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REVIEW

Nature-Based Solutions and Circular Approaches in Professional Water Pollution Prevention and Remediation

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ABSTRACT

Water pollution is one of the most pressing issues in the world that requires new approaches to guarantee the sustainable use of water. This paper discusses the combination of Nature-Based Solutions (NbS) and Circular Economy (CE) concepts as viable solutions to water pollution prevention and treatment. NbS, including wetlands, riparian buffers, and green infrastructure, utilize natural processes to filter and treat pollutants, whereas CE emphasizes resource recovery, water reuse, and waste reduction. These methods have complementary benefits, improved water quality, resource efficiency, and ecosystem resilience. Nevertheless, there are difficulties in scaling such solutions, including technical design, economic investment, regulatory frameworks, and social acceptance. In spite of these challenges, technology, policy, and funding are making inroads into wider adoption. The paper has pointed out the overlaps between NbS and CE, which have created a model for a more sustainable and resilient water management system worldwide. Through these combined strategies, communities will be able to not only solve water pollution but also support environmental sustainability and loop-based resource utilization in the long term.

Keywords: Nature-Based Solutions; Circular Economy; Water Pollution; Resource Recovery; Sustainable Water Management

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1. Introduction

Water pollution is one of the most severe environmental problems of the 21st century [1]. Worldwide, millions of individuals still suffer from a lack of clean water, and contaminated water bodies cause serious ecological damage, biodiversity loss, and negative health effects [2]. With the growing impact of climate change, pressure on available water resources is increasing, necessitating the development of more innovative and sustainable ways to prevent and remediate water pollution. Conventionally, traditional engineering methods have been employed to control water pollution, including chemical treatment, mechanical filtration, and centralized wastewater treatment facilities. Nevertheless, such practices do not always address the root causes of pollution, and their sustainability and environmental impact are increasingly doubtful. Considering these issues, the discussion of alternative, more comprehensive solutions, such as Nature-Based Solutions (NbS) and Circular Economy (CE) principles, has become an urgent and significant topic in the realm of water management [3].

The approaches of Nature-Based Solutions and Circular Economy offer hope of a paradigm shift towards more sustainable, holistic, and resilient solutions to water pollution [4]. Nature-Based Solutions entail applying natural processes and ecosystems to reduce environmental issues, ensuring that more ecosystems can filter and purify water, replenish habitats, and provide other ecosystem services. NbS can provide tools to enhance water quality, reestablish biodiversity, and increase climate change resilience, with the restoration of wetlands and riparian zones, as well as the development of green infrastructure through the construction of wetlands and vegetated swales, being scalable and effective. Circular Economy principles, in turn, focus on recycling and the optimized use of resources, such as water, through closed-loop systems, waste minimization, and resource recovery. Integrating these two paradigms, NbS and CE, can help achieve a more sustainable and regenerative water management approach that aligns with environmental objectives at a larger scale, including waste reduction, resource conservation, and climate mitigation [5].

The originality of this review lies in its integration of Nature-Based Solutions and the Circular Economy into the professional sphere of water pollution prevention and remediation. Although each of the two concepts has attracted a lot of attention separately, the intersection and possible synergies between the two are not well studied in the literature on the subject, especially concerning water pollution. This paper will delve into how a blend of these two strategies can provide a complementary solution that not only addresses immediate water quality issues but also creates a long-term solution through the restoration of natural processes and the reduction of waste. This review will synthesize existing knowledge, case studies, and innovations to demonstrate the transformative potential of NbS and CE to revolutionize the management of water pollution, particularly at the professional scale [6].

Among the main aims of this review is to examine the multifaceted advantages of integrating NbS and Circular Economy approaches in the context of water pollution control [7]. Although traditional water treatment techniques are effective at eliminating contaminants, they usually generate by-products that must be disposed of or utilized, leading to further waste and resource use. Conversely, NbS and CE methods aim to bridge the gap of not only treating water but also reclaiming useful resources, including nutrients, energy, and even water itself. For example, built wetlands may remove pollutants and, at the same time, promote the use of nutrients produced by them in agriculture, making them part of a circular water system. In the same manner, the example of decentralized water treatment driven by a renewable source and designed to treat wastewater at the local level reflects the principles of the circles by reducing transportation costs and environmental footprint and creating resilience in the local area [8]. This review will demonstrate that the combination of NbS and CE can improve these processes by designing systems that are more adaptive, cost-effective, and regenerative.

Furthermore, given that urbanization and industrialization continue to rise, the need to scale such solutions to support the needs of large-scale water management cannot be overemphasized. Green roofs, permeable pavements, and urban wetlands are NbS that provide viable low-cost alternatives to traditional infrastructure in urban areas where water pollution is typically highly concentrated and aggravated by industrial effluents and urban runoff [9]. These solutions not only help reduce water pollution but also offer other benefits, including enhancing urban heat resilience, biodiversity, and community interaction. This review will provide a clear picture of the implementation of NbS and CE across rural and urban settings, and how these solutions can be scaled to professional and municipal water management systems, focusing on their scalability.

Beyond the technical and ecological advantages, the integration of NbS and Circular Economy solutions for water pollution control presents a significant opportunity for policy innovation [6]. To avoid pollution, governments, municipalities, and industries are progressively pursuing policies consistent with the principles of sustainability, circularity, and environmental justice. This review will examine the ways supportive policies, financial mechanisms, and governance structures will contribute to the adoption of NbS and CE solutions. Furthermore, their incorporation into national and international systems, including the United Nations Sustainable Development Goals (SDGs), with SDG 6 (Clean Water and Sanitation) in particular, will be emphasized as a crucial step towards sustainable and fair water management [10].

To sum up, this review is structured to provide a holistic and innovative approach to combining Nature-Based Solutions and the Circular Economy to transform how we address water pollution [8]. It will discuss the scientific basis, practice, issues, and policy for applying these solutions at professional-scale levels of water pollution prevention and remediation. This review will help to open the door to more sustainable, resilient, and resource-efficient water management practices that not only reduce pollution but also replenish natural processes and enhance a circular water economy by highlighting the synergies between NbS and CE.

2. Nature-Based Solutions (NbS) for Water Pollution

Nature-Based Solutions (NbS) are a new, innovative, and sustainable approach to tackling a wide range of environmental issues, such as water pollution [11]. NbS is grounded in ecological principles, tapping into the power of nature and its interconnected systems to deliver benefits that are economically and environmentally viable. Within the water pollution framework, NbS aims to rehabilitate and improve natural systems to clean water, reduce pollution, and enhance the overall well-being of aquatic life. This part explores the fundamental concepts of NbS, how they work in water management, and the practical use that has proven their efficiency.

