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Review

Sustainable Swimming Pool Management Under Climate Stress: A Structured Review of Water-Energy Strategies in Europe

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Abstract: The accelerating impacts of climate change-including intensifying heatwaves, recurrent droughts, and growing water scarcity-are placing increasing pressure on urban infrastructure, including recreational facilities such as swimming pools. The review considers both public and private swimming pool facilities, with particular relevance to urban and tourism-oriented pools that face increasing resource pressures under climate stress. While pools provide important public-health benefits by offering spaces for exercise, social interaction, and thermal relief, they are also highly water-and energy-intensive. This paper develops a conceptual framework for sustainable swimming pool management under climate stress, integrating the water-energy nexus, climate-resilient infrastructure, and sustainability transitions. A structured review of peer-reviewed literature published primarily between 2017 and 2026 (Google Scholar, GreenFILE, and PubMed) synthesizes technical, environmental, and policy evidence on water use, energy demand, and mitigation options in pool operations. The review predominantly draws on European case studies and policy contexts, reflecting climatic, regulatory, and infrastructural conditions common in Southern and Central Europe. The analysis shows that energy use-dominated by pool heating-represents the largest source of environmental impact, making renewable heating technologies such as solar thermal systems, photovoltaic-thermal collectors, and ground-source heat pumps among the most effective climate-mitigation measures. On the water side, backwash water recovery and reuse systems emerge as the single most powerful intervention, capable of reducing freshwater demand by up to 96% in well-designed systems, while low-cost efficiency devices provide essential baseline savings. By reframing swimming pools as adaptive urban infrastructures rather than discretionary amenities, the paper demonstrates how recreational water facilities can function as testbeds for integrated water-energy solutions, contributing to climate adaptation, resource efficiency, and long-term public-health resilience.

***Keywords*:** sustainable pool management, climate change adaptation, water saving, energy saving, public health adaptation, recreational facilities, sustainability

1. Introduction

Water is essential for life and underpins human health, socio-economic development, and ecosystem functioning [1].

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However, the world now faces an escalating water crisis, with warnings that global water use may have already reached its peak [2]. Population growth, urbanization, and economic development are driving increasing imbalances between water supply and demand [3], while the accelerating impacts of climate change are undermining the capacity of existing urban water systems to meet present and future needs [4].

Adequate water quantity and quality are critical not only for domestic, industrial, and agricultural use but also for reducing treatment costs, supporting urban resilience, and mitigating flooding. These challenges underscore the importance of Sustainable Urban Water Management (SUWM), which seeks greater environmental, economic, and social benefits than conventional approaches [2]. As defined by Gleick, sustainable water management involves using water in ways that allow human societies to endure and flourish indefinitely without compromising the hydrological cycle or the ecosystems it supports [5].

The impacts of climate change extend beyond core urban infrastructure, affecting recreational facilities that contribute to community wellbeing. Among these, swimming pools occupy a particularly complex position [6]. Pools provide essential public health and social benefits, offering spaces for exercise, social interaction, and relief from extreme heat-functions that are increasingly important as cities experience more frequent and severe heatwaves. In urban areas, the Urban Heat Island (UHI) effect-caused by dense building layouts and heat-retaining surfaces-amplifies temperatures, exposing city dwellers to more extreme heat than rural populations [7].

The summer of 2025 pushed Europe to extreme temperatures, with record-breaking heatwaves from mid-June sending temperatures above 46 °C in parts of Spain and Portugal, highlighting the growing challenge for Southern European cities, which increasingly rely on water-based coping strategies such as public swimming pools in Barcelona [8]. Another example presented is in Victoria, Australia, where, in order to cope with extensive heat, some local councils offer heat refuges during heatwaves by providing free shuttle services to local swimming pools and extending the hours of air-conditioned facilities, such as libraries [9].

At the same time, swimming pools are among the most resource-intensive, requiring substantial energy for heating, filtration, and ventilation, as well as large volumes of water for filling, maintenance, and evaporation control [10], [11]. Energy demand depends on several factors such as location, pool size, and whether the pool is indoor or outdoor. Heating alone accounts for the largest share of energy use in swimming pools because water constantly loses heat to the environment. Ongoing losses make maintaining comfortable water temperatures energy-intensive, highlighting the importance of energy-saving measures and the use of renewable technologies in both indoor and outdoor pools [12].

