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Benefits of Floating Wetlands beyond water pollution control: A new perspective for Urban Landscape

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Benefícios dos Wetlands Flutuantes além da despoluição da água: Uma nova lente para a Paisagem Urbana

RESUMO

Objetivo - sintetizar e analisar conhecimentos existentes sobre a implementação das *Floating Treatment Wetlands (FTW)* em corpos hídricos, identificando contribuições além da melhoria da qualidade das águas e seu potencial como estratégia da paisagem urbana para promoção das Contribuições da Natureza para as Pessoas (NCP).

Metodologia - Revisão Sistemática da Literatura (RSL) para identificar os principais aspectos abordados sobre o tema em publicações científicas a partir de 2012, recorte temporal que explora o marco teórico das Soluções baseadas na Natureza (SbN), uma referência importante para o olhar multifuncional das FTW.

Originalidade/relevância - os corpos hídricos urbanos encontram-se em crescente declínio, não apenas pela degradação da qualidade da água, mas também por sua invisibilidade ao cotidiano da população, um cenário que revela a profunda desconexão entre as pessoas e a natureza, dessa forma, as FTW podem ser uma estratégia para o uso e apropriação de espaços próximos a água, promovendo valores culturais e ecológicos.

Resultados - a implementação das FTW promove benefícios socioambientais em todas as categorias das NCP (contribuições materiais, não-materiais e de regulação), confirmando seu potencial para integrar o planejamento urbano de forma abrangente, como uma SbN, e não apenas como um tratamento de águas.

Contribuições teóricas/metodológicas - um novo olhar para os benefícios na implantação das FTW na paisagem urbana, valorizando sua multifuncionalidade, inclusive com a sugestão de uma nomenclatura que reflita tal abrangência: Ecossistemas Flutuantes (EF).

Contribuições sociais e ambientais - destaque para o valor socioambiental das FTW na melhoria da qualidade de vida, requalificação do espaço urbano e funções ecológicas na promoção das NCP.

PALAVRAS-CHAVE: Wetlands Flutuantes, Soluções baseadas na Natureza, Contribuições da Natureza para as Pessoas.

Benefits of Floating Wetlands beyond water pollution control: A new perspective for Urban Landscape

ABSTRACT

Objective – To synthesize and analyze existing knowledge on the implementation of Floating Treatment Wetlands (FTWs) in water bodies, identifying contributions beyond water quality improvement and their potential as an urban landscape strategy to promote Nature's Contributions to People (NCP).

Methodology – A Systematic Literature Review (SLR) to identify the main aspects addressed on the topic in scientific publications since 2012, a timeframe that explores the theoretical framework of Nature-based Solutions (NbS), an important reference for the multifunctional perspective of FTWs.

Originality/Relevance – Urban water bodies are in increasing decline, not only due to the degradation of water quality but also their invisibility in the population's daily life, a scenario that reveals the profound disconnection between people and nature. Thus, FTWs can be a strategy for the use and appropriation of spaces near water, promoting cultural and ecological values.

Results – The implementation of FTWs promotes socio-environmental benefits across all NCP categories (material, non-material, and regulating contributions), confirming their potential for comprehensive integration into urban planning as an NbS, and not merely as a water treatment method.

Theoretical/Methodological Contributions – A new perspective on the benefits of implementing FTWs in the urban landscape, valuing their multifunctionality, including the suggestion of a nomenclature that reflects such breadth: Floating Ecosystems (FE).

Social and Environmental Contributions – Emphasis on the socio-environmental value of FTWs in improving the quality of life, the requalification of urban space, and ecological functions in the promotion of NCP.

KEYWORDS: Floating Wetlands, Nature-based Solutions, Nature's Contributions to People.

Beneficios de los Wetlands Flotantes más allá de la depuración del agua: Una nueva perspectiva para el Paisaje Urbano

RESUMEN

ISSN 2318-8472, v. 14, n. 91, 2026

Objetivo – Sintetizar y analizar los conocimientos existentes sobre la implementación de los Humedales Flotantes de Tratamiento (FTW, por sus siglas en inglés) en cuerpos de agua, identificando contribuciones más allá de la mejora de la calidad del agua y su potencial como estrategia del paisaje urbano para la promoción de las Contribuciones de la Naturaleza para las Personas (NCP).
Metodología – Revisión Sistemática de la Literatura (RSL) para identificar los principales aspectos abordados sobre el tema en publicaciones científicas desde 2012, un recorte temporal que explora el marco teórico de las Soluciones basadas en la Naturaleza (SbN), una referencia importante para la perspectiva multifuncional de las FTW.
Originalidad/Relevancia – Los cuerpos de agua urbanos se encuentran en creciente declive, no solo por la degradación de la calidad del agua, sino también por su invisibilidad en la vida cotidiana de la población, un escenario que revela la profunda desconexión entre las personas y la naturaleza. De esta forma, las FTW pueden ser una estrategia para el uso y apropiación de espacios cercanos al agua, promoviendo valores culturales y ecológicos.
Resultados – La implementación de las FTW promueve beneficios socioambientales en todas las categorías de las NCP (contribuciones materiales, inmateriales y de regulación), confirmando su potencial para integrar la planificación urbana de forma integral como una SbN, y no solo como un tratamiento de aguas.
Contribuciones Teóricas/Metodológicas – Una nueva perspectiva sobre los beneficios de la implementación de las FTW en el paisaje urbano, valorando su multifuncionalidad, incluyendo la sugerencia de una nomenclatura que refleje tal amplitud: Ecosistemas Flotantes (EF).
Contribuciones Sociales y Ambientales – Se destaca el valor socioambiental de las FTW en la mejora de la calidad de vida, la recualificación del espacio urbano y las funciones ecológicas en la promoción de las NCP.