2.1. Defining Nature-Based Solutions (NbS) in Water Pollution Control

Nature-Based Solutions have been characterized as activities that entail protection, restoration or sustainable management of natural or altered natural ecosystems as a way of addressing societal challenges and offering biodiversity and human well-being [11]. NbS can be used to enhance water quality, minimize runoff, and restore hydrological equilibrium in the field of water pollution prevention and remediation. These solutions are vastly different from old-fashioned engineering solutions, since they utilize natural mechanisms to filter and process contaminants rather than relying solely on mechanical or chemical processes. Comparing the Nature-Based Solutions with the traditional water treatment methods shows the advantages and constraints of both techniques, as shown in **Table 1** below.

Table 1. Comparison of nature-based solutions and conventional water treatment methods.

Criteria	Nature-Based Solutions (NbS)	Conventional Water Treatment
Approach	Leverages natural processes (e.g., filtration, absorption)	Uses engineered processes (e.g., chemical treatments, filtration)
Cost (Upfront)	Generally low initial investment, but requires land/space	High initial capital expenditure and infrastructure costs
Cost (Operational)	Low maintenance, mainly periodic checks	High operational and energy costs
Environmental Impact	Minimal environmental footprint; biodiversity enhancement	Potential for environmental degradation (chemical waste, high energy use)
Scalability	Limited by available land and local conditions	Can be scaled to large populations but with high costs
Sustainability	Restores ecosystem services, enhances resilience	Does not contribute to ecosystem restoration

The key concept of NbS is the notion of ecosystem services, the benefits that humans obtain due to healthy ecosystems. These services in water management encompass filtration, nutrient absorption, habitat, and water cycle regulation. NbS can offer a better, more sustainable, lower-cost alternative to traditional water treatment systems by creating interventions that simulate or reconstruct these natural processes. As an example, wetlands and riparian areas are natural filters that remove nutrients, sediments, and pollutants from water and support a diversity of species. Moreover, NbS commonly synergies with the local ecosystem, providing advantages of biodiversity conservation, climate resilience, and community involvement, which are often lacking in conventional infrastructure [12].

2.2. Mechanisms of Nature-Based Solutions in Water Pollution Management

The NbS depends on natural processes that clean and control water to be successful in managing water pollution. Several NbS have been utilized globally, with a particular mechanism each that plays a role in minimizing water pollutants [13]. These solutions can be passive or active, depending on their degree of intervention and management needs.

One of the most famous and widely studied NbS that can be used to control water pollution is wetlands [14]. Such ecosystems are self-purifying through physical, chemical, and biological filtration. Plant roots, microorganisms, and sediments collaborate in wetlands to eliminate pollutants (nutrients (nitrogen and phosphorus), heavy metals, and organic matter). Wetlands reduce pollutants in water through processes such as denitrification and sedimentation, improving downstream water quality. Riparian buffers are vegetated regions along rivers and streams that serve as buffers by absorbing pollutants from agricultural runoff and minimizing the effects of stormwater on aquatic environments [15]. Natural processes such as filtration and nutrient uptake are more comprehensible when the visual representation of how NbS can improve water quality is provided, as in **Figure 1**.

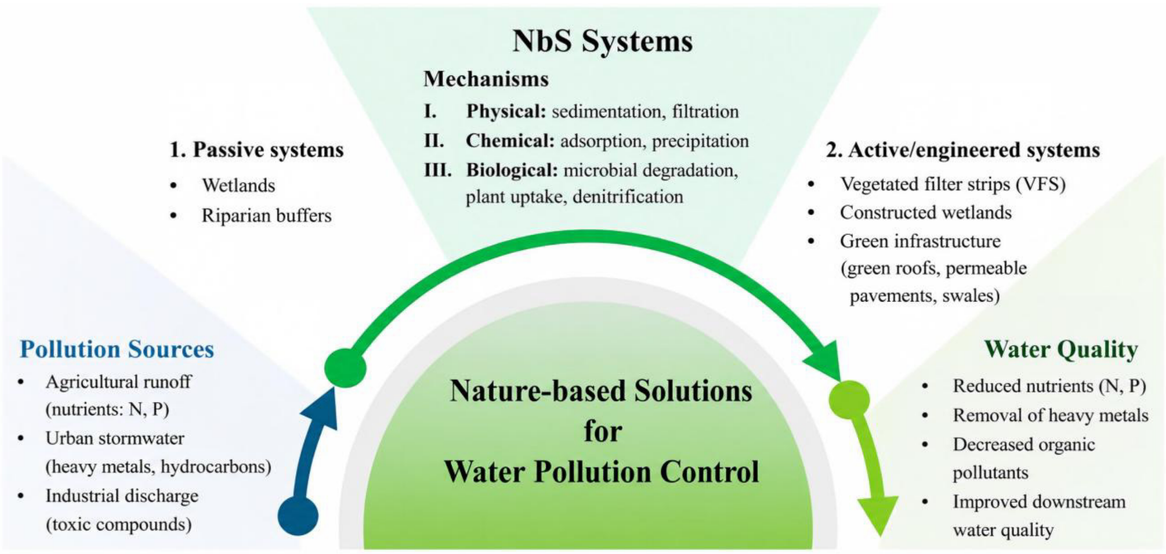

Figure 1. Conceptual diagram of nature-based solutions for water pollution control.

Another popular NbS used in water treatment is vegetated filter strips (VFS) and constructed wetlands. VFS are put in place to capture and slow runoff before it enters water bodies, where vegetation and soil can remove contaminants, such as sediments and excess nutrients [16]. Constructed wetlands likewise replicate the natural processes of wetlands by using plants and soil to filter pollutants, e.g., heavy metals, organic pollutants, and excess nutrients. These systems are meant to treat contaminated water through a series of filtration steps, with natural filtration eliminating contaminants.

Green infrastructure is a collection of NbS that uses vegetation and soil to control stormwater and minimize the effects of urbanization on water quality [9]. These include green roofs, permeable pavements, and vegetated swales. An example of this is the use of green roofs, which absorb rainwater and provide a surface on which plants can filter out pollutants before they reach the ground. Permeable pavements help reduce surface runoff by allowing water to percolate into the soil, where contaminants are naturally removed. These remedies are particularly applicable in urban areas, where traditional stormwater management systems often fail to handle runoff as urban sprawl and impervious surfaces increase.

2.3. Case Studies of NbS in Water Pollution Prevention and Remediation

Many examples of working case studies across the globe demonstrate the efficiency and applicability of NbS in addressing water pollution. These examples demonstrate that NbS can be scaled and implemented in both rural and urban settings.