Tourism in Southern Europe, particularly on Mediterranean islands, depends heavily on water resources, with swimming pools serving as key amenities for visitors. The sector faces pressures such as shoreline erosion, rising water demand, and sea-level rise, and as a result, sustainable practices-including water conservation, responsible waste management, and eco-friendly transportation-are essential for reducing its carbon footprint and supporting the preservation of fragile coastal ecosystems [13]-[17].

This dual role-supporting urban wellbeing while imposing significant demands on energy and water-makes swimming pools an important yet often overlooked focus in sustainability discussions [16]. Consequently, the sustainable management of swimming pools requires context-sensitive and integrated strategies for both energy and water use, explicitly evaluated across the three pillars of sustainability: environmental, economic, and social.

Recent literature has increasingly examined the environmental footprint of swimming pools, focusing on water consumption patterns, energy demand, and technological efficiency measures [18]. Studies highlight that, despite their relatively limited contribution to total urban water use, swimming pools often become symbolic focal points during periods of drought and water scarcity, intensifying social and political debate [19]. At the same time, research emphasizes their potential role as demonstrative sites for innovative water-energy solutions, particularly when embedded within broader urban sustainability and climate adaptation frameworks [20].

Aiming to develop a theoretical framework for sustainable pool management under the climate crisis, this paper's goals are to consolidate insights from recent empirical and technical literature on how pools consume water and energy, to identify key strategies that enable pools to transition toward lower-carbon, water-efficient operation, and to situate pool management within broader theories of resilience, sustainable transitions, and adaptive infrastructure.

The novelty of this paper lies in its synthesis of dispersed technical and policy-oriented research into an integrated conceptual framework that positions swimming pools as adaptive infrastructures within climate-resilient urban systems. Rather than focusing on a single technology or case study, the analysis bridges the water-energy nexus, public health considerations, and sustainability transitions, offering a holistic perspective that can inform both policy development and practical decision-making.

To guide the reader through the structure of the manuscript, the following sections are organized as follows. Section 2 describes the methodological approach and literature selection process applied in this structured review. Section 3 presents the main findings regarding swimming pool water consumption, energy demand, and key mitigation and efficiency measures. Section 4 discusses optimization pathways and integrated water-energy frameworks that support climate-resilient pool management. Finally, Section 5 concludes by summarizing the key insights of the review and outlining future directions for sustainable swimming pool infrastructure under increasing climate stress.

2. Methods and aims

In order to achieve the goals of this paper, scientific search engines and databases such as Google Scholar, GreenFILE, and PubMed were used. Searches were carried out using relevant keywords, including: "swimming pools" AND ("sustainable" OR "sustainability"), "swimming pools" AND "energy". Filters were applied to refine results and to focus on articles published primarily between 2017 and 2026, written in English, and addressing the intersection of climate change, infrastructure adaptation, and sustainable water practices.

From this process, a wide range of scientific articles and case studies was identified, offering insights into technical, environmental, and policy dimensions of sustainable pool management. Selection was based on the relevance of the article titles and abstracts to the central research focus. After reviewing abstracts, decisions were made to include or exclude sources. In many cases, abstracts alone were insufficient for a complete understanding, and therefore full-text analysis was conducted to capture relevant data, methodological approaches, and conceptual perspectives. Although the review addresses international literature, the analysis primarily reflects European policy frameworks, climatic conditions, and infrastructure typologies, and findings should be interpreted within this context. This review is narrative/structured and therefore PRISMA was not applied. A workflow diagram illustrating the main steps of the structured literature review and synthesis process is provided in Figure 1.

