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REVIEW PAPER

Floating Wetlands Islands for Crop Production: A Comprehensive Review and Bibliometric Analysis

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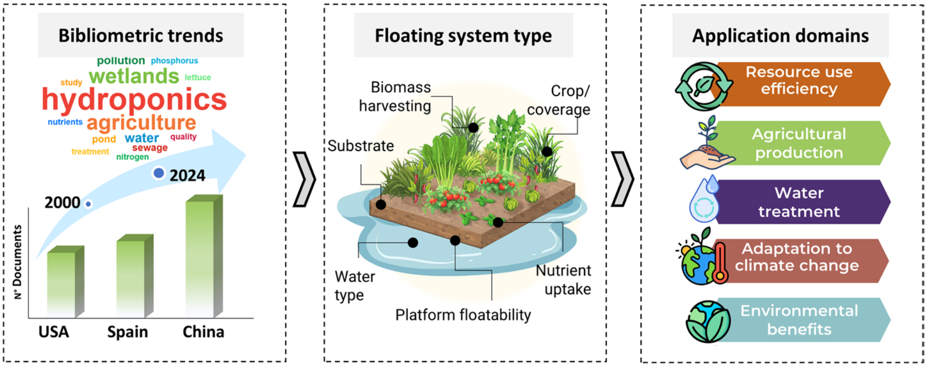
Abstract

Floating wetland islands (FWIs), traditionally applied for ecological restoration and water purification, are increasingly recognized for their multifunctional potential. Their ability to combine environmental remediation with food production positions FWIs as a promising nature-based solution (NbS) for advancing sustainable development. To identify research trends and knowledge gaps in this emerging field, a bibliometric analysis and systematic review of FWIs for crop production were performed using the Scopus database. A total of 83 publications were identified between 2000 and 2024, the majority being research articles (78.3%), with "Environmental Sciences" as the predominant subject area (35.8%). China emerged as the leading contributor, accounting for 71 publications (16.9%). Keyword co-occurrence analysis revealed three main thematic clusters: "agriculture," "hydroponics," and "wetlands," reflecting the interdisciplinary nature of FWIs, which combine elements of hydroponic cultivation, ecological engineering, and water quality management. The review emphasizes the importance of plant selection and system design, not only to enhance nutrient retention but also to maximize biomass productivity, particularly when the goal is to obtain harvestable crops. From an economic perspective, FWIs show favorable viability: revenues from crop sales often surpass operational costs, though construction remains the most significant investment. Social acceptance tends to be high when commercial value is demonstrated; however, barriers such as limited technical training and concerns over food safety remain. Despite varied terminology, FWIs systems consistently demonstrate multifunctionality, offering solutions for both ecosystem restoration and sustainable crop production.

Extended author information available on the last page of the article

Graphical Abstract



Keywords Floating wetland islands · Fodder production · Food production · Sustainable agriculture · Nature-based solution · Water treatment

Introduction

Food production is increasingly challenged by environmental pollution stemming from agricultural practices, aquaculture operations, and domestic waste. Diffuse contamination of water bodies not only jeopardizes freshwater availability but also disrupts the ecological balance of aquatic systems. At the same time, arable land scarcity, climate variability, food security demands, and natural resource degradation intensify the need for sustainable strategies that maintain productivity while safeguarding ecosystem integrity [21]; [59]. Nature-based Solutions (NbS), as defined by the International Union for Conservation of Nature, are "actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits" [38]. These solutions mimic natural processes with minimal mechanical inputs, promote efficient resource use, and are adaptable to diverse environmental conditions [55].

Recognized NbS are floating wetland islands (FWIs), also known as floating treatment wetlands (FTWs). These systems are valued for their low cost, simple installation and maintenance, effective pollutant removal, ecological benefits, and integration into aquatic landscapes. FWIs consist of artificial floating platforms placed on water bodies, such as lakes, ponds, rivers, or canals, composed of a buoyant matrix that supports a growing medium and aquatic or semi-aquatic plant [12]. The substrate not only anchors the plants but also acts as a physical filter for suspended particles and provides a surface for microbial biofilm development [14]. However, this depends on the type of substrate used, and even on whether a substrate is used at all, as in some FWIs, plants can grow directly in contact with water without any supporting medium [23]. Through phytoremediation, macrophytes contribute to contaminant uptake, degradation, or bioaccumulation, improving water quality [63].

Traditionally used for ecological restoration and water purification, FWIs are increasingly being explored for their multifunctionality [12]. They contribute to water conservation, runoff regulation, carbon assimilation, biodiversity promotion, and nutrient recycling, either in marine or aquatic environments [14, 15, 21]. Over the past decade, the integration of FWIs with complementary technologies such as microbial fuel cells, advanced filtration, or aquaponic systems has expanded their utility to support climate adaptation and resource efficiency. Applications now combine environmental and productive functions, such as biogas generation, bioelectricity production, and food cultivation, leveraging the systems potential for sustainable innovation, as shown in Table 1.

Notably, edible crops such as rice, lettuce, and sweet basil have been successfully incorporated into FWIs systems, taking advantage of their ability to thrive in aquatic environments and directly uptake nutrients from the water column [29, 33]. Similar models include hydroponic food production systems in freshwater lakes [22], and integrated aquaculture-crop systems in constructed ponds [31], highlighting FWIs potential to address land scarcity and water-related challenges through sustainable food production.

These systems are inspired by traditional practices, which have historically been used for food production in flooded areas. Floating agriculture, a soil-less indigenous technique, was historically widespread across Mesoamerica and Southeast Asia, enabling crop production in flood-prone areas where conventional crop production was not feasible [61]. In pre-Columbian Mexico, this method was known as chinampa, with records indicating that the Aztecs cultivated floating plots as early as 1150–1350 B.C. Chen and Wong, [21]. Comparable practices have also been observed in the wetlands of Bangladesh, offering a time-tested and ecologically sound model for sustainable agriculture in aquatic landscapes [22].

Despite growing interest, most research on NbS has been focused on environmental remediation, with limited attention given to their contributions to food availability, access, and utilization [55]. Moreover, inconsistencies in terminology and development frameworks hinder a unified understanding of FWIs systems designed specifically for food production. In this context, bibliometric analysis offers a valuable method for assessing the evolution

Table 1 Integrated floating wetland islands (FWIs) for different uses with an ecological approach

Use	Reference
Production and phytoremediation	Locke-Rodriguez et al., [48] Srivastava et al., [74]
Phytoremediation	Astuti et al., [8]
Eutrophicated waters	Zhao et al., [82]
Wastewater treatment	Shahid et al., [71]
Produces marketable crops	García Chance et al., [19]
Biofuels or bioenergy generation	Wilkie and Evans, [79]
Vegetable’s production	Fronte et al., [31]
Edible crops	Escamilla et al., [29]
Valorization in biorefinery	Rodríguez-Domínguez et al., [66]
Saline or marine environments	Calheiros et al., [15]
Urban stormwater runoff treatment	Colares et al., [23]
Biogas generation	Roj-Rojewski et al., [67]
Bioelectricity	Colares et al., [24]
Composting	Montoya et al., [51]
Stormwater treatment	Batista et al., [12]
Livestock effluents treatment	Hubbard et al., [37]
Refinery plants	Li et al., [45]
Floating habitat platforms	Calheiros et al., [14]
Aquaculture systems	Goda et al., [34]

of scientific inquiry in the field. It allows the identification of dominant research themes, intellectual structures, and emerging knowledge gaps, thus providing a roadmap for future innovation [78].

The objective of this review is to conduct a bibliometric analysis on FWIs systems applied to agricultural production. This approach enables researchers to map the intellectual landscape, detect underexplored areas, and understand prevailing research trends. The study also highlights key considerations for implementing FWIs systems for food production, including maintenance, economic feasibility, and social acceptance, ultimately supporting the development of sustainable and multifunctional agricultural practices.

Materials and Methods

Data Sources

The database used for the study was the Scopus search engine. This platform is one of the most internationally recognized for its breadth and quality, indexing more than 25,000 peer-reviewed scientific journals and offering advanced tools for bibliometric analysis [78]. Prior to the search process, initial combinations of keywords were defined, including “floating treatment wetlands”, “runoff water”, and “food production”. However, these combinations did not yield matching results, making it necessary to broaden and refine the search terms to ensure a more comprehensive and representative retrieval of relevant literature. The search was organized into three thematic groups, as detailed in Table 2. The first group covered concepts associated with floating wetland treatment. The second group focused on types of water bodies, and finally, the third group grouped terms related to agricultural production. Boolean logic was applied for the search: “AND” for complementary terms and “OR” for

Table 2 A group of terms and a set of keywords used in the search performed

Grouping of terms (AND)	Keywords
Treatment	“floating treatment wetlands” OR “floating constructed wetlands” OR “constructed floating wetlands” OR “floating wetland island” OR “floating wetland” OR “floating island” OR “floating beds” OR “floating island treatment” OR “floating hydroponic system” OR “floating hydroponics” OR “floating system” OR “floating gardens” OR “floating mat system” OR “floating pot” OR “ecological floating bed” OR “hydroponic system” OR “artificial floating beds” OR “floating Vegetable Gardening” OR “floating agriculture” OR “floating culture system”
Type of water	“freshwater” OR “stormwater” OR “surface water” OR “rainwater” OR “runoff” OR “polluted water” OR “eutrophic water bodies” OR “polluted rivers” OR “natural water” OR “ponds” OR “sub-surface irrigation” OR “polluted river water”
Crop production	“sustainable crop production” OR “crop production” OR “hydroponic crop production” OR “food production” OR “food safety” OR “agriculture” OR “vegetables”

synonyms. The search was conducted on May 5, 2025, and was therefore limited to publications from 2000 up to the year 2024. The documents retrieved were exported as plain text files (.bib) to facilitate subsequent bibliometric analysis.