PALABRAS CLAVE: Wetlands Flotantes, Soluciones basadas en la Naturaleza, Contribuciones de la Naturaleza para las Personas.

ISSN 2318-8472, v. 14, n. 91, 2026

1 INTRODUCTION

Urban water bodies are undergoing progressive degradation driven by prevailing land use and occupation patterns in cities, thereby compromising Nature's Contributions to People (NCP). Historically, human interventions in fluvial systems have been predominantly guided by sanitary engineering paradigms, leading to the widespread rectification and channelization of rivers and streams to expedite water runoff and control disease vectors (Herzog, 2013). Consequently, these structuring landscape elements have been systematically suppressed and fragmented, rendered invisible in the daily lives of the population. They emerge into public consciousness only during crises, such as when floodwaters reclaim their natural floodplains or when pollution becomes conspicuous through foul odors and discoloration. This scenario underscores a profound disconnection between people and water, eroding the cultural, social, and use-values associated with these spaces (Lyra & Constantino, 2024).

In this context, Nature-based Solutions (NbS) emerge as prominent strategies for the conservation, restoration, and resilience of water bodies. Floating Treatment Wetlands (FTWs) are derived from Constructed Wetlands (CWs)—a technique involving engineered, soil-lined basins designed primarily for wastewater treatment. CWs mimic the natural purification processes of wetlands through phytoremediation for nutrient control. FTWs represent a variation of this approach, where vegetated mats are constructed on floating structures, allowing them to be deployed directly on the surface of existing water bodies (Mendes, 2018). Although initially developed with the primary goal of improving water quality and extensively studied for their treatment efficiency, viewing FTWs through the lens of NbS reveals their multifunctionality. This highlights their broader potential for socio-environmental restoration and the effective reintegration of water bodies into the urban landscape (Rigotti, 2020).

To further investigate this multifunctionality, the present study undertakes a Systematic Literature Review (SLR) to synthesize and analyze the existing body of knowledge on the implementation of FTWs in water bodies. The analysis aims to identify the contributions of FTWs that extend beyond mere water quality improvements, exploring their full potential as an NbS capable of enhancing Nature's Contributions to People (NCP). This research is guided by the hypothesis that FTWs, when integrated into the landscape, not only function as a strategy for building more resilient cities but, more fundamentally, can help reverse the state of disconnection between people and urban waters.

2 METHODS

This Systematic Literature Review (SLR) was conducted in April 2022 by surveying publications in the SciELO, Scopus, and ScienceDirect databases. The search query targeted subjects, titles, and abstracts and was structured in two distinct phases: (1) to identify publications in Portuguese, using the terms “ilhas flutuantes” OR “jardins flutuantes” OR “ecossistemas flutuantes” OR “wetlands flutuantes” in conjunction with the term “corpos hídricos”, while excluding from the title the terms “hidroponia”, “efluentes”, and “esgoto”; and (2) to identify publications in other languages, using the terms "constructed floating wetlands" OR “floating treatment wetlands” in conjunction with “waterbodies” AND “ecosystem”. This

ISSN 2318-8472, v. 14, n. 91, 2026

second phase excluded the terms “hydroponic”, “stormwater”, “runoff”, “wastewater”, “effluents”, “sewage”, “nitrogen”, “nitrate”, and “phosphorus”. In addition to these keywords, the search was restricted to a 10-year period (2012–2022). This timeframe was selected to correspond with the emergence of the topic within academic literature, particularly following the establishment of the Nature-based Solutions (NbS) theoretical framework.

The search strategies for Phase 1 and Phase 2 were intentionally different. This distinction was made because the body of national literature on this topic is considerably smaller than the international corpus; thus, a less restrictive search was employed for Portuguese to maximize the retrieval of relevant domestic studies. The exclusion of sanitation-related terms was a crucial step to filter out research focused primarily on treatment efficiency or the reduction of specific physicochemical pollution indicators. The search was designed to isolate studies that examined FTWs within water bodies through a socio-environmental, ecological, or urban landscape lens. The initial search yielded 33 publications in Phase 1 and 39 in Phase 2, for a total of 72 articles. These were imported into the Zotero reference manager, and duplicates were removed. Subsequently, a screening of titles and abstracts was performed to select the most relevant publications based on the following eligibility criteria: (a) Object of Study: Publications where FTWs were the central object of investigation were included, leading to the exclusion of studies that only mentioned the solution tangentially or discussed it in a generalized manner; and (b) Contextual Factors: International studies conducted under environmental conditions not applicable to Brazil, such as those focusing on low-temperature climates or involving flora and fauna non-endemic to Brazil, were excluded.