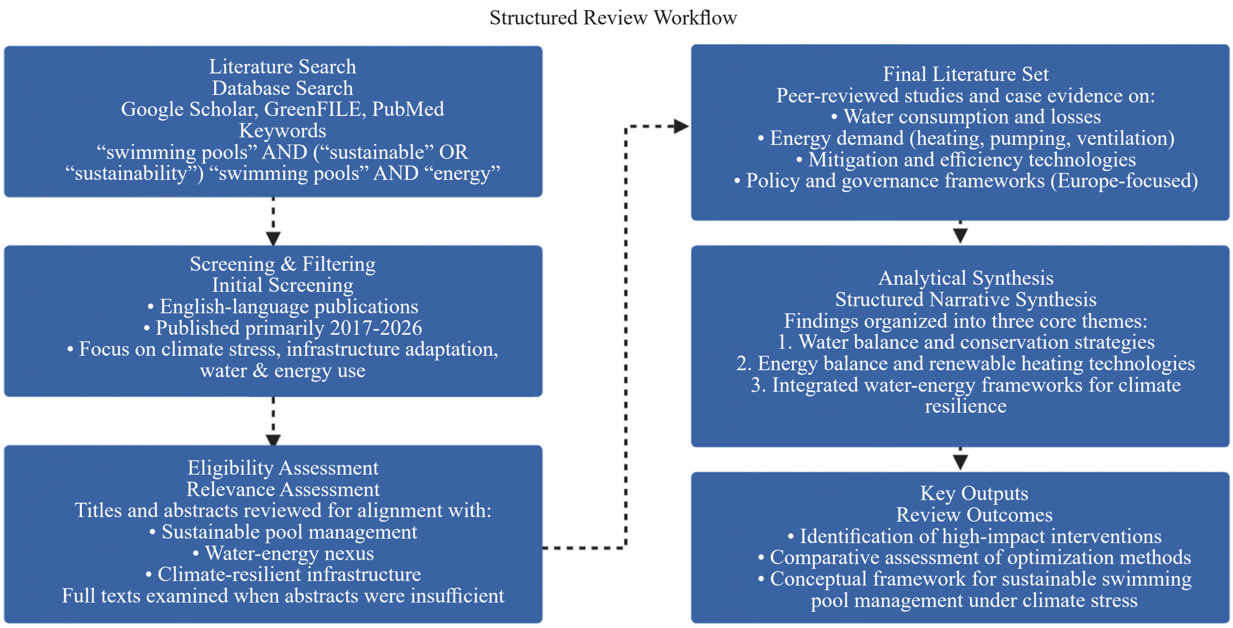

Figure 1. Structured review workflow for sustainable swimming pool management under climate stress

3. Results

Climate change is placing growing pressure on global water resources, intensifying both water scarcity and hydrological extremes across many regions of the world [21]. Rising temperatures, shifting precipitation patterns, and an increasing frequency of droughts and floods are disrupting established water balances, particularly in Mediterranean, semi-arid, and rapidly urbanizing areas [11]. These changes are occurring alongside rising water demand driven by population growth, urban expansion, and economic activities such as agriculture, energy production, and tourism [22]. Together, these trends expose structural vulnerabilities in existing water management systems and underscore the urgent need for more sustainable, resilient, and adaptive approaches to water use [17].

Although attention often focuses on large water users, such as irrigated agriculture or industry, climate adaptation requires a systemic perspective that accounts for the cumulative impacts of diverse, smaller-scale demands embedded in urban and tourism infrastructure. Highly visible uses of water, including recreational amenities such as swimming pools, can play a disproportionate role in shaping public perceptions and policy debates, even when their absolute consumption is relatively limited compared with other sectors [23]. In tourism-dependent destinations, this visibility is further reinforced by visitor expectations, as recent research indicates that tourists frequently perceive swimming pools as essential amenities in tourism accommodations, reflecting the strong demand for such recreational water infrastructure [16]. This visibility creates both challenges and opportunities: while such uses may become focal points of social tension during drought periods, they also offer entry points for demonstrating efficient technologies, adaptive practices, and integrated solutions that can be scaled across the built environment.

From a life-cycle perspective, the sustainability of water services depends not only on direct water withdrawals but also on the energy and material flows required to treat, distribute, heat, and maintain water quality [6]. Climate change further amplifies these interdependencies by increasing energy demand for cooling, treatment, and pumping, while simultaneously constraining water availability. Reducing overall water abstraction and energy use is therefore central to advancing Sustainable Development Goals 6 and 7, as well as to achieving broader climate mitigation and adaptation objectives. Efficiency gains in end-use systems can generate cascading benefits, lowering pressure on freshwater resources, reducing greenhouse gas emissions, and enhancing system robustness during extreme events [2].

In this context, alternative water sources and demand-side management strategies are increasingly recognized as essential components of sustainable water governance. Rainwater harvesting represents a cross-cutting approach that can simultaneously augment local water supply, reduce dependence on centralized systems, and mitigate flood risks by capturing and temporarily storing stormwater. When combined with Integrated Urban Water Management (IUWM) frameworks, rainwater harvesting can be embedded within a wider portfolio of nature-based and decentralized solutions, including green infrastructure, permeable surfaces, and distributed storage [1], [4]. These approaches help restore more natural hydrological functions in urban areas, buffering the impacts of climate variability while improving water quality and urban microclimates.