Bibliometric Tools

The bibliometric analysis was conducted using the pyBibX library in Python (version 3.11.12), a tool designed for comprehensive bibliometric and scientometrics evaluation of raw data files. It integrates advanced artificial intelligence (AI) capabilities into its core functionality [64]. Additionally, a bibliometric mapping was performed using VOSviewer (version 1.6.20), developed by CWTS at Leiden University. This software visualizes keyword co-occurrence networks, where node size and link thickness represent term frequency and co-occurrence strength, respectively [77]. The bibliometric analysis focused on identifying annual trends and the evolution of scientific production, including the number of publications, authorship, contributing countries, institutions, research areas, journals, citations, and keywords (Table S1, supplementary material).

For the VOSviewer mapping, co-occurrence data were extracted from the downloaded bibliographic database. The Keywords Plus, which were present in 72.29% of the data (see Table S2, supplementary material), were grouped into clusters based on their frequency of co-occurrence within the same documents. To minimize noise and highlight the most relevant terms, a minimum occurrence threshold of 7 was applied, generating a minimum of 20 links. The nodes represent keywords, while the size of each node corresponds to the frequency of occurrence. The lines connecting the nodes indicate co-occurrence relationships, for example, how often terms appear together in the same documents. Different colors represent clusters, or groups of closely related terms, suggesting distinct research subthemes [24].

Systematic Literature Review

A comprehensive review of experimental cases on FWIs to agricultural production was conducted, covering both food and fodder production. In this section, the scientific papers from 2025 were also considered, of which there were only two. The review considered experimental conditions, types of water used, species grown, and biomass yields. Likewise, design aspects were analyzed, such as the materials used in the floating structure, the types of substrates and crops used, FWIs coverage and planting features, among other relevant factors. Elements related to crop management, parameters measured in relation to water and crop quality, productivity per square meter or per monetary unit, as well as associated environmental benefits, were also evaluated. Finally, the main challenges and potentialities for the future development of this line of research were identified.

Results and Discussion

Data Analysis and Visualization

Figure 1 shows the number of documents related to the search keywords analyzed from the Scopus database. According to the search conducted in the Scopus database, a total of 83

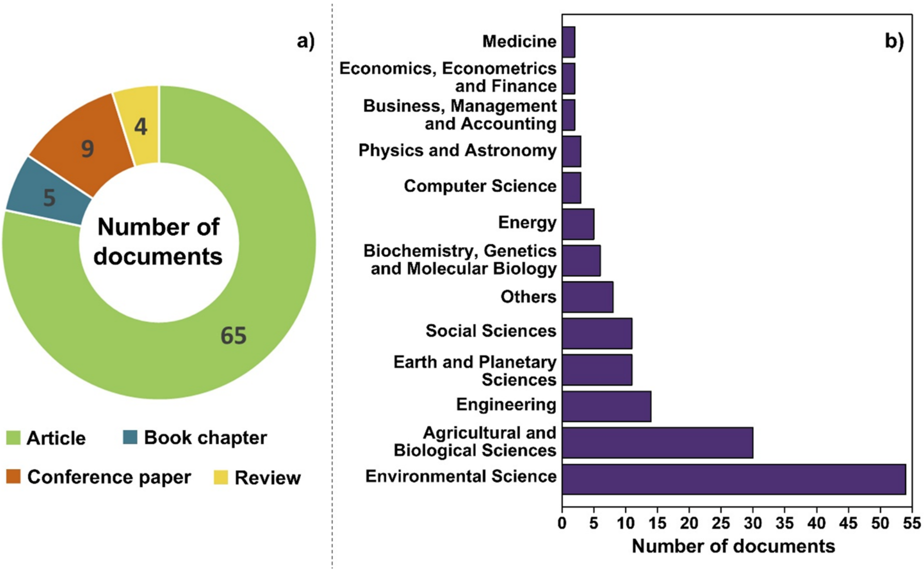


Fig. 1 Publications related to the analyzed search terms from the Scopus database. (**a**) Type of publication, (**b**) categories of main field areas

publications were obtained (Fig. 1a). Of these, 78.3% were classified as "Articles", making it the most common publication type. The remaining 21.7% consisted of "Book chapters" (6.0%), "Conference papers" (10.8%), and "Reviews" (4.8%). The thematic categorization of publications was headed by "Environmental Sciences", with 54 documents (35.8%) (Fig. 1b), followed by "Agricultural and Biological Sciences", with 30 documents (19.9%), and "Engineering", with 14 documents, representing less than 10%. The remaining categories together accounted for 35.1% of the total. It is important to note that journals can be indexed in multiple subject areas, which can result in cumulative percentages above 100%.

Notable studies within the Environmental Sciences category included experiments focused on agricultural production [29] and the remediation of contaminated water bodies [36]. Additional works included environmental risk assessments [39] and Life Cycle Assessment (LCA) [53]. The presence of research areas such as Engineering, Biological Sciences, Social Sciences, and Earth and Planetary Sciences reflects the fact that FWIs are increasingly being approached through diverse technical and societal lenses, highlighting a growing trend toward interdisciplinary integration.

Figure 2a shows the number of documents per year of FWIs for crop production. The first publication appeared in 2000, by Su and Jassby [75], who developed floating agricultural islands anchored to the lakebed of Inle Lake (Myanmar) using bamboo poles. Research activity remained limited between 2007 and 2015, averaging just 2.2 documents per year. During this period, interest in NbS began to emerge, gaining visibility across environmental research, particularly in the context of food security [55]. Studies specifically focused on floating wetlands began to appear around 2011, followed by a more pronounced rise in 2019 [12]. In recent years, a clear upward trend has been observed. Between 2017 and 2024, the average number of FWIs-related documents increased to 7.8 per year, representing a 255%

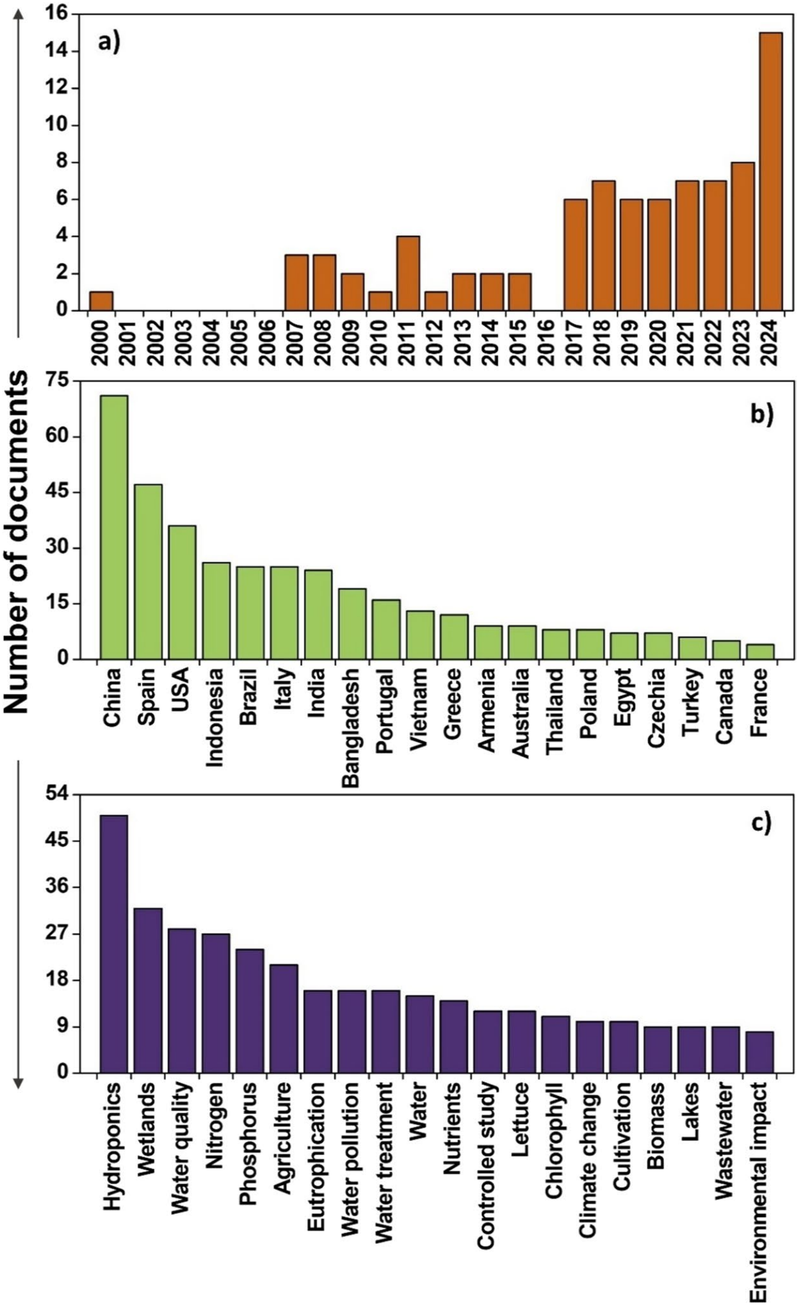


Fig. 2 Publications related to the search terms analyzed from the Scopus database. (**a**) Number of publications per year, (**b**) top 20 countries with the most publications, (**c**) top 20 keywords with the most published studies

growth. This trend coincided with increasing interesting green technologies for water treatment, which began gaining momentum around 2015 and peaked in 2020 [56].