A final corpus of 30 publications met the eligibility criteria. From these articles, the following data points were extracted: general publication data (publication type, date, authorship, country of research, affiliated institutions, thematic area, and language); and study design details (objective, keywords, methodology, context, results, challenges, and recommendations). This extracted information was then synthesized through thematic interpretation and systematically organized into a spreadsheet. This process facilitated the analysis of contextual factors, allowed for data cross-referencing, and enabled the identification and grouping of common themes and findings across the selected studies.

3 RESULTS

3.1 Profile of the Selected Literature

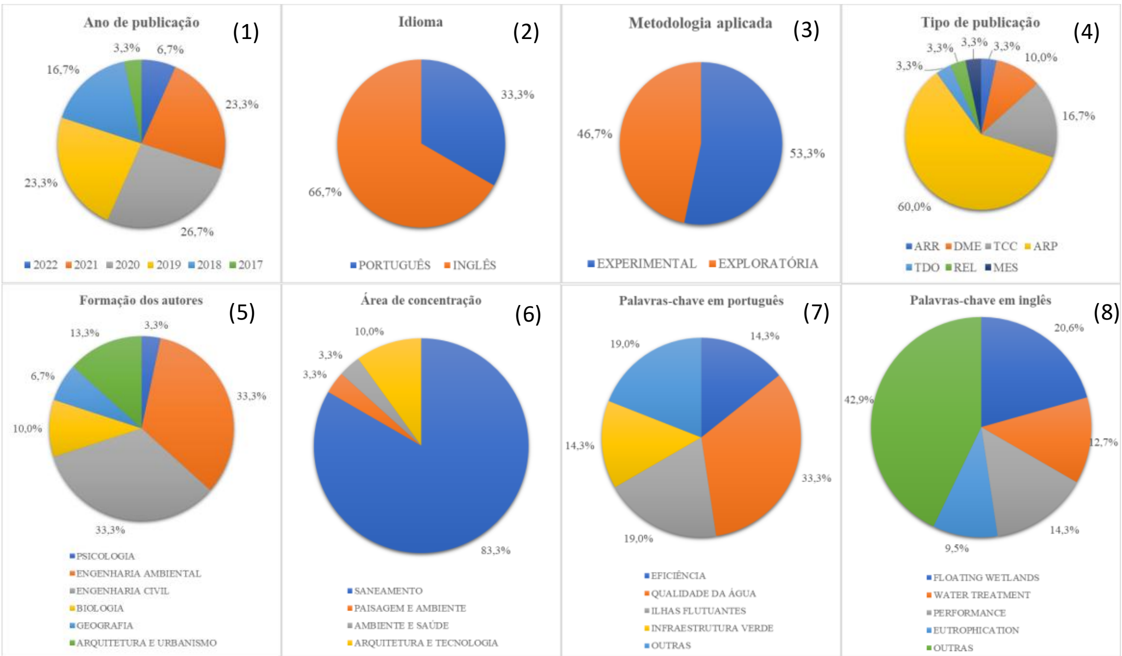
The final corpus of 30 publications was published between 2017 and 2022. The most productive year was 2020 (accounting for 26.7% of the total), followed by 2021 and 2019 (each contributing 23.3%), as illustrated in Figure 1. The absence of studies prior to 2017 underscores the recent emergence and relatively unexplored nature of this research topic. Regarding publication type (Figure 4), peer-reviewed journal articles constituted the clear majority (60%), followed by undergraduate theses (16.7%) and master's theses (10%). The remainder was distributed among magazine articles, specialization monographs, and doctoral dissertations. English was the predominant language of publication (66.7%), compared to Portuguese (33.3%) (Figure 2). In terms of research methodology, experimental studies were the most common

ISSN 2318-8472, v. 14, n. 91, 2026

approach (53.3%), as detailed in Figure 3. A notable finding is the dominant field of study. An overwhelming 83.3% of the publications were related to sanitation and water pollution control (Figure 6), primarily authored by researchers with backgrounds in civil engineering (33.3%), environmental engineering (33.3%), biology (10%), and geography (6.7%) (Figure 5). The remaining studies were categorized under the fields of Environment and Health, Landscape and Environment, and Architecture and Technology. Correspondingly, the authors of these studies had academic backgrounds in Architecture and Urban Planning (13.3%) and Psychology (3.3%).