Technological innovation also plays a key role in addressing water sustainability under climate change. Advances in water-efficient appliances, leakage detection, smart monitoring, and energy-efficient heating and pumping systems enable significant reductions in both water and energy demand across residential, commercial, and recreational uses [22]. In parallel, the integration of renewable energy sources-such as solar thermal and photovoltaic systems-can decouple water services from fossil fuel dependence, reducing emissions and exposure to energy price volatility. Importantly, the effectiveness of these technologies depends on supportive governance frameworks, long-term planning, and user engagement to ensure that efficiency gains are realized and maintained over time [24].

Collectively, these strategies point toward a transition from reactive water management toward anticipatory, climate-resilient water systems. By combining demand reduction, diversified supply sources, nature-based solutions, and energy-water integration, societies can better accommodate uncertainty and extremes while safeguarding essential water services. In this broader framing, sector-specific applications-such as tourism and recreational water use-serve not as isolated concerns, but as testbeds for implementing and demonstrating the systemic changes required to meet long-term water sustainability needs in a warming climate.

Taken together, the reviewed evidence suggests that swimming pool sustainability cannot be addressed through isolated interventions targeting only water or only energy use. Instead, the effectiveness of individual measures is highly context-dependent, shaped by climatic conditions, pool typology (indoor versus outdoor), facility scale, and local governance frameworks. This reinforces the need to interpret swimming pools not merely as discretionary amenities, but as adaptive infrastructures where integrated water-energy solutions can be demonstrated and scaled under conditions of climate stress.

3.1 *Water-energy nexus*

Water and energy are both key components that must be managed in an integrated manner in order to achieve sustainable pool management. Their significance is highlighted through the Sustainable Development Goals (SDGs) where they are addressed as “Clean Water and Sanitation” (SDG 6) and “Affordable and Clean Energy” (SDG 7) [25]. Importantly, the nexus framing emphasizes that interventions targeting energy efficiency often reduce indirect water demand, while water-saving measures can simultaneously lower heating and treatment requirements, creating compounded sustainability benefits. With climate change intensifying pressure on resources, it is imperative to identify adaptive solutions across sectors. In recreational facilities such as swimming pools, sustainable water and energy management can play a key role by using renewable energy sources, reducing thermal demand through efficiency measures, and implementing water-saving practices [10].

3.2 *Hydraulic model*

The swimming pool hydraulic model illustrates how water circulates through the system, the sources of its input, and the causes of its loss. Water is lost through evaporation, splash out, overflow, leaks, filter backwashing, and intentional water renewal, while it is refilled by rain and freshwater filling. Evaporation is the main source of water loss in outdoor pools, while in indoor pools, evaporation is lower, and splash-out or moisture lost to the air is relatively more significant. The main sources of water losses and gains are depicted in Figure 2.

The water is continuously recirculated from the pool to the balance tank, through the pre-filter, pump, and main filter, before returning to the pool, with chemical treatments applied at different stages for pH regulation, disinfection, and coagulation. The purpose of this model is to establish the water balance of the pool, calculate consumption, and identify where losses occur in order to save water. This is important for environmental sustainability and operational efficiency, as it conserves a limited resource and reduces costs associated with filling, heating, and treating the water [6], [26].