A total of 41 countries have contributed to research on FWIs systems for crop production. Figure 2b highlights the 20 most productive countries according to the authors' country per document. China is the most productive country, with 71 documents, followed by Spain (47) and the United States (36). These countries, particularly China and the USA, together account for over 52% of all FWIs-related publications, demonstrating their leading role in this research field [24]. In terms of Funding sponsor, Chinese research was supported primarily by the Ministry of Science and Technology of the People's Republic of China and the National Natural Science Foundation of China, each sponsoring five studies.

The East Asian region leads this research area, with a total of 161 documents, including not only China but also countries such as Indonesia, India, Vietnam, Bangladesh, and Thailand. This is followed by Europe, with 134 documents, where EU countries like Spain, Italy, Portugal, and Greece stand out. European research has been supported by funding from the European Commission (9 research projects) and the Horizon 2020 Framework Programme (7 research projects). In addition, organizations such as the FAO have supported this type of technology, with the TECA project - Technologies and Practices for Smallholder Agriculture in countries such as Bangladesh, in connection with contributions to sustainable development objectives (FAO 2020). Overall, articles on food security framed as NbS were more prevalent in the Global South, including Asia, Africa, and Latin America, with 41 articles, compared to only 10 articles identified in the Global North (Europe and North America) [55].

These trends observed in the bibliometric analysis are consistent with patterns observed in environmental and nature-based technologies, whose development is strongly driven by national policy frameworks and specific research funding [43, 56]. During the 2019–2021 period, identified as the development phase of green technology innovation, governments' strategies to promote low-carbon and resource-efficient technologies significantly improved innovation efficiency in regions such as eastern and central China [43]. At the same time, growing interest in studies on climate-resilient agriculture or climate change in South Asia (e.g., India and Bangladesh) (Kibria and Haroon, [40]; [50]), along with major funding programs in Europe and North America (e.g., Horizon 2020 and the U.S. Department of Agriculture's water initiatives), contributed to the rapid expansion of FWIs research in these countries over the past decade.

Figure 2c displays the top 20 most frequently used keywords across the published documents. In total, 355 Author Keywords were identified. The most frequent term was "Hydroponics", appearing in 50 documents, followed by "Wetlands" with 32 occurrences, and "Water quality" with 28. In the early 2000 s, keywords such as "Water quality" were predominant, reflecting a primary focus on water treatment. By 2008, terms like "Hydroponics" and "Lettuce" began to appear, indicating a growing interest in crop production. The keyword "Wetlands" emerged around 2013, experiencing a surge in use by 2017. Meanwhile, terms like "Agriculture" and "Cultivation" became more prominent in the 2020 s, signaling an expanding focus on the agricultural applications of FWIs systems.

Figure 3 presents a co-occurrence network of Keywords Plus related to FWIs for crop production. The network is divided into three main clusters, as detailed in Table S3, which lists the keywords associated with each thematic cluster. By selecting the keyword, it was possible to more easily visualize the terms that were directly linked. The purple cluster is

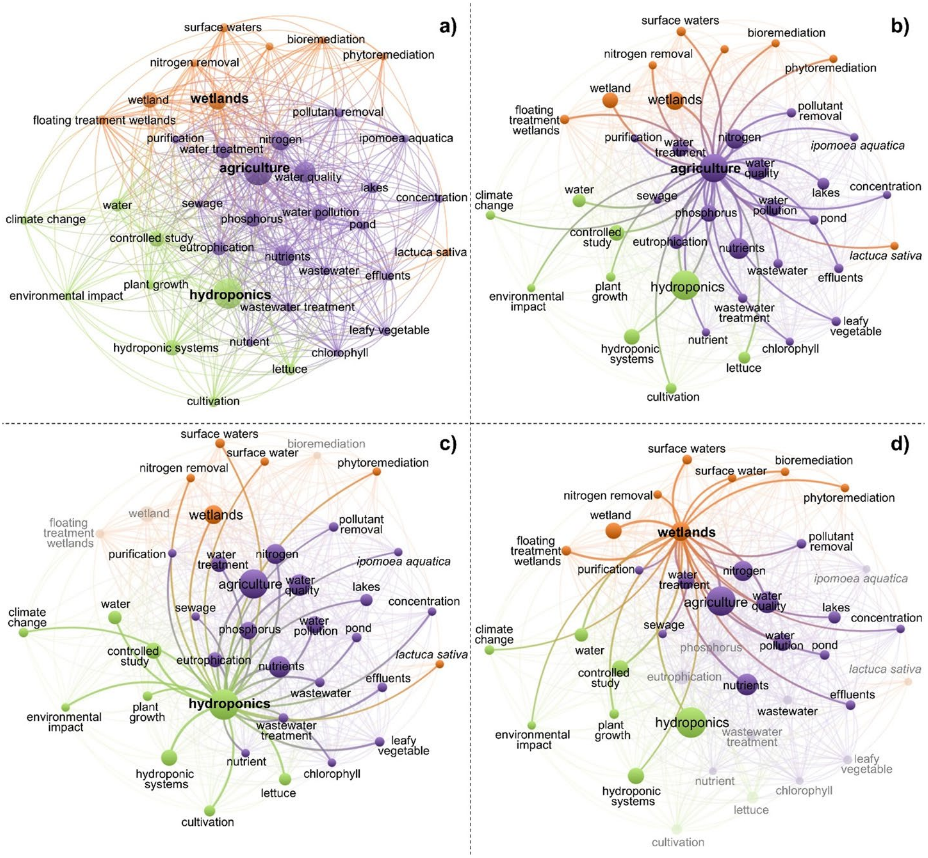


Fig. 3 Co-occurrence network visualization of keywords plus. (**a**) all clusters, (**b**) cluster agriculture, (**c**) cluster hydroponics and (**d**) cluster wetlands

the central and most densely connected, anchored by the keyword "agriculture" (Fig. 3b). It is closely linked to terms such as "phosphorus," "nitrogen," "wastewater," "water pollution," and specific crops like *Lactuca sativa* and *Ipomoea aquatica*. This cluster reflects the integration of plant-based treatment systems with crop production, underscoring the dual role of FWIs in nutrient retention and sustainable agriculture. An example is the study by Rufí-Salís et al., [68], which developed rooftop farming systems fed by a hydroponic system under the keyword "Urban agriculture". This cluster also includes studies that applied FWI to treat "Agricultural Runoff", such as those by Escamilla et al., [29] and Dekle et al., [27].

The green cluster centers on the keyword "hydroponics", and includes terms such as "plant growth," "chlorophyll," "lettuce," "hydroponic systems," "nutrient," and "cultivation" (Fig. 3c). This group represents research on controlled growing environments and crop performance in water-based systems, with implications for resource-efficient agriculture. Additionally, keywords like "environmental impact" and "climate change" highlight connections to sustainability and nature-based solutions. An example of this group is the publications that reused pre-treated agro-industrial water for hydroponic production of lettuce [1] and tomato crops [2], including the evaluation of product quality.

The orange cluster revolves around "wetlands" and includes keywords such as "floating treatment wetlands," "bioremediation," "phytoremediation," "pollutant removal," and "surface waters" (Fig. 3d). This cluster reflects an ecological engineering perspective, emphasizing the use of FWIs for remediating polluted water bodies and providing ecosystem services, as do the wetlands. Notable authors within this cluster include Bell et al., [13], who contributed to the CleanWater3 project, which focused on developing ecologically based treatment technologies, such as FWIs, for the treatment and reuse of agricultural runoff. Similarly, Mukherjee et al., [52] published work on the application of hydroponic systems for the phytoremediation of contaminated water.

Figure 4 displays a Sankey diagram illustrating the relationships among the 15 most productive authors, their affiliated institutions, and their countries of origin. In total, the reviewed publications involved 385 authors, 163 institutions, and were published across 68 different journals (See Table S1). A notable example is the collaboration among five authors, with three publications, forming a strong international research network. Their work is affiliated with institutions such as the Universitat Autònoma de Barcelona (Spain), the University of Bologna (Italy), the University of Freiburg (Germany), and Ghent University (Belgium). This collaboration has resulted in several publications in high-impact journals, including Resources, Conservation and Recycling [5], Science of The Total Environment [6], and The International Journal of LCA [68], all of which emphasize environmental assessment and sustainability.