An analysis of the keywords also revealed distinct patterns. In the Portuguese-language publications (Figure 7), the most recurrent keywords were: qualidade da água (water quality, 33.3%), ilhas flutuantes (floating islands, 19%), and eficiência (efficiency) and infraestrutura verde (green infrastructure), both at 14.3%. In contrast, the most frequent keywords in the English-language publications (Figure 8) included: "floating wetlands" (20.6%), "performance" (14.3%), "water treatment" (12.7%), "eutrophication" (9.5%), and "ecosystem services" (4.8%). The remaining Portuguese keywords were largely related to pollution abatement (e.g., coliformes, desinfecção, fitorremediação, recuperação de rios, balneabilidade) or specific ecological terms (e.g., ecologia aplicada, macrófitas emergentes). The English keywords exhibited greater diversity, with 42.9% of all mapped keywords being classified as 'other,' compared to only 19% in the Portuguese corpus, suggesting a more concentrated thematic focus in the Brazilian studies.

Figure 1 – Year of Publication. Figure 2 – Language of Publication. Figure 3 – Research Methodology. Figure 4 – Publication Type: (ARR) Magazine Article, (DME) Master's Thesis, (TCC) Undergraduate Thesis, (ARP) Journal Article, (TDO) Doctoral Dissertation, (REL) Report, (MES) Specialization Monograph. Figure 5 – Author's Academic Background. Figure 6 – Field of Study. Figure 7 – Most Frequent Keywords in Portuguese Publications. Figure 8 – Most Frequent Keywords in English Publications.



Source: The authors.

ISSN 2318-8472, v. 14, n. 91, 2026

3.2 Contextual Background

The reviewed publications consistently identified contexts broadly related to the increase in urban water pollution. The authors attribute this degradation to several factors, including: sanitation deficits resulting in the improper discharge of untreated wastewater into water bodies and diffuse pollution (Feitosa et al., 2018; Krebs; Oliveira; Schröder, 2021; Licheski, 2018; Moreira, 2019); phenomena such as eutrophication (Johnson, 2021; Karstens et al., 2021; Ritzenhofen et al., 2022; Rocha, 2018); population growth in urban areas associated with the massive consumption of natural resources (De Souza, 2020; Shen; Li; Lu, 2021); the channelization of rivers (Medeiros, 2018); poorly planned tourism activities, which lead to seasonal population peaks that saturate existing infrastructure systems (Scaini, 2019); and other anthropogenic activities that directly or indirectly influence ecosystems and contribute to climate change, such as the burning of fossil fuels, deforestation (Cunha, 2018; Sánchez-Galván et al., 2022), and commercial activities in coastal zones (Takavakoglou et al., 2021).

Peterson et al. (2021) describe the "urban stream syndrome," which they define as: “(...) the consistently observed ecological degradation of streams draining urban land” (PETERSON et al., 2021, p. 1). This syndrome manifests through altered chemical, ecological, and hydrological characteristics in urban rivers and streams, presenting specific symptoms such as increased water temperature, decreased dissolved oxygen (DO), loss of aquatic habitats, and elevated concentrations of heavy metals, nutrients, and salts. According to Barco et al. (2021), when non-floating aquatic plants (emergent macrophytes) are installed on floating structures, they extend their roots hydroponically, fostering a biodiverse community of symbiotic microorganisms within their rhizosphere that removes organic and inorganic pollutants from the water. As the plants develop, their root systems expand, thereby increasing the surface area available for microbial adhesion. Consequently, Bi et al. (2019) found that pollutant removal rates are positively correlated with plant age. This factor also justifies the preference for emergent macrophytes over free-floating ones, as fibrous-rooted plants possess significantly larger root systems and exhibit higher photosynthetic rates, making them more efficient than plants with smaller roots. Furthermore, the literature indicates that free-floating macrophytes are prone to uncontrolled proliferation, as they can spread or be displaced rapidly by wind and water currents.

Johnson (2021) describes how, over time, the extensive root systems become coated with a biofilm. The microorganisms within this film utilize nutrients from the water for their multiplication through assimilation, a process that involves the excretion of enzymes that accelerate pollutant degradation. In turn, the plants benefit, as these reactions transform nutrients into bioavailable forms for their absorption and metabolism, which also supports their growth (Wang et al., 2020a). Additionally, as a product of their respiration, macrophytes release oxygen into the water, which raises the DO level—a critical factor for aquatic life (Wang et al., 2020b). Another identified benefit is the reduction of waterborne pathogens due to direct competition with the beneficial bacteria in the root zone (De Souza, 2020). The author notes that pathogenic bacteria adhere to the roots, eventually dying and settling out with other decaying organic matter. Macrophytes also contribute to the uptake and sequestration of heavy metals, which they store in their tissues (Shen; Li; Lu, 2021). While this accumulative

ISSN 2318-8472, v. 14, n. 91, 2026

characteristic is beneficial for water decontamination, it requires careful management due to potential impacts on the herbivore food chain, as some species can translocate metals to their aerial parts (i.e., leaves) (Samal; Kar; Trivedi, 2019).