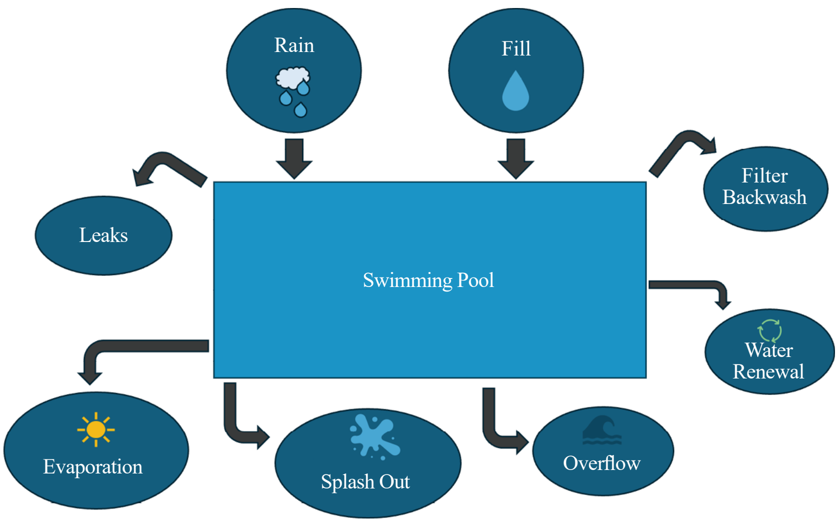

Figure 2. Water balance of a swimming pool

3.3 *Energy balance*

The energy balance defines the relationship between the energy supplied to the pool system and the energy lost or consumed. Thermal losses, primarily from evaporation (outdoor pools) and transmission through the pool walls and floors, represent significant inefficiencies, but can be reduced with covers, insulation, and humidity control. Water heating is one of the highest energy demands, yet the use of efficient technologies such as heat pumps, solar thermal systems, or heat recovery can greatly lower consumption [6], [26]. Notably, water temperature differs between indoor and outdoor pools, with indoor pools typically maintained within a controlled range (approximately 24-29 °C), whereas outdoor pools experience greater seasonal variability. Moreover, optimal temperature preferences and requirements vary according to user type (e.g., recreational bathers versus competitive swimmers) and the nature of the activity [27].

Filtration and pumping, while essential for maintaining water quality, are energy-intensive processes that can be optimized with modern, efficient equipment and better operation practices. In indoor pools, air conditioning plays a key role in regulating temperature, humidity, and air quality, ensuring comfort and protecting infrastructure, though it also adds to energy use. Overall, optimizing the energy balance reduces both operational costs and environmental impact, contributing to more sustainable swimming pool facilities [6], [26].

Implementing energy-efficiency measures in swimming pool facilities can substantially lower both energy use and operating costs. The adoption of technologies such as solar collectors and smart actuation devices can achieve particularly high reductions in energy consumption. In addition, installing sensors enhances scheduling logic and process optimization, leading to significant energy savings and even greater economic benefits compared to scenarios without these technologies. Beyond cost and energy reductions, these measures also contribute to improved system scheduling and enhanced user comfort [28].

3.4 *Optimization methods*

Gathering information from several studies [22], [24], [26], [29]-[34] 8 optimization methodswere chosen and systematically assessed, four for energy savings and four for water savings.

Table 1. Energy sustainability methods

Method	Primary sustainability benefit	Energy/Water savings	Economic/Practical considerations	Environmental impact	Key limitations/ Conditions
Permanent Green Roof [24], [29], [30]	Enhances thermal efficiency; supports year-round sustainable operation	Reduces heating demand and chlorine usage	High initial investment; long-term payback	Significantly reduces fossil fuel consumption; improves microclimate; mitigates the Urban Heat Island (UHI) effect	Requires substantial structural modifications
Solar Thermal Collectors [26]	Provides renewable heat for water	Significant heat contribution	Moderate installation cost; fast operational savings	Reduces CO_2 emissions by substituting fossil fuels	Requires extensive roof area; works best with enclosed pools
Photovoltaic-Thermal (PVT) System [24], [31]	Captures solar heat while generating electricity	Significant reduction in electricity use for pool heating; thermal efficiency improves overall energy utilization	Initial investment can be high	Lowers greenhouse gas emissions by using renewable solar energy; reduces carbon footprint of pool operation	Thermal efficiency varies with sunlight; indoor pools may need extra sunlight; high initial cost
Ground Source Heat Pump [24], [26]	Provides high-efficiency, low-emission heating	Reduces energy usage	Higher upfront cost; long-term energy savings	Extremely low CO_2 emissions; no combustion	Requires drilling vertical boreholes; space constraints may apply

Comparative interpretation of the reviewed methods indicates that energy-related interventions generally deliver the largest reductions in overall environmental impact, since heating dominates operational energy demand in most pool facilities. However, water-reuse technologies-particularly backwash recovery systems-become critical in drought-prone regions, where freshwater availability and regulatory pressures intensify the need for demand reduction. These trade-offs highlight that sustainability pathways must be tailored rather than universally applied.

Table 2. Water sustainability methods

Method	Primary sustainability benefit	Water/Energy savings	Economic/Practical considerations	Environmental impact	Key limitations/ Conditions
Water-Saving Devices (Taps, Showers, Toilets) [22], [24]	Minimizes potable water consumption	Taps: up to 70%; flow restrictors: up to 60%; toilets reduced from 10 L to 3-6 L	Low-cost; immediate reduction in water bills	Reduces stress on municipal water supply; lowers operational water footprint	Impact depends on user behavior; modest compared to energy measures
Rainwater Harvesting [24], [33], [34]	Supplies non-potable water from rain	Reduces water needs	Moderate installation and maintenance costs	Reduces demand for potable water; promotes local resource reuse	Seasonal variability; requires storage infrastructure
Groundwater Utilization [24]	Uses local groundwater to supplement water supply	Variable, depending on treatment and usage	Costs vary with treatment requirements	Reduces reliance on municipal water	Requires ongoing quality monitoring, treatment, and regulatory compliance
Backwash Water Recovery & Reuse [35]	Treats and recycles swimming pool backwash water	Up to 96% of backwash water can be reused	Moderate investment; rapid operational savings	Minimizes freshwater consumption and wastewater discharge; reduces energy use	Requires advanced treatment systems, maintenance, and regulatory approval

