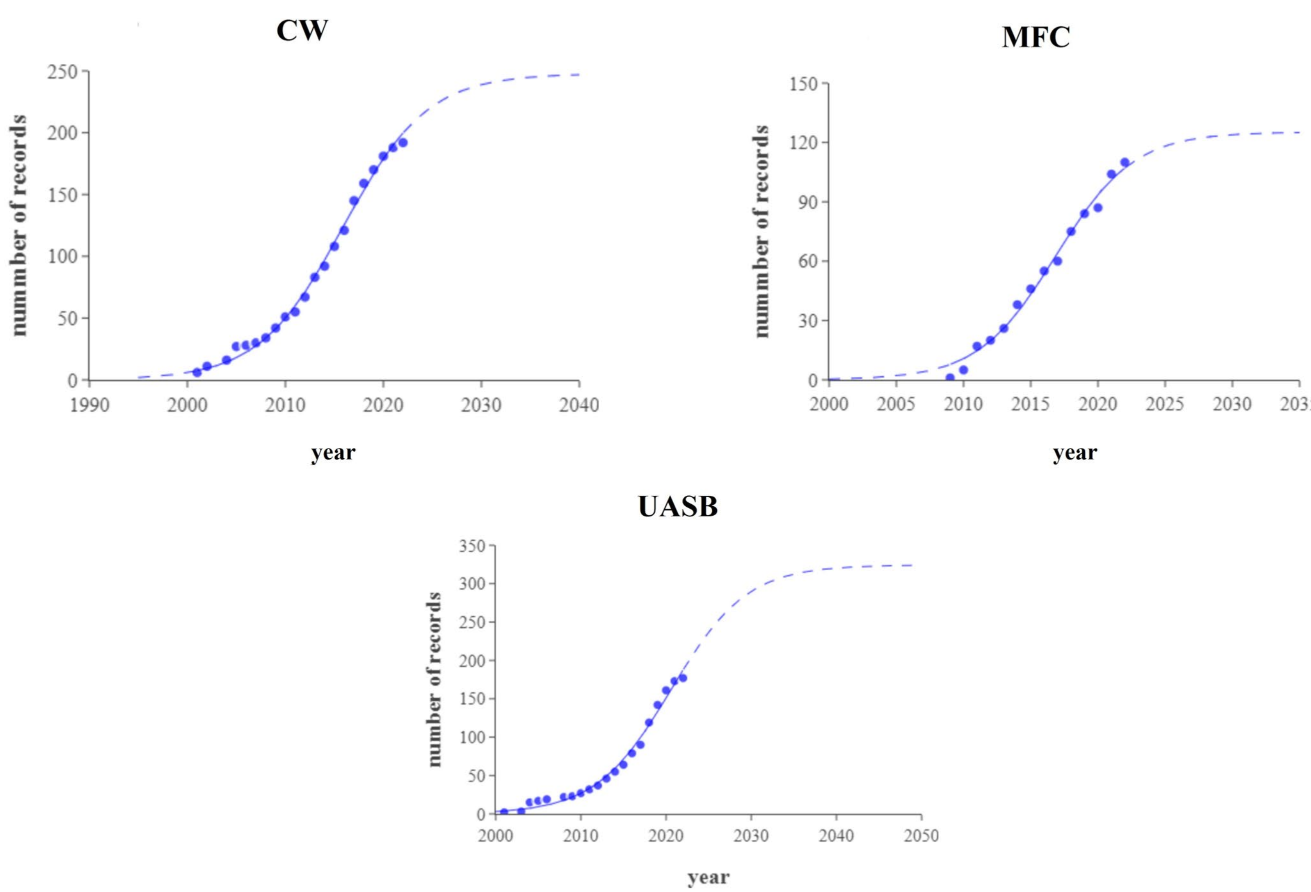


Fig. 9 Comparative S-curve analysis for key SWTT patents; technology life cycle forecasting fit as dashed lines

Table 3 Technology life cycle assessment

Technology	90% sat. level	99% sat. level	K (Max Cumulative Patents)	TM (Mid-point Year)	Technology Maturity Rate [TMR]	Potential Potent Application [PPA]	Estimated Remaining Life [ERL]@99% sat. level	R values
CW	2026	2036	251	2016	74%	66	14 years	0.991
MFC	2023	2030	109	2017	88%	13	8 years	0.921
UASB	2025	2031	241	2018	96%	64	9 years	0.944

are expected to reach similar saturation milestones by 2023/2030 and 2025/2031, respectively. These trajectories are shown in Fig. 9, which compares the S-curve forecasts for CW, MFC, and UASB.

Furthermore, the technology maturity rate (TMR), number of potential patent applications (PPA), and expected remaining life (ERL) at the 99% saturation level were computed according to Eqs. (2,3, and 4) and presented in Table 3. The results show that the TMR for CW, MFC, and UASB was above 50%, confirming that these technologies have reached maturity. Their ERLs were estimated as 14 years (CW), 8 (MFC), and 9 years (UASB). Based on these ERLs, it is estimated that the technical advances of these technologies will be mostly completed between 2030 and 2036, with potential patent applications (PPAs) of 143 patents.

To evaluate the statistical robustness of the logistic growth models applied to each technology, the coefficient of determination (R^2) was calculated. As summarized in Table 3, the results demonstrate strong model fits for CW ($R^2=0.991$), MFC ($R^2=0.921$), and UASB ($R^2=0.944$), suggesting high reliability of the diffusion forecasts generated. No R^2 values are reported for CW-MFC and CW-UASB, as these systems were excluded from the modeling due to insufficient data.