The New York City Watershed Protection Program is one of the most recognized examples of NbS for controlling water pollution. In a bid to safeguard the quality of its drinking water, New York City has invested in protecting and restoring natural ecosystems in its watershed. Instead of spending money on costly water treatment facilities, the city focused on safeguarding riparian buffers, wetlands, and forested lands that naturally filter pollutants and minimize chemical use. This solution has led to significant improvements in water quality and has proven more economical than conventional infrastructure-based remedies [17].

The Danube River Basin, which cuts across various European nations, has faced major pollution problems, mainly from agricultural and industrial effluents. In response, a number of NbS have been adopted, such as restoring wetlands and riparian buffers along the river. Such activities have improved water quality and increased biodiversity in the area. The achievement of this project demonstrates the potential of NbS to solve the water pollution problem in large watersheds across transboundary watersheds [18].

Singapore has been at the forefront of incorporating NbS into its urban water management, particularly through the adoption of green infrastructure. The city-state has established a comprehensive system of green roofs, rain gardens, and permeable pavements that interconnect to control stormwater runoff and decrease water pollution. These NbS alleviate the urban heat island effect, boost biodiversity, and improve water quality by filtering stormwater pollutants before they enter waterways. These efforts have been rewarded with success at the international level, and Singapore has been an example for other cities seeking to incorporate NbS into the urban planning process [19].

2.4. Advantages and Limitations of NbS for Water Pollution Remediation

NbS have many benefits compared to the traditional water pollution control strategies. The greatest advantage is that they are able to deal with the sources of pollution especially through the restoration of the ecosystem and the natural water cycles [20]. This method is not only enhancing water quality but also offers a variety of other ecosystem services including habitat formation, flood control and carbon capture. Moreover, NbS are relatively cheaper over the long run since they are cheaper to run and maintain than conventional water treatment systems.

Nevertheless, the universal application of NbS has its drawbacks. First, the effectiveness of NbS may be highly context-specific, depending on local environmental parameters, including climate, soil type, and pollutant characteristics [21]. The magnitude of NbS might be inadequate in certain situations to deal with large or heavily contaminated water bodies and additional engineering solutions might be necessary. Also, natural ecosystems can be restored through NbS, a slow process whose outcomes are not always apparent. This may be a challenge in regions where rapid changes in water quality are required.

The absence of standard protocols for designing and implementing NbS is another weakness, making it challenging to evaluate its effectiveness and applicability in other regions [22]. Moreover, although NbS offer several co-benefits, including improved biodiversity, they can be quite problematic in terms of land use and space claims, especially in cities.

2.5. Biochemical Limitations and Dynamic Integration of NbS under Challenging Conditions

While Nature-Based Solutions are effective under moderate conditions, their performance degrades significantly when treating high-strength industrial influent, shock heavy metal loads, or operating at low winter temperatures. Constructed wetlands and vegetated filters treating wastewater with a COD exceeding 500 mg/L or ammonia-nitrogen above 50 mg/L experience rapid oxygen depletion, clogging, and reduced hydraulic conductivity. Under such conditions, microbial nitrification is suppressed when dissolved oxygen falls below 2 mg/L, leading to ammonia accumulation. A hybrid configuration that places primary sedimentation or anaerobic pretreatment before the NbS unit is therefore recommended for high-strength effluents [23].

Shock inputs of heavy metals pose another critical limitation. Copper concentrations above 0.5 mg/L, zinc above 1 mg/L, or lead above 0.1 mg/L inhibit microbial enzyme activity and reduce root uptake in macrophytes [24]. For example, Phragmites australis shows a 50–70% drop in metal removal efficiency within 24–48 h of exposure, with recovery taking one to two weeks after clean water flushing. Continuous monitoring and bypass systems are necessary to prevent irreversible damage to the NbS ecosystem.

Low temperatures further restrict NbS performance. When water temperatures fall below 6 °C, nitrification virtually ceases, and plant-mediated oxygen transport declines by more than 80%. In cold climates, NbS alone cannot meet year-round nitrogen removal standards. Mitigation strategies include subsurface flow wetlands with insulation covers, planting cold-tolerant species such as Typha latifolia, and seasonal operation whereby the NbS unit is bypassed during winter and wastewater is directed to conventional treatment [25].

Rather than replacing conventional systems, NbS should be dynamically integrated into a treatment train. A practical configuration consists of industrial effluent flowing to an equalization tank, then a primary clarifier, followed by a constructed wetland (NbS), an anaerobic digester for energy recovery (CE), and finally a sand filter before reuse. Real-time sensors for COD, heavy metals, and temperature can trigger bypass or blending to protect the NbS unit. This hybrid approach combines the low operational cost of NbS with the robustness of engineered processes, ensuring reliable water quality under variable and challenging conditions [26].

2.6. Future Directions for NbS in Water Pollution Management

Irrespective of the difficulties, future of NbS in managing water pollution looks bright. The future of ecological research and technology will probably enhance the efficiency and scalability of NbS. To illustrate, remote sensing technologies and data analytics could be used to track and optimize NbS performance in real time. Moreover, interdisciplinary strategies integrating ecology, engineering, and the social sciences will be crucial for tackling the complex issue of water pollution [27].

Moreover, the need for policy frameworks to facilitate the implementation of NbS at larger scales has become more widely acknowledged. Governments and municipalities need to develop incentives and regulatory frameworks that promote the adoption of NbS in the water management strategies. Funding, information exchange, and stakeholder involvement will also be essential to dismantling the obstacles to mass implementation [28].

With the continued development of NbS, their further integration with the principles of the Circular Economy will open even more opportunities to streamline water pollution prevention and remediation. NbS and the circular methodology, when combined, can result in systems that are not only effective in pollution treatment but also recover valuable resources, including nutrients, water, and energy, contributing to a more sustainable and resilient water management model [5].

3. Circular Economy Approaches to Water Management

Circular Economy (CE) is a shift from the traditional linear economy of take, make, dispose to a more sustainable system that focuses on minimizing waste, reusing resources, and encouraging the regeneration of natural systems [29]. This shift is especially relevant to water management because it offers a new way of thinking to minimize water pollution, recycle wastewater, and streamline water use across businesses and society. By incorporating circular concepts into water pollution prevention and remediation initiatives, one can develop systems that not only reduce pollution but also reclaim valuable resources, including nutrients, energy, and water itself. This section examines the essence of the Circular Economy in water management, how it has been applied to water pollution management, and how it can transform the way water resources are used and managed worldwide.

3.1. Principles of Circular Economy in Water Management

The Circular Economy of water management is founded on a number of principles that strive to close the water-use loop, ensure resource efficiency, and reduce environmental consequences [30]. The main concepts of the Circular Economy, reduce, reuse, and recycle, are also implemented in the management of water to promote a sustainable utilisation of water resources and reduce the effects of water pollution. These principles concern the supply and demand aspects of water consumption.