The optimization methods for water and energy savings shown in Tables 1 and 2 each have several environmental benefits. A permanent green roof significantly cuts down thermal losses and lowers the heating demand, especially when combined with a pool water cover. It also reduces chlorine use since less water evaporates and overall provides a variety of environmental benefits, such as reduced fossil fuel consumption and improvement of the microclimate [29]. Green roofs also manage to mitigate the UHI effect through evapotranspiration, in which plants release water vapor during transpiration, cooling the surrounding air. They also reduce heat gain by shading buildings, which limits the amount of solar radiation absorbed by roofs and walls. In addition, the layer of vegetation provides thermal insulation, slowing the transfer of heat from the outdoor environment into the building [30], [31]. According to the studies [24], [29], due to the high cost of installation and further investments, this method is financially unattractive. However, it is important to mention that the cost-effectiveness of green roofs varies by region and application, influenced by factors such as local climate, labor expenses, availability of materials, and the specific features of the building [31].

Solar thermal collectors use sunlight to heat pool water, providing a clean and renewable option for both indoor and outdoor swimming pools. In indoor pools, they typically operate with a storage tank and controlled pumps, while outdoor pools are linked directly through heat exchangers [24], [26]. Research shows that larger collector areas, higher flow rates, and improved heat-transfer design raise pool water temperature. Solar pool-heating systems can be economically competitive with conventional heaters, offering excellent economic performance and significant CO_2 emission reductions 26. Overall, solar collectors reduce operating costs and emissions, but their feasibility depends on climate, system size, and local economic conditions [24], [26].

PVT systems, which generate both electricity and heat from sunlight, can significantly improve the energy efficiency of swimming pool heating systems-both indoor and open. Combining PVT with additional heating methods can further enhance performance, and placing the panels in or near the pool can save space. Such setups can provide substantial electricity while boosting overall energy efficiency, with glazed panels offering a relatively short payback period for low-temperature pool heating [26], [31].

Geothermal energy provides reliable, low-emission heating for indoor and outdoor swimming pools through ground-source heat pumps, which store heat in the ground in summer and release it in winter. These systems offer high efficiency, significant energy savings, and strong financial performance compared to gas boilers, though they have high upfront costs and require drilling vertical boreholes [24], [31].

According to Pimentel-Rodrigues and Silva-Afonso [22] water-saving devices such as efficient taps, showers, and toilets offer immediate, low-cost reductions in potable water use (up to 70% for taps, 60% for flow restrictors, and a reduction in toilet flushing volumes from 10 liters to 3/6 liters) though their overall impact is smaller than energy measures and depends on user behavior.

Applied to swimming pools, harvested rainwater offers economic and environmental benefits by reducing reliance on potable water. However, its use is constrained by seasonal rainfall, storage requirements, and variable water quality, which depends on air pollution, catchment surface type, tank material, and storage time, as stagnant water may undergo secondary contamination. While pre-treatment and risk-based quality assessment can mitigate health risks, legal regulations for non-potable uses remain inconsistent across Europe, limiting standardized implementation [24], [32], [33].

Groundwater utilization further reduces dependence on municipal water supplies, although savings vary based on treatment needs and regulatory constraints, and its economic performance was not fully quantified [24].

A backwash water recovery and reuse system for swimming pools can recycle up to 96% of backwash water, yielding annual savings of up to EUR 9,000 with a payback period of about two years, while significantly reducing water waste and wastewater discharge, though it requires advanced treatment processes, regular maintenance, and regulatory compliance [34].

Beyond environmental benefits, several of the reviewed interventions also generate indirect public health-related co-benefits. Improved thermal regulation, reduced chemical use, and stable water quality contribute to safer and more comfortable pool environments. In the context of increasing heat extremes, such conditions can support physical activity and social inclusion, particularly for vulnerable population groups [1], [4], [6], [10], [21], [22], [26], [29], [31].