These indicators provide further implications for strategic R&D investment decisions, acting as an early warning signal, as future improvement potentials after 2036 will be minimal, unless a substantial breakthrough or integrated system is revolutionized to an extent that can thoroughly change the current status of the technologies (Song and Aaldering 2019). Mann (1999), also emphasized that each phase in the technology cycle is characterized by a unique technological idea. When technology reaches maturity and saturation stages, the marginal technological progress on cumulative R&D expenditures is negative. Moreover, plans to maximize reliability and reduce costs should become the focus (Sinigaglia et al. 2022a, b). Innovators and decision-makers must consider whether the system's performance can be optimized.

Technology Diffusion Speed [TDS]

Further analysis was carried out to demonstrate which has the highest diffusion speed. The TDS of the technologies was estimated using Eq. (6). The number of patents

Table 4 Technology diffusion speed (TDS) for key sustainable wastewater treatment systems

Technology	Number of Patents	Total of patent citations	TDS
CW	131	651	4.97
MFC	76	310	4.23
UASB	148	400	3.58
CW-MFC	4	7	1.75
CW-UASB	4	8	2.0

considered for this computation spans from 2001 to 2018, as patents typically take an average of 3–5 years to accumulate substantive forward citations. In line with prior studies in patent bibliometrics and environmental technologies, a four-year lag was adopted as a conservative threshold to avoid citation truncation (Hall et al. 2005; van Raan 2017a, b; Wang et al. 2024). The results showed that constructed wetlands demonstrated the highest diffusion speed (4.97), as shown in Table 4. Followed by MFC (4.23), UASB (3.58), CW-UASB (2.0), and CW-MFC (1.75). Although the differences in TDS are not vast, among these key technologies, CW shows greater commercialization potential when compared to the others (OECD, 2009; Sinigaglia et al. 2022a, b). These differences in citation rates can be attributed to several factors. First, technologies like CW and MFCs are often associated with broader sustainability goals, such as nature-based solutions and energy recovery, making them more visible and relevant across multiple disciplines. This increased visibility and relevance, in turn, enhance their citation potential and diffusion rate. For instance, MFCs, despite having fewer patents than UASB, received significantly more citations per patent due to their interdisciplinary applications in bioenergy, wastewater treatment, and electrochemistry. Moreover, technological features such as energy recovery and resource circularity, which align with emerging global research priorities, increase their visibility and impact within both academic and industrial communities (Gude 2018a, b). Additionally, CW technologies benefit from long-standing policy interest and global applicability, particularly in low- and middle-income countries, which enhances their diffusion through citations (Massoud et al. 2009; UN-HABITAT 2008; Vymazal 2010a, b). In contrast, hybrid systems like CW-MFC and CW-UASB, although promising, are still in their nascent stages, with limited commercial uptake and academic engagement, as reflected in their low citation counts and TDS. These trends suggest that technologies with well-established theoretical foundations, policy backing, and interdisciplinary relevance tend to achieve greater diffusion. This finding aligns with prior studies, which emphasize the role of technological novelty, interdisciplinary reach, and market orientation in shaping patent citation performance (Mogoutov and Kahane 2007; Zhang et al. 2019).

However, pairing TMR and TDS as shown in Fig. 10 provides a nuanced view of where each technology stands in the innovation-diffusion continuum. For example, CW demonstrated the lowest TMR (74%) but the highest diffusion speed (4.97). This inverse relationship suggests that while CWs are not the most recently innovated in terms of patent activity, they have undergone rapid dissemination and uptake, as reflected in high citation counts and widespread adoption. This pattern aligns with findings in mature sectors like solar photovoltaics and wind energy, where technologies often plateau in innovation (lower TMR) but continue quickly due to simplicity, cost-effectiveness, and well-established infrastructure (Griibler 1991a, b; Wilson 2012). By contrast, MFCs and UASBs have higher TMR values (88% and 96%, respectively) and slightly lower TDS (4.23 and 3.58), indicating they are still undergoing active innovation and moderate diffusion. This reflects a typical growth phase in which innovation is high, but adoption is still scaling, similar to emerging biotech or carbon capture technologies, which are technically promising but not yet widely deployed (Agyekum et al. 2025). Mosk strikingly, integrated systems such as CW-MFC and CW-UASB have very high maturity (>99%) but low TDS (1.75 and 2.0), indicating limited recent innovation and sluggish diffusion. These systems likely face integration challenges and scalability constraints that hinder broader commercialization. These interpretations are consistent with macro-level evidence showing that novel technologies often exhibit high innovation rates (steeper initial slopes) but slower early diffusion, especially if they involve technical complexity (Comin and Mestieri 2014; Veugelers et al. 2019).

Area of Technological Development

To better understand the core areas of development in the field of SWTTs, we employed the Derwent Manual Codes (DMC) to examine and illustrate the technological areas