Henny et al. (2020) describe FTWs as an effective biotechnology for the remediation of polluted rivers, whose performance can be optimized in critically degraded systems through the integration of artificial aeration. These mechanical devices (e.g., aerators, fountains) can be controlled by timers for intermittent operation and powered by solar energy via photovoltaic panels (Krebs; Oliveira; Schröder, 2021). Another enhancement strategy is the addition of artificial biofilm carriers or extenders, which act as synthetic roots or substrates to provide additional surface area for microbial growth and increase contact time with pollutants. Examples include stereo-elastic packing (plastic media) and electron-donating substrates like organic sawdust and activated carbon (Shen; Li; Lu, 2021). According to Samal et al. (2019), the plant root system reduces water velocity, thereby promoting sedimentation and aiding in the control of suspended solids and erosion. Conversely, the authors caution that a minimum water depth of 0.8–1.0 m must be maintained for the proper functioning of the FTW. In shallower depths, the plants may tend to anchor their roots in the sediment bed, compromising the structure's buoyancy. This situation could lead to the submergence and potential damage of the FTW system during high-water events.

The vegetation provides benefits that extend above the water's surface, such as improving air quality, as plants capture atmospheric carbon dioxide (CO_2) for photosynthesis and release oxygen. Sánchez-Galván et al. (2022) frame carbon sequestration as a key regulating service provided by various ecosystems, including wetlands. The contribution of emergent aquatic macrophytes to carbon sequestration is highly significant; in nutrient-rich waters, their growth is enhanced, leading to a high rate of photosynthesis. According to the author, the carbon stock in the below-ground biomass (rhizosphere) of these plants ranges from 617 to 977 gC/m², and in the above-ground biomass, from 988 to 1515 gC/m². The vegetation also provides critical habitat for birds and pollinators, offering shelter for breeding, nesting, and escape from predators or anthropogenic disturbances. Another factor associated with FTWs is their potential as a tourist attraction and the enhanced quality of life for local populations who interact with the intervention areas, due to the aesthetic enrichment of the landscape and the creation of natural spaces for community interaction and recreation (De Souza, 2020). Thus, the Nature's Contributions to People (NCP) delivered by FTWs encompass water quality improvement, carbon sequestration, habitat provision, educational opportunities, and socioeconomic benefits (Sánchez-Galván et al., 2022).

Based on the contexts discussed, the objectives of the reviewed studies can be grouped into four primary categories: (1) To assess the treatment efficiency of FTWs for improving water quality by analyzing parameters such as BOD, COD, phosphorus, nitrogen compounds, DO, pH, coliforms, and heavy metals (Barco; Borin, 2020; Bi et al., 2019; Cunha, 2018; Feitosa et al., 2018; Grosshans et al., 2019; Henny et al., 2020; Hossain, 2020; Johnson, 2021; Krebs; Oliveira; Schröder, 2021; Licheski, 2018; Moreira, 2019; Peterson et al., 2021; Rocha, 2018; Saeed et al., 2016; Scaini, 2019; Shahid et al., 2020; Shen; Li; Lu, 2021; Takavakoglou et al., 2021; Wang et al., 2020b); (2) To evaluate the design, construction, and operational methods of FTWs (De Souza, 2020; Karstens et al., 2021; Lucke; Walker; Beecham,

ISSN 2318-8472, v. 14, n. 91, 2026

2019; Pavlineri; Skoulikidis; Tsihrintzis, 2017; Rocha, 2018; Samal; Kar; Trivedi, 2019; Takavakoglou et al., 2021; Wang et al., 2020a, 2020b); (3) To assess the effects of FTW implementation on the provision of ecosystem services and their broader environmental impacts (Calheiros et al., 2020; De Souza, 2020; Licheski, 2018; Medeiros, 2018; Rigotti, 2020; Ritzenhofen et al., 2022; Takavakoglou et al., 2021); and (4) To evaluate the performance of specific plant species in terms of water decontamination, carbon sequestration, and other functions (Barco; Borin, 2020; Sánchez-Galván et al., 2022; Wang et al., 2020a).

3.3 FTW Construction Techniques and Operational Principles

The literature identifies a diverse range of construction methods and materials for the floating platform, the vegetation support medium, and the anchoring system of FTWs. Generally, the selection of materials is guided by criteria such as high durability and resistance, hydrophobicity, simplicity of construction, material availability, and financial viability. According to Samal et al. (2019), the buoyancy of an FTW can eventually become self-sustaining as air is trapped within the macrophytes' rhizomes, a process that develops as the plants mature. This suggests that the artificial flotation materials could be designed to be biodegradable or removable once the natural, self-floating root base is established. The most commonly used materials for flotation include PVC, PE, and PP pipes; bamboo poles; polystyrene sheets and polymeric grids; Styrofoam, EVA foam, and other low-density foams; and sealed containers such as barrels, drums, jugs, PET bottles, and inflatable vinyl buoys (De Souza, 2020; Karstens et al., 2021; Samal; Kar; Trivedi, 2019; Scaini, 2019). In addition to the floating structure, an initial support and cultivation medium is necessary to sustain the vegetation during the development of its root system and to provide a surface for microbial colonization. A recurrent use of materials such as plastic mesh or netting and fibrous materials like coir fiber mats, ropes, rods, and wooden planks was identified. It is crucial that these materials are porous, to allow the roots to remain in contact with the water, and chemically inert, to avoid contaminating the environment (Barco; Borin, 2020).