Another research group focused on the application of hydroponic systems using agro-industrial effluents as nutrient sources, publishing primarily in MDPI journals, such as

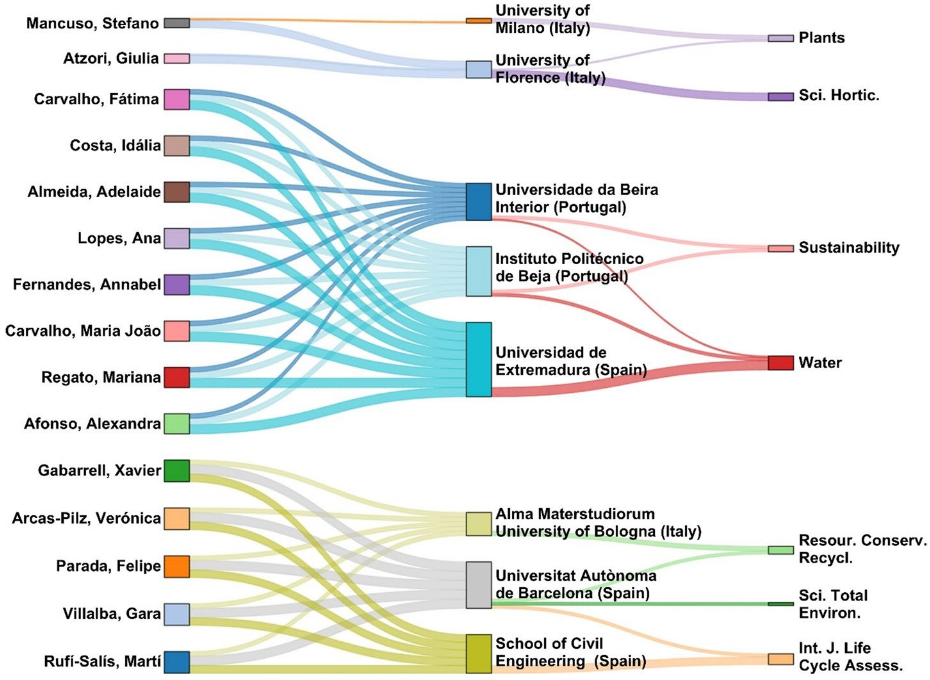


Fig. 4 Sankey diagram for top 10 author by journal and country of the publications analyzed from the scopus database

Sustainability [1] and Water [2]. This line of research involved collaboration between institutions, including the Instituto Politécnico de Beja and the Universidade da Beira Interior in Portugal, as well as the Universidad de Extremadura in Spain. Additionally, a collaboration between Italian institutions, the Department of Biotechnology and Biosciences at the University of Milano-Bicocca and the Department of Agricultural, Food, Environmental and Forestry Sciences and Technologies at the University of Florence, focused on evaluating the quality of agricultural products cultivated in floating systems [9, 16].

Application of Floating Wetland Islands for Crop Production

Despite the growing interest in floating system-based technologies for water treatment and crop production, a standardized nomenclature to consistently characterize these solutions is still lacking. A review of the literature reveals a wide range of terms that, although they share similar structural and functional principles, vary considerably in their denomination, depending on the purpose of the system. Among the most frequent terms are *floating wetlands*, *floating hydroponics*, *floating beds*, *hydroponic biofilters*, *constructed wetlands*, *floating agriculture*, *artificial floating beds*, and others. Although the term *Floating Treatment Wetlands* (FTWs) is widely used for pollutant removal applications, we adopt *Floating Wetland Islands* (FWIs) when referring to their emerging use in food production or agricultural purposes.

A comparative table compiling multiple studies implementing floating systems with dual functionality aimed at both environmental water remediation and plant production has been compiled. This table compiles multiple studies that implement floating systems with a dual functionality oriented both to environmental water remediation and plant production. Tables 3 and 4 summarize the case studies identified in the literature involving FWIs applied to food production and feed production, respectively.

FWIs systems are highly adaptable for treating different water sources, with aquaculture and aquaponic effluents being the most frequently addressed (38%) due to their elevated nitrogen (N) and phosphorus (P) loads. These effluents often reach concentrations up to 122.8 mg/L PO_4^{3-} and 14.9 mg/L total phosphorus (TP), and 1.5 to 17.1 mg/L total nitrogen (TN), sometimes including toxic ammonia levels, reflecting nutrient accumulation and limited water renewal in fish and aquaponic systems [34, 41, 47, 60, 81]. Elevated nitrate concentrations, associated with active nitrification and incomplete plant uptake, have also been reported, although some designs (e.g., ryegrass floating beds) achieved efficient nitrate removal while producing valuable biomass [11].

In addition, FWIs have been widely applied to surface waters (27%) and agricultural runoff (23%), major drivers of eutrophication, particularly in East Asia. Reported concentrations include up to 35.9 mg/L TN and 3.1 mg/L TP in runoff simulations, as well as high TAN (9.2 mg/L) and NH_4^+ (7.6 mg/L) in polluted rivers, with PO_4^{3-} levels of 0.1–0.9 mg/L in eutrophic waters, supporting the role of FWIs as effective nutrient-mitigation strategies [20, 28, 74, 82, 85].

Despite differences in system configuration and treatment objectives, several FWIs-based systems consistently demonstrate the capacity to produce effluents that meet international water quality standards (WHO, [80]; USEPA, [76]; [62]; Sepa, [70]). For example, Cui et al., [25] using a pilot-scale enhanced FTW with a tubular bioreactor, reduced TN to 0.4 mg/L, meeting China's Grade II standard. Similarly, Li et al., [44] using a hydroponic

Table 3 Summary of case studies on floating wetland islands (FWIs) for food production in different water types

Scale	Time (months)	Water type	Treatment system	Platform	Substrate media	Crop	Biomass (kg/m²)	Reference
Mesocosm	2.5	Semi-artificial nutrient (Yellow River in Ningxia)	Floating-bed pot culture	Polystyrene foam	-	*Ipomoea aquatica* (Water spinach)	0.289	Chen et al., [20]
						Lactuca sativa (Lettuce)	0.231	
						Oryza sativa (Rice)	0.924	
Mesocosm	1.5	Tap water + liquid fertilizer	Floating wetlands	Beemats™	Coconut coir	*Ocimum basilicum* (Sweet basil)	0.0457	Escamilla et al., [29]
	2					*Beta vulgaris* (Swiss chard)	0.0389	
Mesocosm	6	Tank fish runoff	Hydroponic	Polystyrene trays	-	*Lactuca sativa* (Lettuce)	41.9	Fronte et al., [31]
						Ocimum basilicum (Sweet basil)	49.9	
Mesocosm	3	Aquaculture wastewater	Floating bed	Nylon net with PVC pipes	-	*Ipomoea aquatica (Water spinach)*	1	Liu et al., [47]
Mesocosm	3	Aquaculture wastewater	Floating bed	Polystyrene rafts	Rice husk ash; old, composted water weeds	*Brassica campestris* (Chinese cabbage)	2.1–5.1	Pantanella et al., [61]
						Lactuca sativa (Lettuce)	0.1–3.0.1.0	
Mesocosm	5.6	Eutrophic lake	Floating culture	Polyethylene foam	Granite soil	Korean japonica rice '*Nampyeon.*'	0.65	Srivastava et al., [74]
Greenhouse	1	Seawater + liquid fertilizer	Floating hydroponic	Polystyrene cell	-	*Spinacia oleracea* (Spinach)	0.05–0.06	Caparrotta et al., [16]

Table 3 (continued)

Scale	Time (months)	Water type	Treatment system	Platform	Substrate media	Crop	Biomass (kg/m²)	Reference
Greenhouse	25*	Nutrient solution	Floating hydroponics	Polystyrene containers	Perlite	*Medicago sativa* (Alfalfa)	0.85	Fabek Uher et al., [30]
						Beta vulgaris (Yellow beet)	2.69	
						Brassica oleracea (Red cabbage)	0.72	
						Foeniculum vulgare (Fennel)	0.22	
Greenhouse	3	Aquaponic solution	Hydroponic	Styrofoam foam board	-	*Lycopersicon esculentum* (Cherry tomato)	37.2	Yang and Kim, [81]
						Ocimum basilicum 'Genovese' (Basil)	24.4	
						Lactuca sativa 'Cherokee' (Lettuce)	16.5	
Pilot	7.9	Urban landscape water	Floating treatment wetland	Moso bamboo	Cane bagasse; Hemp fiber	*Ipomoea aquatica* (Water spinach)	2.1	Cui et al., [25]
Pilot	3	Wastewater from shrimp farming	Constructed semi-dry wetland	N/A	Gravel	*Lactuca sativa* (Lettuce)	97.5	Farias Lima et al., [26]
Pilot	4	Fish farms water	Constructed wetlands	-	Expanded clay	*Lycopersicon esculentum* (Tomato)	38.4	Krivograd and Griessler, [41]
Pilot	4	Aquaculture wastewater	Floating bed	Bamboo and net	-	*Ipomoea aquatica* (Water spinach)	23.58	Li and Li, [46]
Pilot	4	Flood water	Floating culture	Plastic bottles	Soil: manure: rice husks	*Capsicum annuum* (Chili pepper)	2.99	Siaga et al., [72]

Table 3 (continued)

Scale	Time (months)	Water type	Treatment system	Platform	Substrate media	Crop	Biomass (kg/m²)	Reference
Full	6.2	Water pond	Floating agriculture	PVC pipes, net and bamboo sticks	Water hyacinths and water ferns	*Capsicum annuum* (Chili pepper)	3.2	Al-Imran et al., [4]
Full	1–3	Wastewater from fish farming	Floating raft Systems	Styrofoam board	Synthetic sponge	*Cucumis sativus* (Cucumber)	9.2	Goda et al., [34]
						Brassica oleracea (Broccoli)	2.41	
						Solanum lycopersicum (Tomato)	12.83	
						Solanum melongena (Eggplant)	5.91	
						Capsicum annuum (Chili and bell pepper)	12.4	
						Lactuca sativa (Lettuce)	4.88	
Full	2.5	Freshwater swamp	Floating seedbeds	Polyethylene mat	Biochar	*Oryza sativa* (Rice)	5.6–8.2×10^{-10}	Lakitan et al., [42]
Full	8	Fishpond wastewater	Hydroponic biofilter	Ceramic	Ceramsite sand	*Oryza sativa* (Rice)	13.27	Li et al., [44]

*: days

biofilter system, achieving TN values of 2.5–5.1 mg/L and PO_4^{3-} of 0.3–0.4 mg/L, meeting EU thresholds (TN < 10 mg/L; PO_4^{3-} < 0.5 mg/L). Additionally, Duan et al., [28] treated domestic wastewater using floating beds, achieving 40 mg/L Chemical Oxygen Demand (COD), 3.5 mg/L TN, and 0.2 mg/L TP, all within EU and US EPA discharge standards.