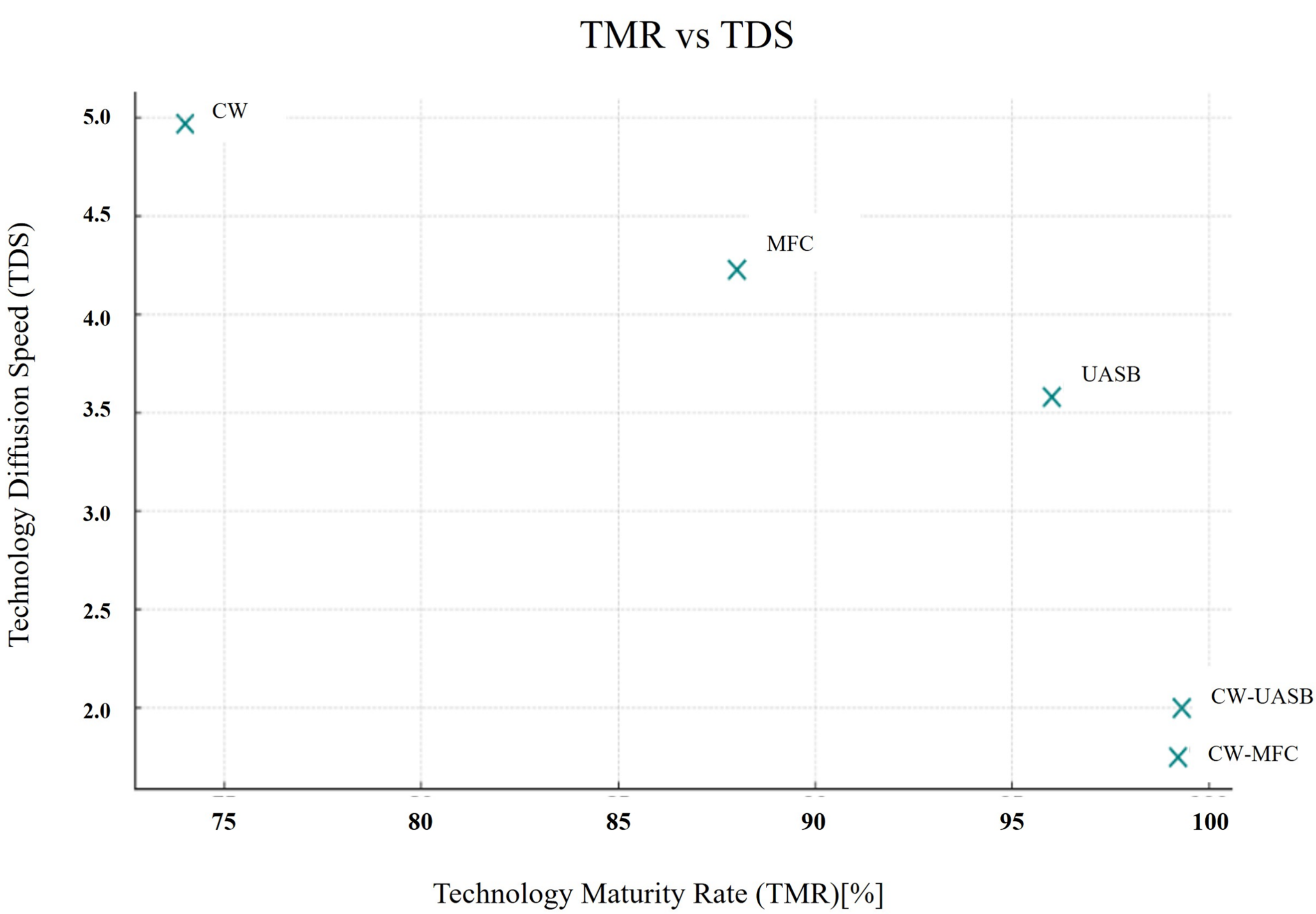


Fig. 10 Comparison of Technology Maturity Rate (TMR) and Diffusion Speed (TDS) for key sustainable wastewater treatment technologies (CW, MFC, UASB, CW-MFC, and CW-UASB)

involved in the field. In DII, DMCs are used to further categorize technologies based on the inventive features. Like the IPC, DMCs follow the same hierarchical structure. However, DMCs are considered superior to IPC because they provide more details and are more up-to-date and thorough than the IPC (Liu et al. 2020). For example, one of the highly recurring codes in our dataset, D04-A01J, specifies "purification of water by biological processes," which identifies microbial or bio-based treatment technologies. Its corresponding IPC codes, C02F3/12, only indicate "biological treatment of water, wastewater, or sewage," without differentiating whether it is CWs, UASB, or MFC systems. This demonstrates how DMCs capture the innovation granularity needed to distinguish between the core SWTTs, while IPC remains too broad for technology-specific analysis.

In DII, each patent is assigned a Derwent class (one capital letter and two-digit code) based on the technical field. In addition to this primary categorization, patents get further classified into different areas of technology, which provides further indexing based on the significant features of the innovation, known as the DMC. When two DMCs appear in the same patent, it denotes the existence of a co-occurrence relationship between the two DMCs. Hence, a co-occurrence map of technology, based on social network analysis (SNA) of DMCs, provides significant details of the relationships among these innovative elements. Therefore, based on the co-occurrence network analysis, it is reasonable to say that the technology category with the most co-occurrence (link strength) with other technological categories has garnered the most attention from a large number of innovators in the field (Ampah et al. 2022; Liu et al. 2020).

From the SNA, as illustrated in Fig. 11, five major technological communities were recognized and represented as red, green, blue, yellow, and purple clusters. Within the largest cluster (red), Q42-D emerged as the central focus, with a total link strength of 832 and an appearance in 116 patent applications. In contrast, across the entire network, D04-A01J demonstrated the highest overall link strength of 1,714 and 215 patents, making it the most interconnected and influential category in the field. The smallest communities (blue, yellow, and purple clusters) representing the third, fourth, and fifth technological communities, respectively, show D04-B07C, A12-W11J, and H09-F03 as their key focus areas. Notably, the three categories with the highest co-occurrence across the network are D04-A01J (purification of water by the biological process), D04-B07C (removal of inorganic nitrogen compounds from water), and D04-A01K2 (Purification of water by oxidation/aeration).