Finally, anchoring systems are fundamental to prevent FTWs from being displaced by water currents, wind, or other disturbances. However, the system must be designed to accommodate water level fluctuations, allowing for the structure's vertical movement. Anchoring can be secured to the bottom or the banks of the water body, depending on site-specific conditions. Typically, anchors may consist of rods, posts, cables, ropes, chains, and other naval hardware. The anchor weights can be composed of iron blocks, concrete, or other materials in various shapes and weights. Beyond the construction materials, the sizing, positioning, shape, and overall design of the project are essential for optimal FTW performance. It is critical to recognize that the interactive processes driving water treatment are dependent on the contact time with the root zone. Therefore, FTWs can be installed in lentic (still water) environments, in calmer regions of lotic (flowing water) systems, or in "offline" diversions (De Souza, 2020). The presence of these elements within a water body alters hydraulic flow paths, affecting both the velocity and the trajectory of the water—a principle that can be leveraged in the design to increase the hydraulic retention time with the root systems (Lucke; Walker; Beecham, 2019; Wang et al., 2020a).

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

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Extensive surface coverage by FTWs can create anoxic zones, which are favorable for processes like heavy metal immobilization and denitrification by heterotrophic bacteria; on the other hand, low oxygen concentrations can be detrimental to certain aquatic fauna. Regions with higher oxygen levels favor biochemical processes such as the decomposition of organic matter and nitrification (Samal; Kar; Trivedi, 2019). Notably, different layouts offer distinct advantages for specific purposes, and it is possible to employ passive reoxygenation strategies—such as leaving open areas for surface interaction with the atmosphere or creating turbulence—or active strategies, like installing aerators or air diffusers. Sunlight exposure (insolation) is another critical factor for plant development. According to Rigotti (2020), with five or more hours of daily sun exposure, macrophytes exhibited more robust foliage, which improves the plant's vertical posture and promotes the colonization of the island with increased plant biomass through photosynthesis. In Figure 1, the arrows indicate the preferential water flow path. It is apparent that with a dispersed layout (A), there is a risk of creating stagnant zones or hydraulic short-circuiting, where water bypasses the root systems. In contrast, the barrier-type layouts (B and C) promote a more homogeneous flow. They differ, however, in the amount of open area available for light penetration to the water column below, oxygen concentration, and gas exchange between the water and the atmosphere (De Souza, 2020).

Figure 1 – Design options for FTW positioning and hydraulic flow simulation (left). Photograph of the implemented project (right).

Source: De Souza, 2020, pg. 63, pg. 122.

According to Ritzenhofen et al. (2022), the implementation of Floating Treatment Wetlands (FTWs) can benefit various classes of ecosystem services (ES), and Rigotti (2020) further identifies co-benefits in the sociocultural and economic spheres. The term ES was originally defined by the Millennium Ecosystem Assessment (2005) as the benefits that humans obtain from ecosystems. These were classified into four broad categories: provisioning (e.g., food, water, raw materials, medicinal resources), regulating (e.g., air and water quality, climate conditions, disease and pest control), supporting (e.g., biodiversity, water cycle, photosynthesis, soil formation), and cultural (e.g., spiritual values, recreation, tourism, education).

However, this concept has since been updated, and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has introduced the framework of "Nature's Contributions to People" (NCP). This new framework recognizes that nature's

GC Revista Nacional de Gerenciamento de Cidades
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ISSN 2318-8472, v. 14, n. 91, 2026

contributions can be either beneficial or detrimental (e.g., disease transmission) and emphasizes culture as a cross-cutting element, placing greater value on traditional knowledge. Thus, the current categorization, as described by Díaz et al. (2018), consists of: regulating contributions (e.g., functional and structural aspects of ecosystems), material contributions (e.g., substances, raw materials, food, energy), and non-material contributions (e.g., subjective and psychological aspects that influence human quality of life).

Table 1. Relationship between NCP and the benefits provided by FTW implementation.

Benefits provided by FTW implementation	Material contributions	Non-material contributions	Regulating contributions
Improvement of water quality in water bodies			
Carbon sequestration and air quality regulation			
Creation and maintenance of wildlife habitat			
Pollination and dispersal of seeds/propagules			
Support for biodiversity and ecological functions			
Protection and decont. of soil and sediments			
Expansion of urban green spaces			
Scientific and educational contributions			
Aesthetic and recreational experience			
Psychological experiences and inspiration			

Source: Prepared by the authors, adapted from De Souza, 2020, p. 129; Ritzenhofen, 2022, p. 6.