The performance of FWIs systems is strongly conditioned by water type and system configuration. Higher removal efficiencies (> 70%) are consistently reported in moderately polluted or hydraulically stable waters, such as diluted surface or irrigation water, whereas eutrophic and nutrient-rich waters exhibit lower and more variable treatment performance [28]. For example, Chen et al., [20] achieved high removal efficiencies in Yellow River water (92.5% TN and 81.3% TP), comparable to those reported by Cui et al., [25] for urban landscaped waters (81.5% TN), highlighting the effectiveness of FWIs under moderate nutrient loads. In contrast, studies conducted in eutrophic waters reported substantially lower efficiencies (40–50% TN and 25–45% TP), coupled with pronounced seasonal variability [82].

Table 4 Summary of case studies on floating wetland islands (FWIs) for fodder production in different water types

Scale	Time (months)	Water type	Treatment system	Platform	Substrate media	Crop	Biomass (kg/m²)	Reference
Microcosm	10*	NO_3^- polluted water	Floating bed	Polystyrene boards	-	*Lolium multiflorum* (Italian ryegrass)	0.166–0.191	Bartucca et al., [11]
Microcosm	3	Tap water + nutrient solution	Floating wetlands	Polyethylene	-	*Rumex japonicas*	12.78	Geng et al., [32]
Mesocosm	2	Nutrient solution	Floating treatment wetlands	Beemats	-	*Carex stricta* (Juncia Tussock)	-	García Chance et al., [19]
Mesocosm	20*	Eutrophic water	Floating beds	plastic trays	-	*Festuca arundinacea* (Grass)	0.051	Zhao et al., [83]
Mesocosm	2.1	Polluted river	Floating bed	Polystyrene foam	-	*Oenanthe javanica* (Water Celery)	1.62	Zhou and Wang, [84]
Greenhouse	20	Aquacultural wastewater	Hydroponic plate	Plate/fabric/grass cell	Unwoven cotton fabric	*Lolium perenne* (Ryegrass)	0.134	Pan et al., [60]
Pilot	3.5	Treated domestic wastewater	Floating bed	Polyethylene foam	Sponge	*Oenanthe javanica* (Chinese celery)	0.112	Duan et al., [28]
		Polluted river water					0.144	
Pilot	15*	Aquaculture wastewater	Floating plant bed	Layers unwoven fabric	-	*Lolium perenne* (Ryegrass)	13.18[a]	Nduwimana et al., [54]
Full	18	Oil-contaminated water	Floating wetlands	Polyethylene (Jumbolon roll)	Soil (70%), sand (20%) and medium gravel (10%)	*Brachiaria mutica* (Pasture grass)	0.67	Afzal et al., [3]
						Leptochloa fusca (Pasture grass)	0.56	
Full	4.3	Polluted river	Artificial floating bed	Pipe (PVC)-rope bed	-	*Oenanthe javanica* (Water Celery)	0.03	Zhu et al., [85]

*: days

In aquaculture-integrated systems, nutrient loads often exceed plant uptake capacity, leading to nutrient accumulation. Comparative analysis shows that system complexity plays a critical role in mitigating these limitations: multi-stage or recirculating designs outperform single-stage configurations. This is evidenced by the higher removal efficiencies reported for hydroponic or recirculating systems (59–65% TN, 68–74% TP, and 71–74% COD; [44]; up to 88.9% TAN and 64.8% NO_3^-N), compared with simpler floating bed systems treating aquaculture effluents [54].

The studies indicate that contaminant removal efficiency in FWIs systems is influenced not only by the type of water treated but also by the crop used. For feed production, the most used crops include ryegrass and other pasture grasses such as *Leptochloa fusca* and *Brachiaria mutica* (see Table 4). In contrast, systems focused on food production predominantly use leafy vegetables, with *Lactuca sativa* (lettuce) representing 38% of the cases and *Ipomoea aquatica* (water spinach) 25%. Cereal crops, particularly *Oryza sativa* (rice), are also widely used, accounting for 25% of the studies. Fruiting vegetables such as *Capsicum annuum* (chili) and *Solanum lycopersicum* (tomato) are each reported in 19% of cases. These species are typically selected for their adaptability to saturated or semi-aquatic environments, particularly *hange o. by Oryza sativa*, which are traditionally associated with flooded cultivation systems.

Several plant species have shown strong nutrient uptake capacity and vegetative growth, with water spinach standing out for its high efficiency. For example, Chen et al., [20] reported 72.0% of TN in floating beds, equivalent to 53.14 g/kg plant tissue. However, results vary by water type: Cui et al., [25] found only 8.3% (0.0012 g/kg) of TN uptake in urban landscape water, while Liu et al., [47] observed 17.2% (7 g/kg) in aquaponics, likely due to higher nutrient loads. This is supported by the findings of Li and Li [46], who also reported a retention of 30.6% of TN and 18.2% of TP using floating beds, amounting to 1.92 g/kg and 0.32 g/kg of plant mass. Another crop such as lettuce also demonstrated notable P uptake. Chen et al., [20] reported a 79.2% (10.12 g/kg) TP uptake in floating bed systems, whereas Yang and Kim [81] using a hydroponic setup, observed lower assimilation rates of 14% (2.06 g/kg) for TN and 11% (0.42 g/kg) for TP.

In the case of rice, Chen et al., [20] reported a TN uptake efficiency of 56.7%, representing 40.37 g/kg of plant mass. Yang and Kim, [81] also evaluated tomato and basil. Tomato showed the highest assimilation capacity among the tested species, with 24% (1.49 g/kg) of TN and 23% (0.37 g/kg) of TP uptake. Basil followed, achieving 16% (1.74 g/kg) of TN and 14% (0.43 g/kg) of TP uptake. Another species, *Oenanthe javanica*, commonly known as Chinese celery, is a semi-aquatic plant with multiple uses, including applications in human consumption, animal feed, and ecological or even medicinal purposes [84]. In a study conducted by Duan et al., [28], floating beds planted with Chinese celery were used to treat river pollution, where 52.5% (2.76 g/kg) of TN and 68.2% (0.48 g/kg) of TP was uptake by the plants. Similarly, Zhu et al., [85] reported that plant species assimilated 23.9% (2.49 g/kg) of TN and 65.0% (0.19 g/kg) of TP in a polluted river system.

Plant nutrient uptake in FWIs systems is closely linked to biomass production, following a positive linear trend [84]. In a full-scale hydroponic biofilter, Li et al., [44] reported 103.1 g N/m^2 and 11.5 g P/m^2 in rice with 13.3 kg/m^2 biomass in a hydroponic biofilter. in one season (3 months) While, Goda et al., [33] observed 44.0 g N/m^2, 5.5 g P/m^2, and 98.3 kg/m^2 biomass in floating beds, also over 3 months. Escamilla et al., [29] evaluated the growth of basil and Swiss chard (*Beta vulgaris*) in mesocosms with floating beds and different fertilization levels (low and high). The highest nutrient contents were recorded the highest uptake in Swiss chard, with up to 20 g N/m^2, 2.9 g P/m^2 over a period of 2 months (56 days).

As for nutrient retention rates, 0.365 g N/m^2 d and 0.052 g P/m^2 d have been observed in basil and swiss chard [29]. In contrast, non-edible grasses such as *Festuca arundinacea* and *Lolium perenne* showed lower retention rates, less than 0.14 g N/m^2 d and 0.02 g P/m^2 d [60, 85]. These retention rates are within the range observed for species commonly used in FWIs systems, such as *Juncus effusus* (0.057–0.505 g N/m^2 d and 0.016–0.220 g P/m^2 d) and *Pontederia cordata* (0.136–1.23 g N/m^2 d and 0.067–0.349 g P/m^2 d), which stand out for their adaptability and efficiency in aquatic environments [17, 18, 73]. In freshwater constructed wetlands, maximum nutrient retention rates of up to 0.027 g N/m^2 d and 0.010 g P/m^2 d have been reported, corresponding to 15% and 10% uptake, respectively, in dominant species such as *Phragmites australis* [63].

Biomass production in FWIs systems varies notably across plant species and water conditions. Lettuce achieved the highest yield, reaching 97.5 kg/m^2 in an aquaponic system treating nutrient-rich shrimp wastewater [26]. In contrast, in low-nutrient waters like eutrophic lakes or agricultural runoff, yields dropped to 0.1–3.0 kg/m^2 [20, 74]. Other crops also showed strong performance in aquaculture or aquaponic waters: tomato and basil reached 37–38 kg/m^2 and 24–50 kg/m^2, respectively [31, 41, 81]. The aquatic spinach yielded 23.5 kg/m^2 with added benefits like nutrient retention and algal bloom control [46], and chili pepper, and rice produced over 10 kg/m^2 in full-scale floating systems [34, 44].

When comparing crop productivity in FWIs systems with other practices, such as hydroponics or conventional agriculture, a meta-analysis shows that hydroponic lettuce yields vary widely, from 5.05 to 41.9 kg/m^2 per cycle, with higher yields in conventional agriculture. However, they depend on the type of species and environmental conditions. Similarly, spinach showed a yield (2–70 to 16.35 kg/m^2 per cycle) six times higher in soil-based growing systems than in hydroponic systems. This could be due to the fact that spinach is a heavy feeder that requires a lot of nutrients to grow healthily. On the other hand, crops such as chilli and peppers grown hydroponically yielded almost twice as much (15.36 kg/m^2) as conventional crops (8.92 kg/m^2) [35].