One of the basic principles of the Circular Economy is to reduce water consumption and pollution [31]. This entails enhancing water-use efficiency in agriculture, industry, and urban infrastructure. Through the application of water-saving technologies, optimization of irrigation systems, and resource-efficient practices, the amount of water required by processes can be reduced. This not only alleviates stress on natural water bodies but also prevents the discharge of excess nutrients and pollutants into the environment.

Reusing water means that wastewater is treated and recycled for non-drinking purposes, such as irrigation, industrial use, or watering lawns [32]. Various technologies can reuse water from sources such as graywater, rainwater, and wastewater, with treatment to levels suitable for specific applications. By encouraging water use, freshwater demand and the environmental impact of wastewater disposal can be minimized.

Recycling of water and recovery of useful resources (e.g., nutrients, e.g., nitrogen and phosphorus) and energy from wastewater are crucial parts of a circular approach to water management [33]. Wastewater treatment plants may be designed not only to clean the water but also to harvest valuable by-products. As an example, biogas recovery through the wastewater treatment processes can be used to produce renewable energy, and the nutrient recovery technologies can convert wastewater into useful fertilizers, eliminating the use of synthetic fertilizers and making sustainable agriculture possible. These principles, when combined, contribute to a more sustainable water cycle that reduces waste and pollution, maximizes resource use, and increases the resilience of water systems to climate change and population growth.

3.2. Applications of Circular Economy Approaches in Water Pollution Control

The Circular Economy offers numerous solutions that can be implemented directly to control water pollution. The circular approach changes the wastewater management into a cycle of reuse and recycling, starting with decentralized water treatment systems, resource recovery technologies, and so on. Such applications not only address water pollution but also provide important co-benefits in energy recovery, nutrient management, and waste reduction [30].

Conventional centralized wastewater treatment technologies generally entail moving large volumes of wastewater to a centralized location, which is not only expensive but also inefficient. Decentralized systems, on the other hand, treat wastewater closer to the source, and hence require less infrastructure and less energy-intensive transportation. Circular principles can be incorporated into these systems by adding water reuse and nutrient recovery to the treatment process. Small-scale treatment in urban or rural areas can produce wastewater to a high standard, and the treated water can be reused for irrigation, industrial purposes, or even non-portable urban uses like flushing toilets [32].

The Circular Economy strategy revolves around recycling and reusing water. Water recycling systems can be introduced in industrial and agricultural facilities to treat and reuse water, thereby conserving freshwater and reducing the amount of pollutants released into the environment. Treatment technologies, including membrane filtration, reverse osmosis, and biological treatment, can be used to treat wastewater to a level that allows it to be reused in processes such as cooling, cleaning, and irrigation. Treated wastewater can also be used on farms to irrigate crops, lessening the strain on freshwater sources and limiting the pollution of natural water bodies from fertilizer and pesticide runoff [34].

One of the most important causes of water pollution is nutrient pollution, especially nitrogen and phosphorus, which leads to eutrophication and hypoxia in waters [35]. Circular Economy solutions aim to extract these nutrients from wastewater and reintroduce them into the supply chain as useful fertilizers. Struvite precipitation, a phosphorus-binding technology, and ammonia stripping, a nitrogen-recovery technology, can be incorporated into wastewater treatment facilities. The retrieved nutrients can be used as fertilizers in farming, reducing reliance on synthetic fertilizers and promoting more sustainable agriculture. This forms a closed-loop system in which the nutrients are constantly recycled in the environment, reducing waste and pollution.

Treatment of wastewater is a highly energy-consuming process, and the Circular Economy provides the possibility of energy recovery. Anaerobic digestion is one of the best methods for converting wastewater into energy by allowing microorganisms to digest organic substances without oxygen, generating biogas. Electricity or heat can be generated using biogas, thereby minimizing reliance on external energy sources and increasing the energy independence of wastewater treatment plants. Besides biogas, other energy recovery methods, including heat exchange and hydro-electricity using wastewater flow, may also make the water management systems more circular [36].

3.3. Integration of Circular Economy in Urban Water Management

With population growth, urbanization, and strain on existing infrastructure, urban areas are struggling to manage water resources. To overcome these challenges, Circular Economy approaches offer a potential solution: encouraging more efficient use of water, reducing wastewater generation, and improving water quality. Water management systems in cities that incorporate the principles of a circle can help minimize the effects of urbanization on natural water systems, reduce pollution, and create new opportunities to recover resources [3].

One of the essential elements of circular water management in urban areas is green infrastructure, including rain gardens, green roofs, and permeable pavements [9]. These solutions help control stormwater runoff, enhance water quality, and alleviate the strain on traditional drainage systems. As an illustration, green roofs retain rainwater and minimize stormwater runoff, and permeable pavements allow water to percolate into the soil, reducing surface water runoff and eliminating pollutants. In addition to handling water, these systems may offer other co-benefits, including benefits for urban biodiversity, reduced urban heat island effect, and added aesthetic value to urban areas.

Implementing the Circular Economy principles in urban water management is a relatively straightforward approach through rainwater harvesting. Cities can decrease their reliance on freshwater resources and minimize stormwater runoff into the drainage system by collecting and storing rainwater to use in non-potable purposes, including irrigation, landscape watering, and toilet flushing [32]. This is not only a water-saving method but also one that minimizes the costs and environmental impacts of conventional water treatment methods.

Water management systems can be optimized through the introduction of digital technologies and data analytics, helping to use water resources more efficiently [37]. Water consumption, leak detection, and real-time optimization of water distribution can be managed using smart meters, sensors, and automated control systems. With the potential to provide more precise water usage data, these technologies will improve decision-making and interventions to minimize water waste and pollution. Moreover, to discover water reuse opportunities and resource recovery in urban systems, data-driven insights can be utilized.

3.4. Challenges and Opportunities in Circular Economy Approaches for Water Pollution Control

The potential of Circular Economy approaches in water management is promising; however, a number of challenges must be overcome to ensure their widespread adoption. These factors are technical, economic, and regulatory.

Circular Economy solutions for water management often require significant infrastructure and technological change. The process of integrating water recycling, nutrient recovery, and energy recovery technologies into existing water treatment systems can be complex and costly. Furthermore, local conditions, such as water quality and flow rates, may affect the performance of certain circular technologies, including nutrient recovery systems, which may require customization and optimization [38].

Initial expenses of adopting the circular water management system can be high, especially in countries or areas with limited finances. Circular solutions can also result in long-term cost savings by reducing water and energy use, but the initial investment in new technologies, infrastructure, and training can be an obstacle for many municipalities and industries. Nonetheless, in the future, as the advantages of Circular Economy approaches become more evident and technology costs decrease, the economic case for such solutions will likely improve [39].