Table 5 describes the top 10 categories in the field of sustainable wastewater treatment technologies. This result reveals that the innovations in this field mainly emphasize the purification of water by biological processes (which

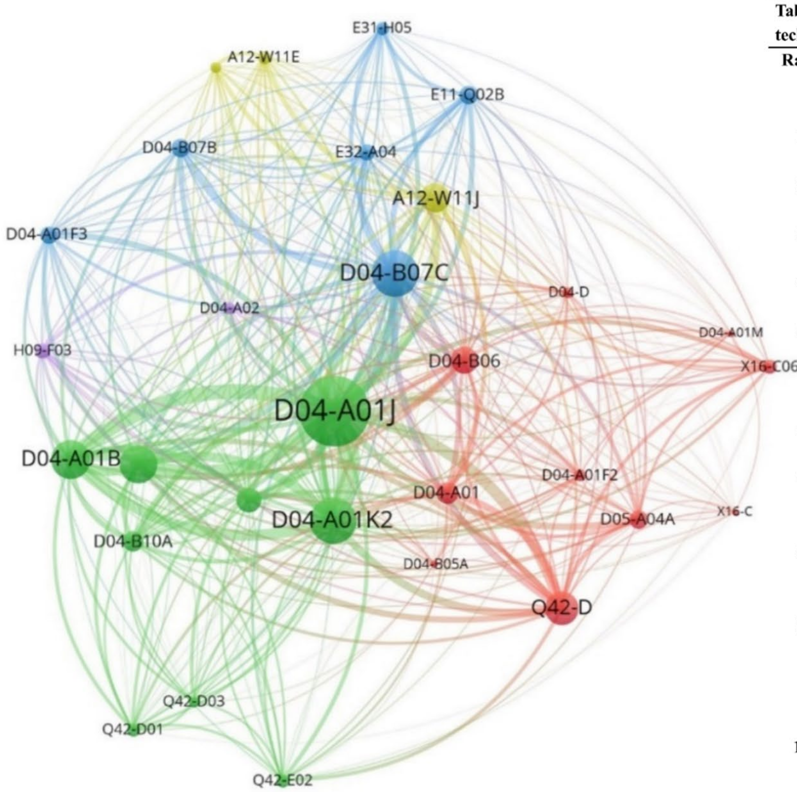


Table 5 – DMC subclasses for key sustainable wastewater treatment technologies.

Rank	DMC subclass	Technology category	Total link strength	Patents count
1	D04-A01J	Purification of water by biological process	1714	215
2	D04-A01K2	Purification of water by oxidation/aeration	1126	129
3	D04-A01	Purification of water	534	117
4	Q42-D	Water supplies for human and animal consumption	832	116
5	D04-B07C	Removal of inorganic nitrogen compounds from water (nitrates, ammonia, and inorganic carbamates	1132	112
6	D04-A01B	Purification of water by precipitation, flocculation	952	102
7	D04-A01F1	Purification of water by other filtration processes, adsorption, active C	916	100
8	A12-W11J	Water treatment (compositions) scale inhibition; corrosion prevention	708	80
9	D04-B06	Removal of specific organic materials, general and 'other' means (e.g., organic dyes, hydrocarbons, phenolic compounds, and surfactants)	668	75
10	X16-C06	Bio-fuel cell (Includes, e.g., cells with electrodes having a 'biocatalyst.	350	63

Fig. 11 Co-occurrence network and table for core technological categories in SWTTs

involves the use of aerobic and anaerobic microorganisms for the removal of different types of contaminants present in water Hussain et al. 2021; Mao et al. 2022). This truly represents what CW, MFC, UASB, and their integrated systems represent as cost-effective and energy-efficient bio-dependent treatment systems. It is also revealing from the second-highest technology category (D04-B07C) that the majority of the innovative ideas for the field have centered on using these treatment systems for the removal of inorganic nitrogen compounds, such as NO_3, NH_3, and NH_4-N removal (Mao et al. 2022; Rahimi et al. 2020).

3.6 Research Terminologies and Thematic Areas.

This section provides a detailed discussion of innovative advances in the field. Based on the study focus, a total of 467 patent documents were retrieved for all sustainable treatment technologies (CW, MFC, UASB, CW-MFC, and CW-UASB), and an aggregate keyword analysis was extracted using ITGInsight to identify the relevant terminologies in the field to identify and inform innovative hotspots. From the social network analysis as shown in Fig. 12a, the top three terminologies or subject words with the highest occurrences were "wastewater treatment system", "wastewater", and "sedimentation tank" with 244, 236, and 147 occurrences, respectively. However, "wastewater treatment system" and "wastewater" form the core concepts of the field, so their high occurrence is expected. If these are excluded, "sedimentation tank" remains the term with the most occurrence (147) in developing SWTTs. Following in that order is the artificial wetland, and so on, according to the node sizes, which denote the frequency of occurrence in patents published. However, to simplify the discussion under this section, the top 20 terminologies were further reclassified into thematic clusters and summarized into core thematic areas to which they belong. This type of classification is often used to identify innovative areas that have gained the widest attention in the study (Ampah et al. 2022; Mao et al. 2022). Five main thematic zones were delineated: technologies, development of pretreatment techniques, contaminants that have gained the greatest attention, component features given the most innovative attention, and others, as shown in Fig. 12 (c).