The analysis of plant species used for fodder production in FWIs systems reveals generally low biomass yields, typically below 1 kg/m^2. Afzal et al., [3] demonstrated the potential of using resilient grasses such as *Brachiaria mutica* and *Leptochloa fusca* in a full-scale FWI for the remediation of oil-contaminated water, achieving biomass yields of 0.5–0.6 kg/m^2. Among forage species, *Lolium perenne* produced 0.13–0.19 kg/m^2 [11, 60], while *Festuca arundinacea* yielded even less (0.051 kg/m^2). Despite the low productivity, tall fescue biomass was found to be rich in calcium, magnesium, iron, and manganese, offering a nutritionally valuable feed source capable of meeting the daily mineral requirements of livestock and poultry [83].

Biomass productivity varied strongly with system scale. Pilot-scale systems exhibited the highest mean biomass (32.9 kg/m^2), while full-scale systems showed more stable but moderate values (7.4 kg/m^2). Greenhouse and mesocosm studies exhibited wide variability, reflecting differences in experimental design and management intensity and underscoring their transitional role between controlled research and real-world applications. This scale-dependence represents a key limitation for upscaling, as high variability and low yield reproducibility highlight the need for standardized design and operational criteria.

Design and Operation of Floating Wetland Islands Treatment Systems

Table 5 presents a comparative summary on specifications and case design characteristics of studies that have used FWIs for crop production. It is observed that FWIs have been studied at all scales of implementation, from laboratory and greenhouse experiments to applications in real field conditions, with a progressive shift toward productive contexts. Approximately 38% of the studies have been developed at controlled conditions, which is consistent with the initial phases of research and optimization of technical variables. For example, Chen et al., [20] simulated agricultural irrigation conditions in a mesocosm system with representative nutrient solution from the Ningxia River. In contrast, Srivastava et al., [74] conducted a mesocosm experiment directly in Lake Seo (South Korea), evaluating system performance under natural environmental conditions.

The pilot scale, with 27% of cases, represents the key intermediate stage for evaluating the technical and economic feasibility of FWIs systems prior to full-scale implementation. At this stage, a greater diversity of floating wetland designs can be observed, including enhanced or integrated systems [26, 41], recycled structures [46, 54], and novel experimental formats [25]. For their part, full-scale projects represent 23% of the total and are characterized by implementations in real environments such as lakes, ponds or aquaculture systems. A prominent example is the use of FWTs in an oil-contaminated well in Pakistan, where 218 floating beds planted with *Leptochloa fusca* and *Brachiaria mutica*, covering a total area of 3058 m^2 [3]. Similarly, Al-Imran et al., [4] implemented 24 floating beds of 6.0 × 1.35 m with *Capsicum annuum* in flooded agricultural areas of Barishal, Bangladesh, achieving a production of 3.21 kg/m^2 of fresh biomass.

The analysis of full-scale implementations shows that the highest level of technological maturity of FWIs based agricultural systems is currently concentrated in specific regions, particularly Asia and parts of North Africa. Countries such as China [44], Pakistan [3], Bangladesh (Imran et al., 2025), Indonesia [42], and Egypt (Goda et al., 2024) report applications under real environmental conditions, with operational periods ranging from a few months (2–4 months) to more than one year. Despite being classified as large-scale, most systems remain site-specific and spatially constrained, indicating an intermediate level of technological maturity rather than fully consolidated field adoption.

In contrast, research in Europe is predominantly conducted at laboratory (Fronte et al., 2021) or greenhouse scale [16], while large rural regions in Latin America remain largely unrepresented, with Brazil as a notable exception through pilot-scale applications in shrimp farming [26]. Although operational feasibility has been demonstrated in rural water bodies such as ponds, rivers, and aquaculture effluents, critical gaps remain regarding scalability, long-term performance, and the transferability of FWI systems across diverse agricultural, climatic, and socioeconomic contexts.

When considering floating structures, polyethylene-based foams or boards and expanded polystyrene are among the most widely used materials due to their high buoyancy, lightweight nature, and ease of handling [11, 31, 65, 74]. Patented solutions, such as Beemats™ featuring pre-cut holes for root support [19], and Diamond® Jumbolon polyethylene sheets [3] enhance plant growth performance and structural durability compared to conventional foams. However, these advanced products may entail higher costs or limited accessibility. Despite this, conventional polyethylene and polystyrene materials provide reliability and consistent flotation, making them suitable for standard applications.

Table 5 Summary of design specifications and characteristics of floating wetlands islands (FWIs) for crop production

Scale	Floating bed	Dimensions (m) (l x w x h)	Platform area (m^2)	Floating cover (%)	Substrate media	Crop	Planting features	Crop density (plant/m^2)	Reference
Microcosm	Expanded polystyrene boards with a 30 µm nylon membrane	0.36 × 0.28 × 0.06	0.1	94	-	*Lolium multiflorum* (Italian ryegrass)	20 pots	0.60*	Bartucca et al., [11]
Mesocosm	Polyethylene foam (Beemats) with nylon connectors	0.60 × 0.30 × 0.02	0.18	15	-	*Carex stricta* (Tussock sedge)	20 biodegradable aerator cups	111.1	García Chance et al., [19]
Mesocosm	Polyethylene foam	0.66 × 0.51 × 0.015	0.33	86	Sponge	*Oenanthe javanica* (Chinese celery)	16 holes with a sponge and seedlings	95	Duan et al., [28]
Mesocosm	Foam mat (Beemats)	0.6 × 0.6 × 0.01	0.36	31	Coconut coir	*Beta vulgaris* (Swiss chard)	Mat had 10 pre-cut holes, 5 cm suction cups	27.8	Escamilla et al., [29]
		1.2 × 0.6 × 0.01	0.72	63		*Ocimum basilicum* (Sweet basil)	Mat had 20 pre-cut holes, 5 cm suction cups	13.9	
Mesocosm	Polyethylene boards	0.5 × 0.4	0.2	100	-	*Ocimum basilicum* (Sweet basil)	-	30	Fronte et al., [31]
						Lactuca sativa (Lettuce)		25	
Mesocosm	Nylon net (grid diameter 2 cm) with PVC pipes	1.5 × 1.0	1.5	25	-	*Ipomoea aquatica* (Water spinach)	-	1.0[a]	Liu et al., [47]
Mesocosm	Polystyrene foam	0.5 x 0.0.4 × 0.076	0.2	83	Hydroton pebbles	*Ocimum basilicum* (Basil)	8 holes for net pots	40	Rašković et al., [65]

Table 5 (continued)

Scale	Floating bed	Dimensions (m) (l x w x h)	Platform area (m²)	Floating cover (%)	Substrate media	Crop	Planting features	Crop density (plant/m²)	Reference
Mesocosm	Plastic (polyethylene terephthalate, PET) mineral water bottles with PVC (polyvinyl chloride) pipes	2.0 × 1.0 × 0.078	2	25	Soil: manure: rice husk	*Capsicum annuum* (Chili pepper)	24 polybags with mixed media	9	Siaga et al., [72]
Mesocosm	Polyethylene foam	1.2 × 0.9 × 0.2	1.1	5.4	Granite soil	*Oryza sativa* (Rice variety *Nampyeong)*	8 Pots with weathered granite soil	74	Srivastava et al., [74]
Greenhouse	Styrofoam board and black plastic liner	1.0 × 1.0 × 0.05	1	100	Sponge	*Cucumis sativus* (Cucumber); *Brassica oleracea* (Broccoli); *Solanum melongena* (Eggplant)	25 pots with synthetic sponge	72	Goda et al., [34]
						Capsicum annuum (chili and bell pepper); *Lactuca sativa* (Lettuce); *Solanum lycopersicum* (Tomato)		96	

Table 5 (continued)

Scale	Floating bed	Dimensions (m) (l x w x h)	Platform area (m²)	Floating cover (%)	Substrate media	Crop	Planting features	Crop density (plant/m²)	Reference
Greenhouse	Plate/fabric/grass cell	0.4 × 0.4	0.16	13	Unwoven cotton fabric	*Lolium perenne* (Ryegrass)	Plates with 30% of their bottom perforated	31.3	Pan et al., [60]
Pilot	Polyethylene tubes rolled in circles and moso bamboo	12 × 0.1 diameter x 0.0003; 2.5 m diameter rolled	5	-	Palm fiber and cane bagasse	*Ipomoea aquatica* (Water spinach)	Planting holes (1 cm Ø) in the upper part between 50 cm along the length	1–2^{b}	Cui et al., [25]
Full	Jumbolon role (cells of polyethylene resins) with aluminum foil rim and polypropylene	1.83 × 1.22 × 0.10	7.32	25	Soil (70%), sand (20%), and medium-sized gravel (10%)	*Leptochloa fusca* and *Brachiaria mutica* (grass)	14 holes with one pot	1.91	Afzal et al., [3]
Full	Polystyrene	1.0 × 1.0 × 0.05	1	25	Land	*Oryza sativa L.* (Rice)	Net pots standardized with holes 5 × 5	30	Goda et al., [33]
Full	Ceramic	0.5 × 0.5	0.25	57.8	Ceramsite	*Fengliangyou1* (Rice)	Four wells drilled with plastic pots and ceramsite substrate	9.24	Li et al., [44]
Full	Knotted ropes with PVC-pipes (40 mm)	2.0 × 1.0	2	40	-	*Oenanthe javanica* (Water Celery)	33 rope knots	16.5	Zhu et al., [85]

(lxwxh): length×width×height; *: g/pot; a: kg/m^2; b: plant/hole

In contrast, a wide range of alternative materials has been tested for constructing floating frames or rafts to ensure adequate buoyancy, reflecting a growing trend toward sustainable and low-cost solutions. For instance, Siaga et al., [72] employed 69 plastic mineral water bottles (1.5 L each) arranged in three rows of 23 bottles, tied together with fishing line, encased in a metal net, and reinforced with PVC pipes to form the raft rectangular structure. Similarly, Liu et al., [47] developed an ecological floating bed using a PVC pipe frame and a nylon net with a 2 cm grid to support aquatic spinach cultivation. An innovative and eco-friendly approach was proposed by Cui et al., [25], who incorporated circularly coiled tubular bioreactors attached to a floating bed made of bamboo, enhancing both flotation and functionality.