The implementation of Circular Economy solutions in the water management sector is often supported by policies, regulations, and incentives. Regulatory frameworks are not yet well-adjusted to the concept of circles in many regions, and people might not be willing to implement alternative strategies because of water safety and quality concerns. The policymakers must develop structures that are conducive to water recycling, wastewater treatment, and resource recovery without compromising the health and environment of the people [6].

3.5. Future Directions for Circular Economy in Water Pollution Management

The future of the Circular Economy in water management is promising, with continued innovation in technology, policy, and practice. Key areas for further development include scaling up the integration of circular principles into wastewater treatment plants, enhancing resource recovery from wastewater, and promoting decentralized water management systems. Research into new, more efficient technologies, such as advanced filtration systems and decentralized nutrient recovery methods, will be crucial to improving the effectiveness of Circular Economy approaches [33].

In addition, the creation of more favorable policy environments, along with increased investment in circular infrastructure, will help to drive the adoption of these approaches at larger scales. As cities and industries seek to meet sustainability goals, integrating Circular Economy principles into water management will play a pivotal role in achieving more sustainable, resilient, and resource-efficient systems [40].

4. Synergies between Nature-Based Solutions and Circular Economy

The combination of Nature-Based Solutions (NbS) and Circular Economy (CE) strategies can be considered a new step in the evolution of water pollution management that provides a comprehensive approach to water pollution management, focusing on sustainability, resource reuse, and ecosystem rehabilitation [3]. These two methods focus on resilience, environmental stewardship, and long-term sustainability and, together, can yield complementary synergies that can contribute to the overall effectiveness of water pollution prevention and remedial measures. Here we discuss the synergies of NbS and CE, including how the combination of these two strategies can create more integrated, efficient and resilient water management systems. We also speak about the possible advantages which could be gained by combining these methods and we use practical examples which help to see the potential of these methods in solving the problem of water pollution.

4.1. Complementarity between Nature-Based Solutions and Circular Economy

The essence of both NbS and CE is that they aim to promote sustainability, reduce waste, and enhance the efficiency of resources [4]. Whereas NbS concentrates on the utilization of natural processes to enhance water quality and ecosystem restoration, CE focuses on the reuse, recycling, and recovery of resources, i.e., water, energy and nutrients. These strategies provide a potent combination to respond to water pollution when used in combination to improve the environmental and economic results.

Management of water pollution is one of the main areas of synergies between NbS and CE. NbS like wetlands, riparian buffers and constructed wetlands inherently filter pollutants and decrease nutrient loading in water bodies. Such systems are able to not only enhance the quality of water but also extract useful resources out of the wastewater when coupled with CE principles. As an illustration, the nutrient-enriched wastewater that has undergone NbS in built-in wetlands may be reworked to release nitrogen and phosphorus that can be used in agriculture to eliminate the use of synthetic fertilizers and decrease nutrient contamination. By so doing, NbS and CE collaborate to develop a closed-loop system that not only tackles pollution but also encourages resource efficiency [5].

Whereas NbS aims at restoring the functions of ecosystems, CE is concerned with the recovery and reuse of resources. Indicatively, NbS like wetlands or vegetated filter strips, serve as natural purifiers as they absorb pollutants and surplus nutrients in water leading to better water quality. The same systems can be modified to be used as resource recovery systems like extracting nutrients in wastewater to be utilized in agriculture. Integrating the ecological services of NbS along with the resource recovery principles of CE allows developing the systems, which would regenerate ecosystems and resources in a sustainable and circular fashion [10].

NbS as well as CE are part of creating a climate change resilience. NbS have the advantage of increasing the buffering capacity of natural ecosystems, which can help them cope with the new climatic conditions, including higher rainfall and temperature extremes. As an example, wetlands can reduce the effects of flooding because they absorb the excess water during heavy rain and also minimize the effect of droughts since the wetland water ensures that the groundwater is maintained. Meanwhile, CE facilitates sustainable resource management and alleviates the pressure on the ecosystems, as well as makes water management systems more flexible to the changing environmental conditions. NbS and CE combine to constitute a mutually reinforcing system of developing more resilient water management systems that can adapt to the unpredictability of climate change [21].

4.2. Potential Benefits of Combining NbS and Circular Economy Approaches

The integration of NbS and CE provides numerous benefits that go beyond the individual contributions of each approach. By combining natural systems with circular resource management practices, these synergies can lead to more sustainable, cost-effective, and adaptable solutions for water pollution control [33]. The complementary benefits of combining Nature-Based Solutions and Circular Economy approaches in water pollution management are summarized in **Table 2**.

Table 2. Synergies between nature-based solutions and the circular economy in water pollution management.

Benefit	Nature-Based Solutions (NbS) Contribution	Circular Economy (CE) Contribution	Integrated Benefit (NbS & CE)
Water Quality Improvement	Natural filtration (wetlands, riparian buffers)	Recycling and treatment of wastewater for reuse	Cleaner water through filtration and resource recovery
Nutrient Management	Reduction of nutrient load through natural processes	Recovery of nutrients from wastewater (e.g., phosphorus, nitrogen)	Circular nutrient cycling and reduced eutrophication
Energy Recovery	Biogas production from organic waste in constructed wetlands	Energy recovery from wastewater (e.g., biogas)	Reduced energy costs through biogas production and reuse
Climate Resilience	Ecosystem restoration (e.g., wetlands, vegetation)	Reducing reliance on external resources and waste	Enhanced resilience to floods, droughts, and resource scarcity
Cost-Efficiency	Low maintenance and operational costs	Reduced the need for freshwater by recycling water	Long-term cost savings from resource recovery and reduced infrastructure needs

The synergy between NbS and CE is not merely additive but process-based. Under variable pollutant loads, the components of an NbS system, macrophytes, biofilm, and sediments, perform sequential purification: sedimentation of particulates, microbial denitrification in anoxic zones, and plant uptake of metals and nutrients. When coupled with CE practices, such as nutrient recovery via struvite precipitation from wetland sediments or biogas capture from anaerobic zones, the system adapts dynamically. During high-flow events, a portion of the influent can be diverted to a conventional clarifier to prevent scouring of the wetland; the recovered sludge can then feed an anaerobic digester for energy production. This dynamic integration ensures stable effluent quality while maximizing resource recovery, even under fluctuating hydraulic and pollutant loads [41].

NbS provide a variety of co-benefits by default, such as conserving biodiversity, sequestering carbon, and restoring habitats. All these environmental gains can be further increased when applied alongside CE principles. To illustrate, managing water quality in cities with NbS, which is applied to green roofs and permeable pavements, reduces water pollution and, in addition, alleviates the urban heat island effect, improves air quality, and enhances biodiversity. These systems can help achieve greater environmental objectives, including reducing greenhouse gas emissions and preserving natural resources, by incorporating circular practices such as water recycling and energy recovery [42].