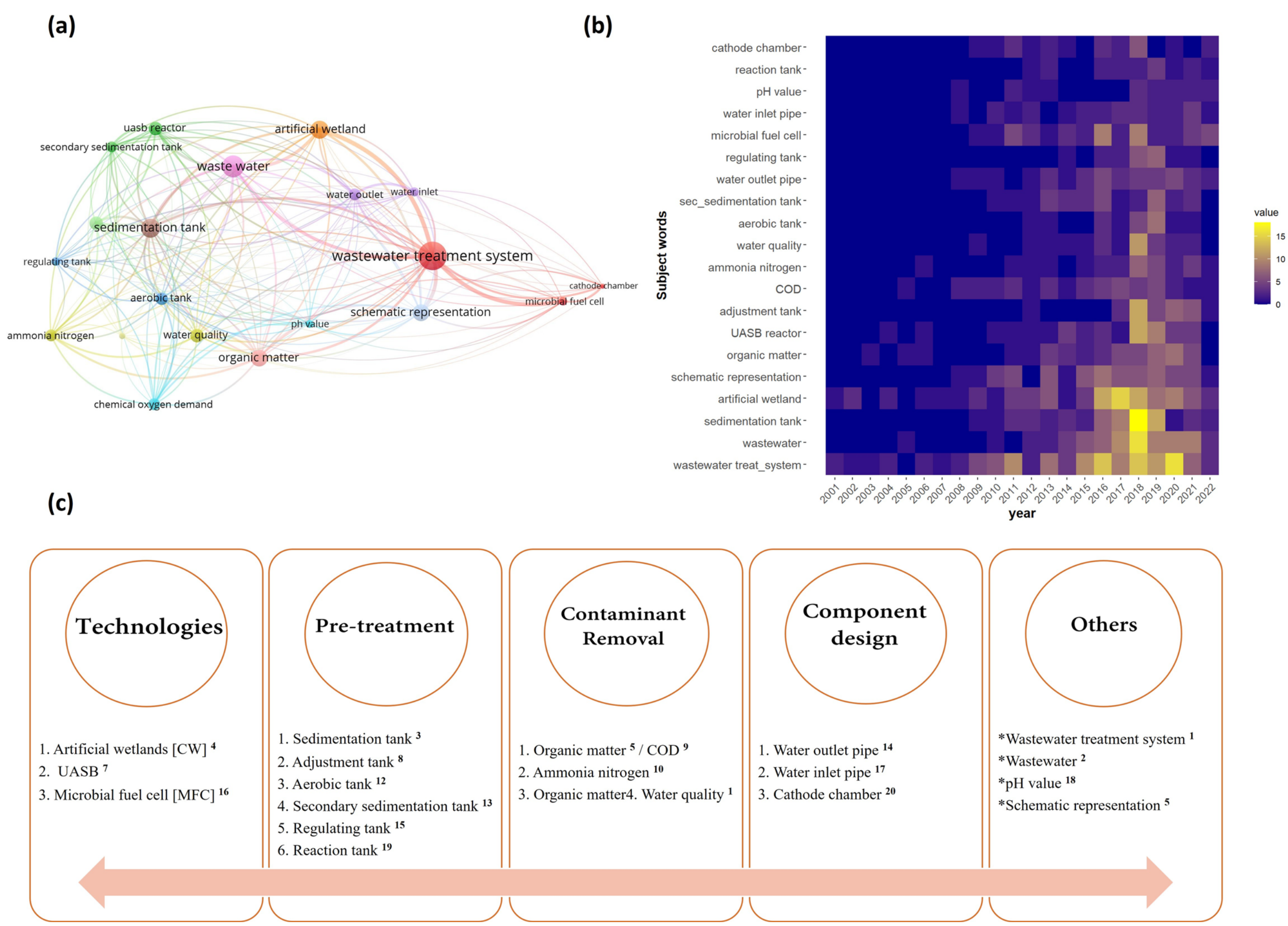


Fig. 12 The social network analysis of the top 20 terminologies for all SWTT and their integrated systems **b** the year dynamics of terminologies, and **c** the main thematic areas based on the top 20 terminologies. Note: superscript indicates rank

Technologies

Under the theme of technologies, the key terminologies identified were artificial wetlands, UASB, and microbial fuel cells, ranking 4th, 7th, and 16th on the top 20 terminologies with 135, 81, and 35 occurrences, respectively. The order in terms of ranking indicates that among the three treatment technologies, CW is the most exploited. This result agrees with the number of patents filed for each technology described in Sect. "Patents Trends and Growth Patterns for Key Sustainable Treatment Technologies". In addition, it also affirms the results of Sect. "Area of Technological Development", which, according to the DMC, the main technological category focuses on the purification of water through biological processes. The dominance of CW can be attributed to its relatively lower technological complexity, broad applicability across diverse wastewater types, and comparatively lower implementation and operational costs. These advantages make CW more accessible for both developed and developing regions, thereby encouraging wider adoption and stronger patenting activities compared to MFC and UASB (Miwornunyuie et al. 2025; Vymazal 2010a, b).

Pretreatment Cluster

The pretreatment category is the largest category with six terminologies among the top 20 subject words. It accounts for 30% of the total subject words. Under this category, the most frequent keywords include “sedimentation tank”, “adjustment tank”, “aerobic tank”, “secondary sedimentation tank”, “regulating tank”, and “reaction tank”. Due to the complexity of wastewater composition and high concentration of pollutants, optimum removal efficiency in CW, UASB, and MFC remains a significant challenge (Mao et al. 2022; Vymazal 2002a, b). Biological treatment systems are generally recognized to be slow in degrading complex substrates in wastewater and might require additional pretreatment techniques (Zafar et al. 2022). For example, high concentrations of suspended solids in CW often lead to the clogging and subsequent flooding of filtration beds. Several studies from different CWs have highlighted the clogging phenomenon as a significant setback in CW, and this is primarily attributed to inappropriate pretreatment mechanisms (Surabhi Singh 2022; Vistanty and Crisnaningtyas 2021a, b; Vymazal 2002a, b). Similarly, pretreatment techniques are equally essential for the performance of UASB and MFC. Mainardis et al. (2020) and Zafar et al. (2022) stated that proper pretreatment application in UASB and MFC systems increases bioenergy yield and enhances microbial biodegradation activities, ensuring the continuous operation of these systems. Hence, the bulk representation of pretreatment terminologies indicates innovative efforts geared towards addressing these major setbacks and ensuring the optimum efficiency of these systems. For example, the sedimentation tank, also known as a settling tank or clarifier, which ranked first on the list, plays a crucial role in wastewater treatment by allowing suspended particles (such as clay, flocs, silt, etc.) initially present in wastewater to settle by gravity (Voutchkov 2004a, b). One of the very recent patents in CW with a focus on sedimentation tanks as a pretreatment technique was filed by Zhou et al. (2020), from Yunnan Investment Ecology and Environment, Patent No. CN210505945-U designed a utility model for a wetland sewage treatment device. They set up an anaerobic tank and a sedimentation tank in front of the artificial wetland pool to absorb and filter the pool and preprocess the sewage to effectively prevent system clogging and significantly improve the purification degree of the sewage treatment. Also, the adjustment tank, which is also used for preconditioning wastewater before treatment, is primarily used to adjust the pH or temperature of wastewater. For example, Patent No. CN114105394-A used a UASB reactor to remove high-efficiency leachate (total nitrogen treatment). Their innovative design involves discharging leachate into an adjustment tank to adjust the temperature of the leachate entering the upflow anaerobic sludge reactor to a suitable range (Jian et al. 2020). Also, for pH adjustment in the removal of metal ions, hydroxide ions are added to raise the pH of wastewater; as a result, dense soluble metal particles are formed in the adjustment tank that can be removed by filtering (Matthews 2014; Wang et al. 2005). Due to the multiple pretreatment conditions and techniques required, two or more pretreatment techniques are often used concurrently or sequentially. It is important to note that the significance of this thematic area in sustainable wastewater treatment technologies is demonstrated by the extent of occurrence and related patents filed under this section. It is also worth highlighting that the majority of the patents filed under this thematic point, according to the year dynamics as shown in Fig. 12b, occurred between 2017 and 2019.