Overall, the literature suggests that no single optimization strategy is sufficient on its own. Effective sustainable pool management requires combinations of renewable heating, efficiency measures, and advanced water reuse systems, selected according to local climatic constraints, institutional capacity, and economic feasibility. In this sense, swimming pools can serve as pilot infrastructures for broader sustainability transitions, linking operational resource savings with climate adaptation objectives in urban and tourism-dependent regions.

4. Integrated water-energy frameworks for climate resilience and public health

Climate change poses severe threats to public health, driving direct impacts such as heatwaves, floods, and wildfires, and indirect effects including food insecurity, disease spread, malnutrition, and population displacement [35]. Vulnerable populations, particularly in urban areas and low-and middle-income countries, face heightened risks, while aging populations and rapid urbanization further amplify health impacts. Addressing these challenges requires effective climate change governance, which integrates scientific knowledge, public administration, private sector engagement, and civil society participation. Global and local cooperation, equitable leadership, and coordinated mitigation and adaptation strategies-such as clean energy transitions, resilient infrastructure, and water management-are essential to reduce health risks, promote sustainability, and ensure societal resilience in the face of climate change [36].

The Sustainable Development Goals (SDGs), adopted by the United Nations in 2015, provide a global framework for ending poverty, protecting the environment, and promoting well-being for all. They emphasize the interconnected nature of social, economic, and environmental challenges and highlight the need for efficient use of resources such as energy and water. This framework supports sustainable development by guiding actions that foster healthier and more resilient communities [25]. Poor water resource management causes significant health, environmental, and economic losses, hindering development and poverty reduction. This has driven local and global policy actions, including the SDGs, which aim for sustainable water availability, sanitation, and ecosystem protection. Effective water management supports poverty alleviation, inclusive growth, and all pillars of the green economy. However, managing water is complex due to uncertainties and externalities, such as pollution and health risks, which require coordinated institutional frameworks, community participation, and long-term, integrative approaches [37].

The REPowerEU plan aims to strengthen the EU's energy independence, support the clean energy transition, and create a more resilient energy system. It focuses on saving energy, producing renewable energy, diversifying energy supplies, and coordinating investments and reforms. The plan expands upon the Fit for 55 initiative, aiming to cut greenhouse gas emissions by at least 55% by 2030 and achieve climate neutrality by 2050, in accordance with the European Green Deal. Key priorities include energy efficiency, supply diversification, and accelerating renewables deployment [37]-[39].

Transitioning swimming pool facilities from fossil-fuel-based energy systems to clean, affordable, and energy-efficient solutions directly supports good health and well-being (SDG 3) by improving indoor air quality, reducing emissions from pool water heating, space heating, and ventilation systems, and ensuring reliable energy supply for year-round operation. It also contributes to sustainable cities and communities (SDG 11), as swimming pools are among the most energy-intensive public buildings and their energy optimization can significantly reduce urban energy demand, local air pollution, and carbon emissions while strengthening the resilience of public sport infrastructure. By improving energy efficiency and integrating renewable energy technologies in heating, dehumidification, and pool water systems, swimming pool facilities promote responsible consumption and production (SDG 12), lowering operational energy use, minimizing environmental impacts, and optimizing resource utilization. At the same time, replacing fossil fuels with renewable energy in swimming pool energy systems is essential for climate action (SDG 13), given their continuous operation and high heating demand, offering substantial potential for emission reductions and supporting long-term carbon neutrality goals [25], [40], [41].

The Organisation for Economic Co-operation and Development (OECD) Principles on Water Governance provide a comprehensive framework to help governments and stakeholders design, implement and assess effective, efficient, and inclusive water governance systems. These principles, developed through a multi-stakeholder process and endorsed by numerous countries and organisations, emphasise that good water governance must be context-specific, adapt to changing conditions, and involve clear roles, responsibilities, and accountability across all levels of government and sectors. They focus on enhancing policy effectiveness, maximising efficiency in water management, and building trust and engagement among stakeholders-promoting transparent decision-making and stronger collaboration to address challenges such as water scarcity, quality, infrastructure resilience, and equitable access to water resources. Urban water governance is shaped by both internal factors, such as ageing, capital-intensive infrastructure and water losses, and external factors, including institutional reforms, stakeholder coordination, and cross-sector interactions [42], [43]. Climate change and urban growth increase water-related risks, requiring cities to integrate technical, regulatory, economic, and governance measures to enhance efficiency, resilience, and long-term planning. While many adaptations are planned and implemented by public authorities, challenges remain in evaluating their long-term effectiveness, social acceptability, and potential for unintended consequences, including maladaptation, highlighting the need to consider local context and the diverse environmental, social, and economic impacts of different strategies [44].