The NbS and CE combination provides more water availability and efficiency. NbS, like wetlands and riparian buffers, may increase groundwater recharge and water retention, thereby improving the overall supply of freshwater resources. These systems can be used in conjunction with other CE strategies, such as water recycling and rainwater harvesting, to optimize the use of available water, reduce reliance on external sources, and minimize the effects of water shortages. As an example, stormwater management, coupled with green infrastructure development, may harness rainwater for irrigation, reducing the need for potable water and preventing flooding during downpours [32].

Community engagement and participatory processes are frequently part of NbS because they are often intended to operate at local ecosystem and cultural scales. NbS, together with CE principles, can help make water management practices more sustainable and socially equitable. As an illustration, the rehabilitation of wetlands or riparian areas can provide cultural and recreational opportunities for local communities by creating spaces for education, tourism, and environmental care. Moreover, through decentralized water treatment systems that rely on NbS and CE, communities can be empowered to own their water resources and participate in local water quality management [33].

4.3. Real-World Examples of Combined NbS and Circular Economy Approaches

NbS and CE have several potential synergies in preventing and remedying water pollution, as demonstrated by several real-world examples. **Table 3** presents some successful examples of NbS and CE integration in water pollution management. These case studies present real-world applications of integrated approaches and show how the integrating natural systems and circular resource management can create more effective and sustainable water management solutions.

Table 3. Examples of successful integration of NbS and CE in water pollution management.

Case Study	Location	NbS Involved	CE Practices Applied	Outcomes
New York City Watershed Protection Program	United States	Riparian buffers, forest, and wetland restoration	Water reuse (rainwater harvesting) and nutrient recovery	Improved water quality, reduced chemical treatment costs
Danube River Basin Integrated Management	Europe (multiple countries)	Wetland restoration, riparian zones	Nutrient recovery, wastewater treatment	Reduced eutrophication, enhanced biodiversity
Singapore Integrated Water Management	Singapore	Green roofs, permeable pavements, vegetated swales	NEWater (wastewater recycling), stormwater management	Efficient water use, enhanced urban resilience, and sustainable water systems
Agro-Ecological Water Management	India	Constructed wetlands, vegetative buffer zones	Irrigation water recycling, nutrient cycling	Increased agricultural yield, reduced water usage, improved water quality

The Danube River Basin is a transnational river that covers ten European countries and has, over time, experienced water pollution due to agricultural run-offs, industrial effluents, and urban sewage. In response, various initiatives have been implementing NbS alongside circular practices to restore river health and improve water quality. e.g., Wetlands have been reinstated along the riverbanks to absorb nutrients and pollutants from agricultural runoff, and nutrient recovery systems have been installed to recover phosphorus and nitrogen from wastewater. All these combined not only enhance water quality but also have other positive effects, such as increased biodiversity, flood control, and carbon sequestration [18].

Singapore is a pioneer in applying NbS and CE to urban water management. To address stormwater runoff and water pollution, the city-state has introduced various green infrastructure measures, such as green roofs, rain gardens, and permeable pavements. Also, Singapore has adopted circular water management, including wastewater treatment and reuse via the NEWater program. This NbS + CE combination has helped Singapore establish a highly efficient and sustainable water system in which treated wastewater is recycled for industrial, agricultural, and non-potable domestic applications [19].

As one of the largest and most successful instances of NbS in water quality management, the Watershed Protection Program in New York City employs an amalgamation of natural systems and circular economy principles to maintain drinking water quality to standards. The program aims to protect and restore forests, wetlands, and riparian buffers within the city's watershed that serve as natural water filters. Moreover, the city has also implemented water reuse projects, such as collecting rainwater for non-potable use, to reduce the amount of treated water required. This combination has not only enhanced water quality but also minimized the costs associated with installing expensive water treatment systems [17].

4.4. Challenges and Opportunities in Integrating NbS and the Circular Economy

Although the potential for synergy between NbS and CE is very high, there are several challenges to integrating these approaches into the practice of water management. These are technical barriers, economic factors, and the requirement of supportive policy frameworks.

Combining NbS and CE may require extensive knowledge of local environmental conditions, water quality issues, and ecosystem processes [11]. Developing systems that effectively integrate NbS and CE principles can be complicated, as it may require expertise from various fields, such as ecology, engineering, and urban planning. Moreover, the performance of integrated systems can vary with local factors, including climate, land use, and pollutant load, complicating the standardization and scaling of these methods.

Although NbS and CE reduce costs in the long run, the upfront costs of implementing integrated solutions may be high, especially in urban settings where space is a limiting factor and land value is high. Also, the financial gains from resource recovery and pollution reduction are not always obvious, which can make integrated methods difficult to implement. Governments and industries must overcome such barriers by creating financial incentives, subsidies, and cost-sharing mechanisms to aid in the adoption of NbS and CE solutions [6].

The effective implementation of NbS and CE in water management practices will require the development of regulatory frameworks and policies that promote the use of sustainable solutions. The policies are to be developed in such a way that it is easy to use green infrastructure, water reuse, and resource recovery without compromising environmental standards or the needs of the people. Governments, industries, and local communities will collaborate to formulate policies that facilitate the scaling of NbS and CE [7].

4.5. Future Directions for Synergies between NbS and Circular Economy

With rising awareness of the need for sustainable water management, the role of NbS and CE in addressing water pollution is set to grow in significance. Further studies on the technical and economic facets of these combined methods will be crucial in streamlining their power and usability. Moreover, the existence of policy frameworks to encourage innovation and collaboration between sectors will be essential to advancing the implementation of solutions at larger scales. The key to the future of water pollution management is the harmonious integration of natural systems and circular resource management, creating a genuinely regenerative water cycle that benefits people and their environment [5].

5. Challenges and Innovations in Implementing NbS and Circular Approaches

Although there is considerable potential to apply the principles of Nature-Based Solutions (NbS) and the Circular Economy (CE) to water pollution prevention and remediation, several obstacles hinder large-scale implementation of these strategies. These issues span technical, economic, regulatory, and social levels and require addressing to optimize the benefits of NbS and CE in water management. Nevertheless, these obstacles are also opportunities for innovation, research, and development. This part will discuss the main barriers to the mainstream adoption of NbS and CE, as well as the innovations and approaches that can mitigate these challenges [4,7].

5.1. Technical and Operational Barriers

The technical complexity of designing, implementing, and maintaining integrated systems is one of the most significant challenges in implementing NbS and CE for water pollution management. The successful implementation of NbS is also context-dependent; i.e., the effectiveness of these solutions may vary widely depending on local environmental conditions, the scale of implementation, and the specific water pollution problems being addressed. Also, implementing NbS alongside CE principles requires a multidisciplinary approach that integrates ecological knowledge, engineering skills, and resource recovery technologies [43].