Contaminant Removal

The third largest community in this is the contaminant removal cluster. The keywords under this cluster include “organic matter”, “COD”, “ammonia nitrogen”, and “water quality” in descending order (Fig. 12[c]). The essence of wastewater treatment is to eliminate high concentrations of contaminants to meet the required concentration standards according to usage category (Silva 2023). Hence, determining the quality of wastewater effluent and influent, as well as the efficient removal of contaminants in wastewater, is crucial to every wastewater treatment system. Wastewater contains various contaminants in varying quantities and concentrations depending on their sources (Kiepper 2013). In the present study, the results of our co-occurrence network analysis show that the most common contaminants that have gained the widest attention in CW, UASB, and MFC development include “organic matter”, “COD”, and “ammonia nitrogen”. However, organic matter (OM) and COD are closely related and could be regarded as one. Three main parameters are used to determine organic matter content in wastewater: Biological Oxygen Demand (BOD), COD, and Total Organic Carbon (TOC). Therefore, COD is the measuring parameter used to determine the organic strength of wastewater. The complex matrix, varying sources, and common availability of organic pollutants in wastewater pose a potential threat to human health and aquatic ecosystems (Hashim et al. 2021). According to Yang et al. (2014), the presence of OM in wastewater poses a significant challenge for efficient treatment, since it may cause disinfection toxic by-product formation and low coagulation efficiency (Gursoy-Haksevenler and Arslan-Alaton 2020).

Following OM and COD, ammonia nitrogen is shortlisted among the top 20 terminologies for sustainable wastewater treatment technology patents. Ammonia nitrogen in wastewater exists in two forms: ionized ammonia (NH_4^+) and non-ionized ammonia (NH_3). An increase in pH and temperature has been studied to favor the formation of the more toxic ammonia nitrogen, while a reduction in pH favors the ionized form (USEPA 2023; Zhao et al. 2023). Their excessive abundance in water is associated with water eutrophication and depletion of dissolved oxygen, leading to blackish, smelly, and deteriorated water quality (Zhao et al. 2023). Reducing ammonia nitrogen contaminants in water bodies is crucial to maintaining water quality that supports both aquatic and human life. However, the degradation of ammoniacal nitrogen involves physical, chemical, and biological methods, such as ammonia stripping, precipitation, ion exchange, nitrification, denitrification, advanced oxidation processes, and UV-based techniques. However, numerous studies have shown the cons of these treatment mechanisms, such as high retention time, sludge formation, and treatment cost (Pani et al. 2020). Nowrouzi et al. (2021a, b) comprehensively analyzed various activated sludge-based wastewater treatment technologies in meat processing units. The study evaluated the cost-effectiveness and removal efficiencies of these technologies concerning COD and ammonia. The findings highlighted that while certain technologies offered higher removal efficiencies, they also incurred significantly higher operational and maintenance costs. This underscores the financial challenges of treating high-strength wastewater containing elevated levels of COD and ammonia. Hence, the associated threats, cost, and difficulty in handling these contaminants, coupled with their abundance in nature (which makes them a very common pollutant), might have stimulated innovative efforts in the exploration of these technologies (CW, UASB, and MFC) for their effective and efficient removal. For example, in MFC, an intervention with Patent No. CN102557200-A, designed by the Chinese Academy of Science, is a utility model of a membrane aeration microbial fuel cell to remove COD and nitrogen contaminants in sewage synchronously. Their invention achieved a high removal rate of COD and ammonia nitrogen at a reduced construction cost while simultaneously generating electricity (Hu and Yu 2012). Also, one of the most cited interventions in UASB with patent No. CN104326561-A developed a multi-stage microbial treatment of livestock wastewater. The model was helpful and efficient for removing COD, NH_3, and TN from wastewater (Chen et al. 2015).