Integrated Urban Water Management (IUWM) and Integrated Water Resources Management (IWRM) both recognize water's interconnected role in urban resilience, ecology, and sustainability. While IWRM, a key SDG 6 target, defines actions, responsibilities, and governance levels, IUWM treats urban water holistically. Effective governance under both approaches relies on coordinated stakeholder collaboration to manage water sustainably and advance the SDGs [44], [45]. Furthermore, the emerging approach known as Sustainable Urban Water Management (SUWM) focuses on adaptive, integrated management of the entire urban water cycle and promotes efficient use of water resources through flexible, multi-scale strategies. A key aspect of SUWM is the implementation of decentralized, multifunctional water infrastructure with minimal ecological impact, often utilizing local water sources, which collectively enhance the sustainability and resilience of urban water systems [4].

5. Conclusion

This study demonstrates that the sustainability of swimming pool facilities under conditions of climate stress cannot be achieved through isolated technological fixes but instead requires an integrated water-energy approach aligned with broader principles of climate resilience and sustainable transitions. Swimming pools, while often perceived as resource-intensive and non-essential, can be considered as adaptive urban infrastructures that contribute to water conservation, energy efficiency, and public health objectives when appropriately managed.

From a sustainability perspective, the findings highlight that energy-related measures deliver the largest reductions in environmental impact, particularly those addressing pool heating, which represents the dominant share of operational energy demand. Renewable energy technologies such as solar thermal collectors, PVT systems, and ground-source heat pumps consistently emerge as high-impact solutions, capable of substantially reducing fossil fuel dependence and greenhouse gas emissions over their life cycle. Although these systems are often associated with high initial investment costs, their long-term performance, emission reductions, and contribution to climate mitigation make them central to sustainable pool operation, especially in facilities with year-round use.

At the same time, water-saving and water-reuse strategies play a critical role in enhancing sustainability, particularly in water-scarce and climate-vulnerable regions. Among the evaluated options, backwash water recovery and reuse systems stand out as the most effective single water-saving measure, combining high reuse rates, rapid payback periods, and significant reductions in freshwater abstraction and wastewater discharge. Water-efficient fixtures provide immediate, low-cost savings and represent an essential baseline intervention, while rainwater harvesting and groundwater utilization offer additional benefits when local climatic, regulatory, and quality conditions permit.

Nature-based and passive measures, such as permanent green roofs, contribute important co-benefits by reducing thermal losses, mitigating the Urban Heat Island effect, and improving local microclimates. However, their high capital costs and structural requirements limit their universal applicability, positioning them as complementary rather than primary sustainability measures.

Overall, the evidence synthesized in this paper supports the conclusion that the most sustainable pathway for swimming pool management lies in combining renewable energy integration, high-efficiency water heating systems, and advanced water reuse technologies, supported by operational planning and facility-level management practices. Notably, the adaptation strategies recommended for sustainable swimming pool management are more effective when tailored to local climatic conditions and regulatory contexts.

In this context, climate services such as seasonal forecasts, drought monitoring, and heatwave early-warning systems could support more proactive pool operation under climate stress. By anticipating periods of elevated energy demand or water scarcity, facility managers may adjust heating schedules, water reuse practices, and resource planning accordingly.

Moreover, while heating demand dominates environmental impacts in many European case studies, regional differences in climate and governance may shift sustainability priorities. In particular, in drought-prone contexts, water scarcity and tightening regulatory restrictions may become the primary limiting factor for swimming pool operation. When considered within integrated urban water and energy management frameworks, swimming pools may offer opportunities to pilot climate adaptation and resource-efficiency measures. This is particularly relevant in urban and tourism-dependent regions facing increasing climate stress.

6. Limitations & future research

This study is subject to certain limitations that indicate directions for future research. As a structured review, it synthesizes evidence from diverse contexts and pool typologies, which limits the direct generalizability of specific performance estimates. Future research should therefore focus on empirical and comparative studies across different climatic regions and facility types, further exploring region-specific trade-offs between energy mitigation and water conservation, especially in areas facing acute freshwater stress, as well as on integrated life cycle and techno-economic assessments of combined water-energy solutions. Further investigation into governance frameworks, user behavior, and monitoring indicators would also support the effective scaling of sustainable swimming pool management as part of broader climate adaptation strategies.

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Conflict of interest

The authors declare no actual or potential conflicts of interest.

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