NbS can be quite complex and require careful design to ensure they are effective in mitigating water pollution and providing other ecosystem services. For example, constructed wetlands, riparian buffers, or vegetated filter strips should be designed to meet local hydrological conditions, pollutant types, and available space. These natural systems, when integrated with the practice of CE, e.g., resource recovery or water recycling, introduce another dimension of complexity. Designing systems that optimize water treatment and resource recovery requires advanced design and modeling capabilities to predict performance under various environmental and operating conditions [44].

Although NbS are typically inexpensive to maintain compared with traditional engineering solutions, they still require ongoing monitoring and management to remain effective over time. Wetlands and vegetated filter strips can be given as examples; they should be regularly evaluated for their ability to filter pollutants and may need to be restored or adjusted to a changing environment. The combination of CE strategies, including nutrient recovery and wastewater energy production, brings new operational issues. For example, nutrient recovery systems designed to extract nutrients from wastewater or generate energy via biogas might face technical challenges with efficiency, scalability, or operational stability [33].

One of the main obstacles to the popularization of NbS and CE is the lack of standardized data and performance indicators to evaluate their efficiency. Although these approaches have been proven successful in a variety of case studies and pilot projects, robust long-term data on the effectiveness of the different aspects of these approaches across various environmental and operating conditions are lacking. The ecological, economic, and social components of NbS and CE need to be studied to make evidence-based recommendations on their application [27].

5.2. Economic Barriers and Financial Considerations

Significant initial investments in infrastructure, research, and capacity-building characterize the introduction of NbS and CE [45]. The upfront cost of these solutions may be an obstacle to their implementation in areas with limited funds or where the economic value of these strategies is not immediately evident. **Table 4** lists the main policy and regulatory obstacles to applying NbS and Circular Economy solutions in the management of water pollution.

Table 4. Policy and regulatory barriers to implementing NbS and CE in water pollution management.

Policy/Regulatory Barrier	Nature-Based Solutions (NbS) Impact	Circular Economy (CE) Impact	Potential Solutions
Lack of Standards for Resource Recovery	Difficulty in standardizing nutrient recovery and treatment from natural systems	Limited recognition of the value of recovered resources (e.g., phosphorus, nitrogen)	Develop and adopt national and international standards for resource recovery from wastewater
Regulatory Restrictions on Water Reuse	Restrictions on using treated wastewater for non-potable purposes	Barriers to decentralized wastewater treatment and reuse systems	Introduce flexible regulations for water reuse and resource recovery in various sectors
Incentive Gaps for Investment in NbS and CE	High upfront costs for the implementation of NbS, limiting adoption	Lack of financial incentives for resource recovery projects	Create funding mechanisms such as subsidies, tax incentives, and low-interest loans for NbS and CE implementation
Fragmented Water Management Policies	Fragmented policies create silos between different water management practices	CE approaches, such as decentralized water management, may not align with existing regulations	Develop integrated, cross-sectoral policies that align water management, environmental protection, and resource recovery
Public and Stakeholder Resistance	Public perception of NbS is less reliable than conventional solutions	Lack of awareness regarding the benefits of resource recovery and water reuse	Launch educational campaigns, demonstrate successful pilot projects, and engage stakeholders early in the decision-making process

Although NbS systems like wetlands, green roofs, or permeable pavements may be cheaper in the long term than conventional water treatment systems, they entail high upfront costs. Moreover, resource recovery systems, e.g., nutrient recovery from wastewater or energy production via biogas, require substantial capital investment in specialized equipment and infrastructure. These expenses might discourage municipalities, industries, and governments from implementing NbS and CE strategies, especially in developing states or in areas that have limited budgets [9].

The second issue is that it is hard to estimate the financial gains of NbS and CE. Although these methods have many environmental and social co-benefits, including increased biodiversity, flood management, and climate resilience, the economic value of these services is not always clear [22]. An example is that the benefit of ecosystem services delivered by wetlands or riparian buffers, like carbon sequestration or water quality, may not be directly indicated in cost-benefit models. Such uncertainty of financial payoff may deter investments in NbS and CE, especially when decision-makers encounter more short-term financial imperatives.

Implementing NbS and CE in most situations may require financial incentives or subsidies to cover the high initial costs. Governments and industries should put in place financial systems such as grants, tax credits, or low-interest loans to facilitate the implementation of green systems in water management. Moreover, the required economic incentives to make the shift to more circular and nature-based systems could be provided by policies that promote the recovery of resources from wastewater or the use of green infrastructure [31].

5.3. Regulatory and Policy Challenges

Although NbS and CE solutions are very promising, the regulatory frameworks in most areas are not yet prepared to support them [28]. The regulatory environment is typically organized around traditional engineering solutions, such as centralized wastewater treatment plants and chemical treatments, which can limit the flexibility and scalability of NbS and CE systems.

Many current water quality standards and regulations are based on traditional treatment methods and fail to account for the range of pollutants that NbS can effectively treat. As an example, nutrient recovery systems, such as those that recover phosphorus from wastewater, may not yet be incorporated into national or regional wastewater treatment regulations, and it is hard to integrate them into standard water management. Likewise, treating wastewater for non-drinkable uses (e.g., irrigation or industrial use) can fall under tight regulatory constraints. However, this is essential to encourage water reuse in a closed-loop economy [32].

Besides the old regulations, in most cases, regulatory bodies tend to resist the adoption of new untested methods. The fact that NbS and CE are not fully developed, may only be effective in the long term, and may pose threats to population health or require new monitoring systems may make water management professionals and regulators reluctant to adopt these approaches [11]. The only way to overcome this resistance is to establish the credibility of such practices by conducting rigorous scientific studies and pilot projects, and presenting effective case studies.

Implementation of NbS and CE in the water pollution management system requires coordination of policies across sectors such as water management, agriculture, urban planning, and environmental protection. For example, sustainable agricultural policies and policies that mitigate nutrient runoff can be used to supplement NbS that remove excess nutrients from water bodies. Likewise, the implementation of the CE in wastewater management can be supported by policies that promote decentralized water treatment and resource recovery. But when various sectors have fragmented policies, this can create obstacles to implementing integrated solutions. To address this, policymakers must work on cross-sectoral policies that promote cooperation among water management agencies, urban planners, environmental agencies, and other stakeholders [6].

5.4. Social and Cultural Challenges

Social acceptance, community involvement, and stakeholders' willingness to adopt new practices also play a crucial role in the successful implementation of NbS and CE approaches. Solutions to water management that combine natural systems and circular practices should be socially fair, culturally acceptable, and affordable to all communities [27].