Component Design and Material

The fourth thematic area focuses on efficient design and material components for system optimization, with keywords such as “water outlet pipe”, “water inlet pipe”, and “cathode chamber”. The inlet and outlet pipes essentially distribute influent into the treatment technologies and control the flow path. They help prevent “dead zones” where water movement is poor. Their significance to the effective functioning of treatment technologies cannot be overlooked since inappropriate inlet and outlet pipe design can lead to system clogging and wastewater detention time (UN-HABITAT 2008). Of the 185 patents filed under CW for the study period, 102 (55%) were directly or indirectly related to inlet and outlet pipes. Whereas 14 patents (8%) out of 177 patents in UASB and 6 patents (6%) out of the 96 in MFC featured water inlet and outlet pipes as key terminologies related to their developments. They play a significant role in these technologies, especially in CW by determining the contact time between microbes and substrates and the system's flow rate (Othman et al. 2020). Hence, the exploration of a suitable water outlet and inlet pipe design to maximize even flow distribution and minimize the potential for short-circuiting and clogging is of utmost importance for system optimization. For example, in the development of CW, patent No CN103387320-A with one of the highest citation records describes an artificial wetland system with the water inlet pipe, an aeration device, a water outlet, and a preprocessing area in which an aeration device was set to the multifunctional area, wetland unit, and the multifunctional area are distributed at intervals. The input and output ends of the controllers were provided with filter material. The advantage of this utility design is that the system does not easily block and exhibits a good pollutant removal effect, high dissolved oxygen levels, and a strong adsorption effect (Li et al. 2013). Also, Patent No. CN106045031-A installed multiple inlet and outlet pipes in the UASB reactor for secondary treatment of secondary effluent and municipal wastewater by lateral-flow synchronous treatment (Peng et al. 2016). Their system was economically advantageous and energy efficient, with high nitrogen removal. According to the heat map (Fig. 12[b]), this area became a focus of development from 2008 to 2021, which suggests that it was not an initial focus during the early stages of the technologies until later. Finally, one of the patents filed under MFC technology development developed a utility model incorporating "water inlet pipe", "water outlet", and "cathode chamber", which ranked last among the top 20, and in this thematic cluster was filed by the University of Chongqing with Patent No. CN103159331-A. The novelty of their model was a design of photocatalysis-associated MFC technology whose anode chamber and cathode chamber are provided, respectively, with a water inlet and water outlet for simultaneous sewage treatment and power generation. The cathode chamber plays a significant role in bioelectricity generation (Fan et al. 2013). However, it is important to state that the terminology "cathode chamber" is solely related to MFC or CW-MFC hybrid technologies, which are sensitive to redox conditions (Gude 2018a, b; Saravanan et al. 2022). Figure 12 shows the keywords for each sub-technology (Fig. 13).

Conclusion

This study analyzed the development status and trends of key sustainable wastewater treatment technologies (CW, UASB, and MFC) and their integrated systems (CW-MFC, CW-UASB), from 2001 to 2022, based on 467 patent publications. The findings reveal that CW are the most widely patented, reflecting their technological maturity and broad applicability, while MFC remains an emerging technology with niche opportunities for energy recovery. UASB demonstrates the highest maturity and proven scalability, particularly for high-strength wastewater. Geographically, China leads in patent volume, driven by strong policy support. Whereas, the USA shows a comparatively higher degree of international collaboration. Innovation hotspots are concentrated around pretreatment processes and nutrient removal efficiency, while integration pathways (e.g., highlight opportunities to combine system strengths.

To synthesize these findings, a comparative SWOT analysis of CW, MFC, and UASB is presented in Table 6, highlighting their relative strengths, weaknesses, opportunities, and threats based on patent trends, diffusion patterns, and known technological characteristics.

Overall, the results indicate that CW has the fastest diffusion but is not yet fully mature, offering significant scope for innovation, particularly through integration with MFC.