As indicated in Table 1, regulating contributions are closely linked to the environmental conditions that shape the life experiences of both humans and animals, directly influencing non-material contributions and potentially impacting the generation of material contributions, as their availability depends on the biophysical balance of ecosystems. Thus, directly or indirectly, the implementation of FTWs tends to offer benefits to the area of influence, acting as a regulating agent of environmental conditions. This forms a foundational basis for maintaining ecological habitats and the quality of natural resources, which in turn enhances the provision of elements essential for human existence (e.g., water). Equally important are the psychological experiences, inspiration, and learning, which promote personal well-being (e.g., improved self-esteem, mood, stress reduction), cognitive development, social integration, reduced mortality rates, and even lower levels of crime and violence in urban areas. In economic terms, FTWs can reduce public expenditures, such as those related to controlling eutrophication through nutrient removal via phytoremediation—consequently controlling odor, fixing carbon, and providing thermal comfort—and an increase in the perceived value that people attribute to more ecologically abundant environments. These factors highlight the need for sustained investment not only in the implementation but also in the long-term maintenance of FTWs to ensure that these benefits persist over time (De Souza, 2020).

ISSN 2318-8472, v. 14, n. 91, 2026

The results observed for habitat creation and maintenance, pollination, seed dispersal, and vegetation development were based on visual observation. De Souza (2020) reported the colonization of the FTWs by new plant species over the course of the study. At the beginning of the implementation, the FTWs had 4–6 planted species; by the end of the monitoring period, 20–22 species were recorded, revealing a high rate of colonization, with a predominance of the Cyperaceae family, followed by the Asteraceae and Marantaceae families. Regarding wildlife habitat, the author observed various species of birds, butterflies, caterpillars, bees, spiders, and ladybugs actively interacting with the FTWs for perching, hunting, nesting, and feeding on the plants' fruits and nectar. The presence of aquatic animals, such as fish fry and tadpoles, swimming among the structures and near the floating platforms was also identified (Rigotti, 2020). Carbon sequestration (CS) rates were investigated by Sánchez-Galván et al. (2022) for FTWs with Cyperus papyrus and Pontederia sagittata species located in a eutrophic urban lagoon in Mexico. CS calculations were based on plant growth (above-ground biomass) and root growth (below-ground biomass). Although growth varied according to seasons, species, and FTW location, relatively high growth rates were measured: 0.125 and 0.142 d^{-1} for P. sagittata and C. papyrus, respectively. The resulting CS rates were 1.90 ± 0.94 $kg \cdot m^{-2}$ and 4.09 ± 0.73 $kg \cdot m^{-2}$ for P. sagittata and C. papyrus, respectively. The contribution of the roots to CS was also significant, at approximately 4.58 ± 0.59 $kg \cdot m^{-2}$.

Regarding public environmental perception, De Souza (2020) reports the results of a survey of 54 individuals who interacted with FTWs in a lake environment. One open-ended question asked about the device's function and its perceived benefits: 32% of respondents believed its function was for fish use, such as shelter, reproduction, and feeding; 22% thought it was a physical barrier to limit fishing hooks; 18% associated the device with water quality improvement through renaturalization with plants; 9% attributed its function to aesthetic beautification and attracting people; 6% answered it was a fish attractant for strategic fishing; 5% stated it was a simulation of a natural environment to improve animal quality of life and benefit users through relaxation and inspiration; 4% thought it was a device for birds (perching, shelter, feeding); 2% believed it encouraged microorganism production; and finally, 1% related the FTWs to safety and the reduction of potential environmental impacts. Another question assessed the degree of agreement with the FTWs' functionalities, project approval, and support for expansion: 80% of users rated its utility for water quality positively, 88% rated its utility for wildlife positively, and 76% rated its utility for landscape beauty positively. Regarding project approval, 92% of respondents were in favor, and 58% were in favor of increasing the number of islands.

Another important point in the social sphere is the promotion of environmental education through the implementation of solutions like FTWs. In addition to raising awareness about environmental issues, education enables the dissemination of information on the benefits and impacts of these solutions, creating a foundation of understanding for their replication and maintenance (Meneses et al., 2023).

Several limitations of FTWs were also identified in the literature, including susceptibility to temperature, sun exposure, water depth, pollution concentration, performance variability, root surface area, and macrophyte species. At low temperatures, microbial activity and plant growth are reduced, decreasing nutrient removal from the water. Sunlight is

ISSN 2318-8472, v. 14, n. 91, 2026

fundamental for photosynthesis and, consequently, oxygen control, which also influences nutrient management. Greater water depth and lentic ecosystems can lead to stratification of the water column, limiting the FTW's purification performance. Finally, excessive concentrations of phosphorus and/or ammonia can be toxic to the plants (Johnson, 2021; Shen; Li; Lu, 2021). According to Barco et al. (2021), a certain vulnerability exists in FTWs due to their reliance on natural processes, highlighting the essential need for the cataloging and selection of appropriate species for this solution to prevent this from becoming a limitation. Their research identified plant species (e.g., P. australis and T. latifolia) whose development was severely compromised when nutrient and organic matter levels in the water increased. However, other species (e.g., I. pseudacorus) exhibited a different response, with an increase in biomass production above the support medium. Overall, all species had a relatively high survival rate, even when impacted by extreme climatic events and exotic animal populations.