Substantial variation in platform size and floating coverage was observed across studies. Small floating platforms ($\leq 2\ m^2$) were commonly used in mesocosms or greenhouse experiments, while full-scale systems reached individual units of up to 7 m^2. For example, Goda et al., [33] developed modular 1 m^2 floating units that were assembled to cover a total area of 400 m^2. Similarly, Afzal et al., [3] interconnected 218 mats, each measuring 7.32 m^2, to build a large floating island with a total surface area of 3058 m^2. Notably, both studies covered approximately 25% of the water surface, a commonly recommended coverage ratio for full-scale systems. This ratio is effective in maintaining adequate hydraulic flow and avoiding excessive shading, which could otherwise impair system performance [24].

Among the reviewed studies, only three reported platform coverages below 20%, whereas seven employed coverages exceeding 50%. Coverage is considered one of the most influential design parameters in FWIs performance. Very high coverages ($> 50\%$) may reduce water oxygenation and negatively impact aquatic fauna, while very low coverages ($< 10\%$) may be insufficient for effective nutrient retention or biomass production. For treatment oriented floating systems, it is generally recommended to maintain coverage between 18% and 50% to ensure optimal treatment efficiency [24].

However, when the objective shifts toward plant production, coverage can be increased to between 30 and 60%, provided that water quality is not adversely affected. For example, Li et al., [44] conducted a full-scale study of hydroponic rice cultivation in floating beds with 57.8% surface coverage in a 425 m^2 pond, achieving a total biomass yield of 13.2 kg/m^2. Similarly, other studies using 63% and 86% coverages with *Ocimum basilicum* and *Oenanthe javanica*, respectively, reported biomass yields of 34 g and 47 g per plant. However, these studies were conducted in mesocosms [28, 29]. The cost-coverage relationship is also worth noting. Awan et al. [10] reported a significant negative correlation between levelled cost ($\$/m^2$ per year) and percentage FWI coverage, indicating that higher coverage ratios lead to greater cost efficiency. This trend is primarily explained by the distribution of fixed installation and maintenance costs over a larger productive area.

Various substrate media have been used in floating systems, including synthetic sponges [34], coconut coir [29], ceramsite [44], hydroton clay pebbles [65], manure-based mixtures [72] and soil or sand [3]. Coconut fiber enhances nutrient retention due to its natural adsorption and filtration properties. Similarly, expanded clay aggregates show high affinity for P, improving its retention and boosting biomass production [24]. However, a common practice is the use of plastic pots or aeration cups without any substrate, allowing roots to remain in direct contact with water [11, 19]. Beyond providing physical support, substrates serve as particle filters and surfaces for microbial biofilm formation. This was demonstrated by Cui et al., [25] using a 3:1 mixture of palm fiber and bagasse as substrate media, with the fiber serving as the biofilm support and the bagasse as the carbon source. This combination resulted in a higher abundance of aerobic heterotrophic genera associated with denitrification (30.5%) and anoxic denitrification (19.5%).

Within FWIs, soil-based systems have also been explored. Goda et al., [33] applied soil-filled floating beds for rice crops improving productivity, water use efficiency, and nutrient uptake. Similarly, Afzal et al., [3] covered floating mats with a stratified mixture of 70% soil, 20% sand, and 10% medium gravel to grow *Leptochloa fusca* and *Brachiaria mutica*. A similar concept developed by Al-Imran et al., [4] was to construct a floating agricultural system using bamboo canes and PVC pipes filled with water hyacinth and aquatic ferns to a height of 1 m. The results showed improved moisture retention, nutrient availability and pH stability, which contributed to increased shoot and root growth of the *Capsicum annuum* crop.

The planting characteristics and density in FWIs systems vary according to the intended purpose, the plant species used, and the system scale. For water treatment applications, planting densities typically range from 4 to 10 plants/m^2 [24], while systems aimed at biomass or crop production tend to use higher densities, generally between 10 and 30 plants/m^2. Several studies have explored how plant density affects plant performance and system efficiency. Goda et al., [33] evaluated three planting densities (20, 25, and 30 plants/m^2) and found that the highest density (30 plants/m^2) resulted in greater plant height (86.1 cm) and seed production rate (59.1%). However, nutrient content was highest at the lowest density (20 plants/m^2), with values of 2.6% for N and 1.6% for P, suggesting a trade-off between productivity and nutrient accumulation.

Fronte et al., [31] tested vegetable production in mesocosms using *Ocimum basilicum* and *Lactuca. sativa*, planted at 30 and 25 plants/m^2, respectively. They reported fresh biomass yields of 135.4 g/plant for basil and 175.7 g/plant for lettuce, reinforcing the role of density in maximizing productivity in crop oriented FWIs. Escamilla et al., [29] further investigated the effect of planting coverage using a constant density of 10 plants per floating mat. In *Ocimum basilicum*, this configuration represented a density of 13.9 plants/m^2 (50% coverage), while in *Beta vulgaris*, it corresponded to 27.8 plants/m^2 (100% coverage). Both species grew well and showed moderate nutrient retention capacity, with *Beta vulgaris* performing slightly better, highlighting the species-specific responses to planting density and system function.

In addition to density, planting configuration also plays a role. Several studies have used a fixed number of plants per pot or hole (typically 1 plant/pot), with total planting density depending on the number of planting holes and the surface area of the floating platform [19, 65, 72, 85]. Common planting methods include perforated pots, aeration cups, pre-cut holes in foam rafts [28, 29], knotted ropes to support root anchorage [85] and polyethylene bags filled at varying depths of submergence [72]. Reported plant spacing ranges from 12 cm [19] to 50 cm [25], with typical values between 18 and 20 cm being the most adopted [33, 85].

High planting densities may improve nutrient retention, however they can also intensify competition and limit light availability, particularly in crop-oriented systems. Moreover, excessive biomass can compromise buoyancy, thereby reducing platform stability and overall system functionality. Consequently, the efficiency of FWIs systems depend not only on plant species selection but also on water quality, nutrient loading, and structural design. Achieving optimal performance requires a balance among these factors to meet both treatment and production objectives.

Key Components, Challenges, and Future Opportunities

To ensure effective functioning of FWIs and fully harness their benefits, several factors must be considered. Figure 5 presents an overview of the key dimensions involved in their design and operation, covering structural configuration, practical implementation, crop production, water treatment, associated environmental benefits, and potential future developments.

Although FWI are NbS with generally low maintenance demands, regular system monitoring is essential to ensure optimal performance. Maintenance tasks usually include assessment of plant health, harvesting, buoyancy of the structure and periodic monitoring of water quality parameters, especially during installation and adaptation. However, some studies have focused exclusively on plant productivity, neglecting the evaluation of water treatment efficacy [4, 42, 72].

Routine water quality monitoring often includes daily measurements of in situ parameters such as pH, temperature, dissolved oxygen, and electrical conductivity. Nutrient concentrations, especially various N and P species, are typically analyzed weekly or biweekly. Less frequently, additional indicators such as chemical oxygen demand (COD) [25, 47], total, suspended and volatile solids (TS, SS, or VS) are used [41] or even chlorophyll-*a* as an indicator of algal biomass are evaluated [41, 74].

Regarding plant monitoring, vegetative growth parameters such as shoot height, root length, and leaf number are often recorded on a daily or weekly basis [42, 72]. At harvest, biomass weights (shoots and roots), nutrient accumulation [20, 41], and physiological indicators such as photosynthetic pigments content or antioxidant capacity may be assessed [16, 30]. Some studies also evaluate heavy metal uptake [54] or compositional traits of plant tissues [74]. Monitoring duration generally follows crop growth cycles, with some researchers recommending seasonal assessments to capture potential environmental variability [82].

Crop harvesting is another key aspect of maintenance, both for treatment efficiency and system productivity. By removing plant biomass, recirculation of nutrients such as N and P to the water is prevented, improving the sustained removal of pollutants [84]. In addition, periodic harvesting contributes, by renewing plant uptake capacity, reduces the risk of clogging due to excess roots and maintains structure buoyancy [63]. The frequency and timing of harvesting should be adapted to the crop cycle and the peak of nutrient accumulation in the tissues. and in some cases, it is possible to perform successive harvests during the season maximizing production [29].

In five successive cycles, Fronte et al., [31] demonstrated that regular harvesting in aquaponic systems sustained continuous production and enhanced nutrient uptake, with significantly higher lettuce biomass (335.8 g/plant) compared to the hydroponic control (175.7 g/plant), while basil showed similar yields across both systems. Similarly, García Chance et al., [19] evaluated the performance of various ornamental and horticultural species grown in FWI irrigated with treated wastewater. Plants were harvested at the end of each 8-week cycle and assessed for their commercial viability after transplantation. They exhibited high survival rates and good aesthetic quality (average ratings > 4 on a 1–5 scale). Although plants in FWIs showed slightly slower growth (by 1–2 weeks) compared to conventional systems, they reached marketable size and were deemed suitable for sale.