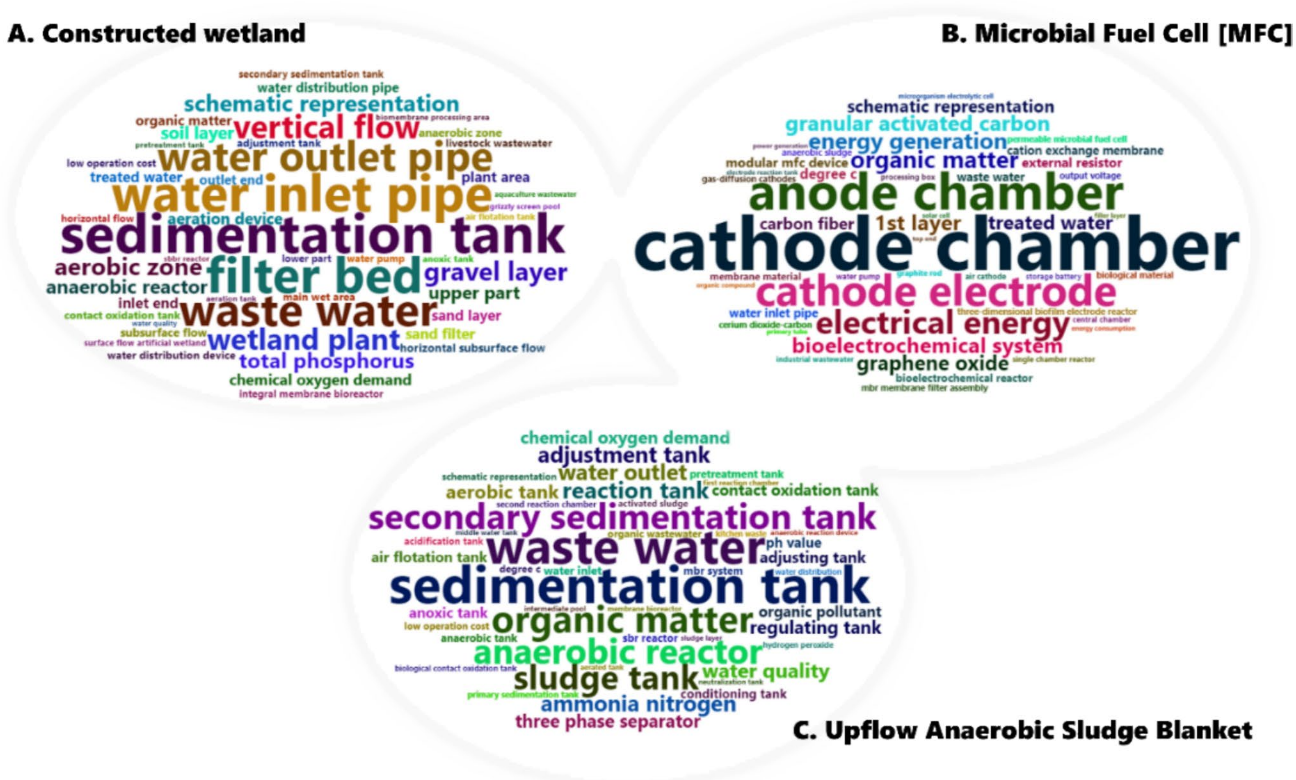


Fig. 13 Key innovative areas for CW, MFC, and UASB technologies

Table 6 Comparative SWOT analysis of Constructed Wetlands (CW), Microbial Fuel Cells (MFC), and Upflow Anaerobic Sludge Blankets (UASB) based on patent trends, diffusion patterns, and known technological characteristics

SWOT Factor	Constructed Wetland (CW) (TMR = 74%; TDS = 4.97 – fastest diffusion, moderate maturity)	Microbial Fuel Cell (MFC) (TMR ≈ 78%; TDS = 3.04 – slow diffusion, emerging maturity)	Upflow Anaerobic Sludge Blanket (UASB) (TMR ≈ 84%; TDS = 3.65 – moderate diffusion, highest maturity)
Strengths	Mature, widely implemented nature-based system; low cost & energy use; strong nutrient removal; low sludge production; ecological co-benefits; fastest diffusion rate among the three	Dual wastewater treatment & electricity generation; low sludge; adaptable for integration with CW; moderate maturity suggests further innovation potential	High COD removal; compact footprint; biogas for energy recovery; highest maturity indicates strong commercialization readiness
Weaknesses	Large land footprint limits urban use; slower treatment rates; seasonal efficiency variations	High capital cost (electrodes, catalysts); low power density; operational complexity; slowest diffusion speed limits current adoption	Methane emissions if uncaptured; sensitive to temperature & toxic shocks; sludge granulation issues
Opportunities	Integration with MFC for energy recovery (CW-MFC); alignment with SDG & Ramsar goals; rising demand for decentralized/rural applications	Technological optimization (multi-anode, advanced electrodes); niche off-grid energy recovery; hybrid systems (CW-MFC) for combined treatment-energy goals	Integration with CW for nutrient polishing (CW-UASB); expansion into industrial wastewater markets; carbon credit potential from methane capture
Threats	Urban land scarcity; climate change impact on vegetation/microbes; industrial wastewater limitations without pre-treatment	Competition from low-cost renewables & treatment systems; electrode fouling & long-term material degradation; limited investor confidence	Competition from other anaerobic digestion systems; operational disruptions from toxic shocks; tightening GHG emission regulations

MFC remains at an emerging stage with slow diffusion but holds niche opportunities for energy recovery in hybrid systems. UASB shows the highest maturity and proven scalability, especially for high-strength wastewater, though environmental regulations on methane emissions may drive future design improvements. These insights offer a decision-support tool for policymakers, investors, and researchers seeking to prioritize sustainable wastewater technologies with the most significant long-term potential.

Moreover, the results from the study also indicate that the national policy framework can have a decisive influence on the innovation trajectory of sustainable wastewater treatment technologies. For example, China's 13th and 14th Five-Year Plans explicitly prioritized environmental innovation and water management, channeling resources into R&D, pilot projects, and patent protection, which aligns with China's dominant share of SWTT patents. Similar policy support, combined with incentives for international collaboration, cross-sector partnerships, and technology transfer, could accelerate the diffusion and commercialization of sustainable wastewater treatment technologies in other regions.

While this study offers a robust patent-based perspective, further research should integrate environmental impact assessment metrics such as life cycle greenhouse gas emissions and energy footprint, along with commercial performance indicators including cost–benefit analysis and operational reliability in full-scale plants. Expanding the analysis to include forward citation data and patent legal status could help distinguish high-impact innovations from lower-value filings. Additionally, exploring the techno-economic and environmental synergies of integrated configurations like CW-MFC and CW-UASB may reveal pathways to combine the strengths of individual systems while reducing their limitations.

Despite the robustness of patent-based analysis, this study has several limitations. First, it relied solely on the Derwent Innovation Index, which, although comprehensive, may not capture patents exclusive to other databases or jurisdictions. Second, the use of patent counts as a proxy for innovation has inherent limitations, since not all innovations are patented and patenting strategies vary across countries, institutions, and firms. Third, the S-curve diffusion analysis was applied to relatively small datasets in some sub-technologies, which may reduce the robustness of life-cycle state estimations. These limitations suggest that the findings should be interpreted with caution and complemented in future work by integrating multiple patent databases, triangulating with publication and commercialization metrics, and applying alternative modeling approaches better suited to smaller datasets.

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Data Availability The data that support the findings of this study are openly available in repository Pub2025@DataAvailable at https://drive.google.com/drive/folders/153xTGBI4xiDavJt5Ec5T6JbMFggZw4K8?usp=drive_link.

Declarations

Competing interest The authors declare that they have no competing interests.

Ethical Approval This manuscript does not contain any studies with human participants or animals performed by any authors.

Consent to Participate Not applicable.

Consent for Publication All authors gave their consent for publication. Supplementary file1 (DOCX 1039 KB).

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