Wang et al. (2020) reveal another challenge regarding FTW implementation in rivers, as water velocity in these lotic systems can be relatively high, and they present complex environmental conditions that complicate anchoring and lead to low island stability. Consequently, large plants and low stability caused the vegetation to topple and, in some cases, the entire structure to break loose during seasons with strong winds and heavy rains. To mitigate this fragility, the research tested a novel composite with minerals (e.g., zeolite and sponge iron, also known as Direct-Reduced Iron – DRI) placed below the islands' support medium. This addition increased their stability, promoted greater plant resilience within the structure, and even enhanced water purification efficiency, particularly at low temperatures.

4 CONCLUSION

Despite a search methodology designed to identify contributions beyond water treatment, the theme of decontamination remained omnipresent. Indeed, no study was found that did not, to some extent, address the improvement of water quality, confirming that this is a primary and exhaustively studied function of FTWs. However, the SLR was successful in identifying a body of work that, starting from this essential function, expanded its analysis to investigate multiple socio-environmental co-benefits, thereby aligning with the broader perspective of Nature-based Solutions (NbS) and Nature's Contributions to People (NCP).

This review indicates that FTWs are emerging systems suitable for implementation in natural or artificial water bodies, such as rivers, lakes, and lagoons, and possess the capacity to provide diverse socio-environmental benefits related to NCPs. Despite vulnerabilities tied to factors beyond direct anthropogenic control—an inherent characteristic of an NbS—the reported outcomes were predominantly positive, leading to a reduction in the ecological footprint of human populations on natural resources and demonstrating their potential as an important tool for climate adaptation. Among the benefits associated with FTW implementation, perhaps the least discussed to date is the aesthetic enhancement of the urban landscape and the design of cities more integrated with nature, revealing a promising new field of study to be explored. Furthermore, these environments could be linked to tourism through the integration of floating decks and walkways into the FTW matrix, creating areas for rest and walking, wildlife observation points, and even environmental education centers.

ISSN 2318-8472, v. 14, n. 91, 2026

This literature review thus confirms the hypothesis that a greater understanding of the application of FTWs within the urban landscape context, viewed as an NbS, is necessary. This perspective opens up the possibility of implementing this solution in non-polluted water bodies, specifically as a tool for fostering integration between people and water. Given that the contribution of FTWs extends far beyond their efficiency in water treatment, a starting point for future research would be the development of a nomenclature capable of encompassing all the concepts and functions presented. Therefore, the term **Floating Ecosystems (FE)** is proposed.

5 RECOMMENDATIONS

A significant portion of the reviewed research was conducted at the pilot scale. Consequently, several authors recommended the development of full-scale investigations coupled with long-term monitoring to better understand the behavior and maintenance requirements of FTWs in more complex, real-world contexts (Bi et al., 2019; Karstens et al., 2021; Lucke; Walker; Beecham, 2019; Peterson et al., 2021; Rigotti, 2020; Rocha, 2018; Samal; Kar; Trivedi, 2019; Shen; Li; Lu, 2021).

As a nature-based solution, FTWs are intrinsically linked to the specific ecological, cultural, and hydrological context of their implementation site. Therefore, projects must be designed using native macrophyte species, with their design and scale tailored to the pollution levels and other specific characteristics of the water body in question (Cunha, 2018; Licheski, 2018; Sánchez-Galván et al., 2022; Scaini, 2019; Shen; Li; Lu, 2021).

It is essential to understand not only the benefits of FTWs but also the potential negative impacts arising from their implementation, as well as the operational challenges and adaptive management strategies needed to mitigate risks such as secondary pollution (e.g., the creation of anoxic "dead zones," sediment deposition, and issues related to excessive surface coverage and dissolved oxygen depletion), ecological imbalance, and system abandonment or vandalism (Feitosa et al., 2018; Rigotti, 2020; Samal; Kar; Trivedi, 2019; Shen; Li; Lu, 2021; Takavakoglou et al., 2021).

FTWs should be strategically positioned near pollutant discharge points in water bodies, as their root systems can act as a physical barrier to contain the dispersion of pollutants. Further investigation is required to establish the relationship between water depth and the vertical growth of the plant root systems (Bi et al., 2019; Henny et al., 2020; Hossain, 2020; Samal; Kar; Trivedi, 2019).

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DECLARATIONS

AUTHOR CONTRIBUTIONS

Maria Estela Ribeiro Mendes: Conceptualization, Data Curation, Formal Analysis, Investigation, Writing – Original Draft, Writing – Review & Editing.

Silvia Aparecida Mikami Gonçalves Pina: Conceptualization, Methodology, Writing – Review & Editing, Supervision.

CONFLICT OF INTEREST STATEMENT

The authors, **Maria Estela Ribeiro Mendes and Silvia A. Mikami G. Pina**, declare that for the manuscript titled **"Benefits of Floating Wetlands beyond water pollution control: A new perspective for Urban Landscape"** there are no conflicts of interest. Specifically:

1. **Financial Interests:** The authors have no financial interests that could have influenced the results or interpretation of this work.
2. **Professional Relationships:** The authors have no professional relationships that could have impacted the analysis, interpretation, or presentation of the results.
3. **Personal Conflicts:** The authors have no personal conflicts of interest related to the content of this manuscript.