The population's perception of NbS and CE is one of the challenges in implementing these solutions. Natural systems are often perceived as less reliable and technologically advanced compared to traditional water treatment systems, e.g., the use of chemicals or a large-scale filtration plant. It is possible that people are worried about the safety and efficiency of solutions such as constructed wetlands or water reuse systems, especially when they are not familiar with these practices. To resolve these issues, it is necessary to conduct public outreach, education, and open communication. Including the community in the design and implementation of NbS may help build trust and increase support [46].

The challenge is making NbS and CE solutions available to every sector of society, especially in developing areas or underserved communities [12]. These systems have positive effects, such as improved water quality and resource recovery, which should be allocated fairly to prevent the worsening of existing disparities. Also, such communities should be part of the decision-making process so that the water management solutions are culturally sensitive and responsive to the local needs.

NbS and CE may often demand that other stakeholders, such as governments, industries, non-governmental organizations, and local communities, work together [28]. The interaction of these groups must be effective to ensure that policies are coordinated, resources are distributed effectively, and stakeholders are fully involved in the implementation process. In other instances, conflicts of interest can arise, especially when the priorities of different sectors conflict. The stakeholders need to be ready to cooperate, exchange experiences, and set shared objectives that advance the common good in addressing these challenges. **Figure 2** defines the policy frameworks that would be required to achieve the integration of NbS and CE in water management, with an emphasis on the need for cross-sectoral cooperation and enabling regulations.

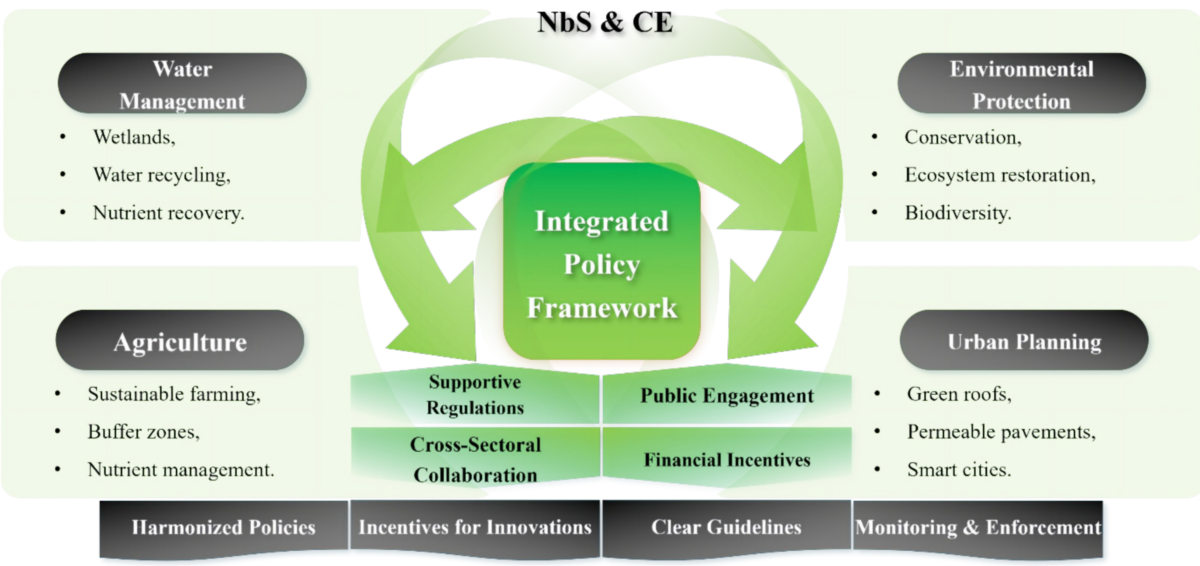

Figure 2. Policy framework for integrating NbS and CE in water management.

5.5. Innovations in Overcoming Challenges

To break these barriers, various innovations are emerging in the water management field. These innovations include technological breakthroughs, financial schemes, and regulatory systems that are helping to entrench NbS and CE into mainstream water pollution prevention and remediation policies [47].

Increases in sensor technologies, data analytics, and automation can now provide more efficient monitoring and optimization of NbS and CE systems [37]. The example of optimizing the work of constructed wetlands by real-time tracking of water quality and pollutant levels and the efficiency of resource recovery systems by data analytics can be provided. Additionally, new decentralized treatment technologies, such as mobile wastewater treatment units and small-scale nutrient recovery systems, are simplifying the implementation of NbS and CE solutions across various settings.

New financial approaches, including impact investing, green bonds, and pay-for-success plans, are helping direct investment towards NbS and CE initiatives. These mechanisms have the potential to decrease the financial load on the governments and municipalities through the lure of the private sector and incentives of performance-based results. Also, the economic case for NbS and CE can be strengthened through financial models that capture the full spectrum of co-benefits, including improved health, resilience to climate change, and biodiversity protection [6].

A number of nations are starting to consider NbS and CE in their water management policies. In the case of the European Union, the potential of NbS has been recognized in the Water Framework Directive, which encourages the adoption of green infrastructure in city planning. Correspondingly, the United Nations Sustainable Development Goals (SDGs), and in particular Goal 6 (Clean Water and Sanitation), also offer a framework for aligning NbS and CE with the wider sustainability objectives [10]. With policy changes to facilitate such strategies, NbS and CE adoption will likely gain momentum.

6. Conclusion

Nature-Based Solutions (NbS) and the Circular Economy (CE) are two paradigm shifts in the prevention and remediation of water pollution, providing sustainable, resilient, and cost-effective alternatives to traditional water management approaches. The approaches reduce water pollution, as well as allowing resources to be recovered and ecosystem services improved, and lead to long-term environmental sustainability by taking advantage of natural processes and maximizing the utilization of the resources.

The combination of NbS and CE offers complementary advantages as it is a holistic approach to water pollution management. NbS, including wetlands, riparian buffers and green infrastructure, naturally purify pollutants, reestablish hydrological balance, and improve ecosystem health. Together with the concepts of CE, including resource recovery, water reuse, and nutrient recycling, the solutions will be able to develop regenerative, which will close the loop of water use, minimize waste, and make water management systems more resilient.

Although these combined solutions have a bright future, there are still issues with upscaling. There is a need to tackle technical complexity, economic barriers, regulatory limitations and social acceptance so that the full benefits of NbS and CE can be enjoyed. Innovations in technology, policy and financing are however coming in to break these barriers. As more research is conducted, more people join hands and invest in this to bring about a revolution of NbS and CE, the world will have cleaner and more sustainable water systems.

To sum up, NbS and CE provide an avenue to more sustainable and regenerative water management, which not only improves water quality but also supports broader environmental and social objectives.

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Conflicts of Interest

The author declares no conflict of interest.

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