Economic considerations are increasingly relevant for evaluating the feasibility and scalability of FWIs systems. Awad et al., [10] evaluated the costs of FWIs for water treatment, with annual investment costs ranging from US\$15/m^2 to US\$780/m^2. However, cost-benefit

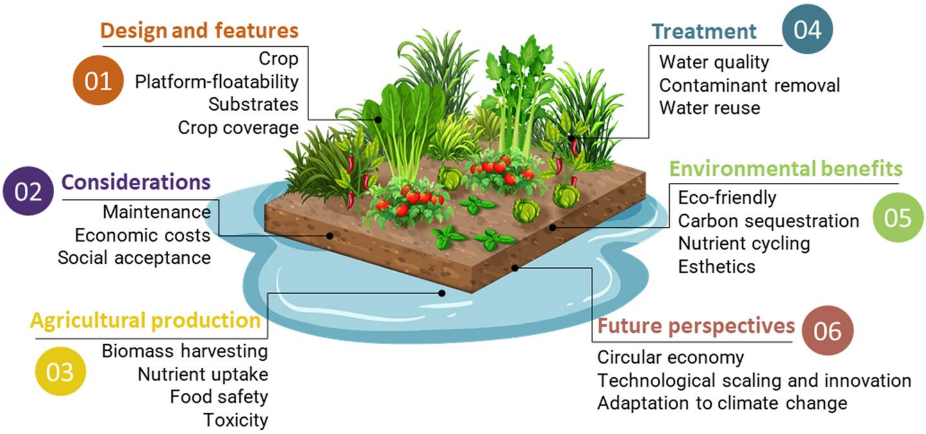


Fig. 5 Key components of floating wetlands island for crop production

analyses from several studies have shown that income from floating agriculture often exceed the associated costs [22]. The most significant expense in FWI systems is construction, which can account for 65% to 90% of total costs, depending on factors such as materials (floating supports, structure), crop type, labor, coverage, scale, location, climate, transportation, and local infrastructure [10, 57]. Operating and maintenance costs vary between 30% and 65%, being highest in FWIs involving plant harvesting [10].

FWIs for agriculture range from 11 to 258 US$/m^2, with the platform being the main factor influencing cost. Pantanella et al., [61] reported platform construction costs in Thailand between 2.6 and 8.0 US$/m^2, depending on the materials used, such as polystyrene, composted aquatic weeds, or rice husk ash.). In China, a hydroponic system with ryegrass (*Lolium perenne*) using plate/fabric/grass modules was estimated at approximately 1.32 US$/m^2, with fabric costing 0.004 US$/m^2, plates 1.3 US$/m^2, and seeds 0.01 US$/m^2. As for commercial platforms, the prices are higher. The Beemats platform costs approximately 38 US$/m^2, while BioHaven systems reach around 377 US$/m^2 [49]. The Diamond Jumbolon Rolls from Pakistan at 30–50 US$/m^2, depending on thickness and density. Additional transportation and import costs should also be considered.

Some costs that are reduced in FWIs systems include land rental, irrigation water (in both quantity and quality), energy use, and infrastructure materials, especially when recycled materials are employed. The main source of income comes from crop sales, which can range from 0.38 US$/m^2 to 9.8 US$/m^2 depending on the crop type [22]. For example, Pantanella et al., [61] cultivated cabbage and lettuce on floating platforms and sold them in local markets at 1.43 US$/kg, resulting in gross revenues of 5.58 to 9.87 US$/m^2 per crop cycle. Similarly, Goda et al., [33] compared a conventional rice cultivation system with an intensive floating platform system, finding that the net income from the floating system (527.9 US$/400m^3) was 5.45 times higher than that of the conventional system. The Earthen Pond-based Floating Bed (EPFB) also achieved a superior revenue-to-cost ratio (143.9%) and a return on sales of 56.9%. with short payback periods of 0.4 to 0.5 years.

Social acceptance and farmers perception are key factors for the successful implementation of FWIs. Studies like García Chance et al., [19] highlighted that when FWIs produce commercially viable crops, they are well received by farmers and nursery operators. Pantanella et al., [61] also showed high acceptance in low-resource settings, where recycled materials and traditional knowledge were integrated into low-cost floating platforms. In Bangladesh, for example, the adoption of floating agriculture was initially met with skepticism from local communities; however, with some initiatives more than 150 villagers switched to floating agriculture after realizing its comparative advantage over traditional methods [42].

However, several barriers may hinder the adoption of FWIs systems, including limited technical training, concerns over food safety, and insufficient knowledge regarding crop quality. Notably, only one study incorporated the analysis of metals and biological indicators such as *Escherichia coli* in both influent and effluent, highlighting the limited attention given to these parameters in FWIs monitoring [83]. To reduce risks, sanitary monitoring (metals, pathogens, coliforms) should be conducted before harvest. Furthermore, the study evaluated the nutritional content of the harvested crops, revealing high levels of protein and micronutrients, suggesting their potential use as animal feed [74, 82]. Another strategy to minimize risks is to select crops whose edible parts are positioned well above the water. Although roots generally accumulate the highest concentrations of contaminants, previous studies have shown that trace amounts can also be found in edible tissues, such as leaves and fruits, posing a potential health risk when these crops are consumed raw [28, 54, 82].

Additional constraints of FWIs systems include their vulnerability to weather extremes, water turbulence, and sediment resuspension. Harvesting is often labor-intensive and difficult to mechanize, and although the systems are technically simple, installation remains cost-intensive [12]. Furthermore, the absence of specific regulatory frameworks and agronomic guidelines for certifying food production in FWIs systems represents a significant barrier [21]. Therefore, FWIs could be considered as a complementary option rather than a substitute for conventional or hydroponic agriculture.

FWI systems have demonstrated the potential to contribute to climate change mitigation by biogenic carbon absorption and reducing greenhouse gas emissions. Studies report low net emissions of CO_2 (2.78 g/m^2d) and CH_4 (0.146 g/m^2d), while carbon uptake by vegetation can offset these values, resulting in a positive balance [58]. Vegetation plays a vital role in FWIs for carbon assimilation, particularly when fast-growing species with extensive root systems are used due to their high biomass productivity. Although harvesting removes stored carbon, it also prevents its release as CO_2 or CH_4 through decomposition and promotes plant regrowth, enabling repeated cycles of carbon uptake and organic matter removal. Together, these processes enhance the role of FWIs as active, temporary carbon sinks [7, 58]. Beyond their carbon uptake capacity, such vegetation enhances biodiversity, mitigates local heat stress, and ensures system functionality under fluctuating water levels [7].

The LCA of FWIs remains limited, particularly regarding their application in crop production. They exhibit notable differences depending on their primary purpose, whether water treatment or food production. FWIs for water treatment have a carbon footprint of 0.055 to 5.3 kg CO_2eq/m^3 of treated water [69]. While a system focused on agricultural production such as a hydroponic system varies depending on the type of vegetation ranging from ~ 0.49 kg CO_2eq/kg for tomato, while vegetables such as spinach or arugula are higher with 6.8 kg CO_2eq/kg y 3.7 kg CO_2eq/kg [68]. The study by San Miguel et al., [69] considered forage production for animal feed where the carbon footprint was 0.070 kg CO_2eq/m^3 therefore the FWI system estimated a total production of 0.012 kg CO_2eq/m^3. Although the carbon footprints reported in most LCA studies are expressed per unit of production, they typically overlook the biogenic carbon stored in plant biomass, potentially leading to an underestimation of the climate-mitigation potential of FWIs.

FWIs offer promising prospects for the future of agriculture as a sustainable solution that aligns with the principles of the circular economy, technological innovation, and climate change adaptation. By recovering nutrients from wastewater and reallocating them to food production, these systems contribute to closing nutrient cycles and reducing dependence on external inputs. However, current evidence indicates that FWIs remain at an intermediate level of technological maturity, with most applications being context-specific and concentrated in a limited number of geographic regions. Key challenges such as scalability, long-term performance, and adaptability to diverse climatic, environmental, and socioeconomic conditions remain insufficiently addressed. For FWIs to transition from promising site-specific solutions to widely transferable agricultural strategies, these limitations should be addressed through field-scale studies, geographically diversified research, and targeted technological development. Under such conditions, FWIs are positioned as a resilient, efficient, and climate-smart agricultural strategy, contributing to sustainability and food security in the context of global environmental change.

Conclusions

The FWIs represent a resilient and multifunctional NbS, increasingly implemented in regions vulnerable to climate change, that primarily targets environmental remediation, while food production remains a secondary and still emerging function. Although FWIs have demonstrated the capacity to cultivate diverse crops, such as leafy vegetables, cereals, and herbs, their agronomic performance is highly variable and depends heavily on crop selection and water quality. High nutrient retention efficiencies, exceeding 90% in some cases, confirm their effectiveness as combined remediation and production systems. Regardless of terminological differences, FWIs consistently deliver multiple ecosystem services (e.g., water purification, carbon sequestration, and habitat support) and provide a controlled pathway for sustainable biomass production in managed aquatic environments. However, current evidence also indicates that biomass productivity remains highly context dependent. Promising yields are often reported at pilot scale and within geographically concentrated case studies, while reproducibility and performance stability at full-scale remain limited. Moreover, food safety issues (e.g., metal and microbial accumulation) still lack standardized assessment and monitoring frameworks. Consequently, priority research lines include the development of agronomic and engineering design standards, long-term evaluation of maintenance, operation, economic viability, and integrated analysis of regulatory and social acceptance, especially when FWIs operate with contaminated or reclaimed water sources.

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Declarations

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