A CONSTRUCTION OF NATURE-BASED SOLUTION FOR WETLAND PURIFICATION WITH ANALYTIC HIERARCHY PROCESS AND FUZZY SET QUALITATIVE COMPARATIVE ANALYSIS

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Abstract. Wetland parks have been widely studied for their roles in purifying water and enhancing ecological sustainability. This study proposes a methodology from a natural and social perspective for testing water purification effects through a case study in the Daqitou wetland in Foshan, China. Innovatively, it assessed the wetland's efficiency in removing contaminants such as nitrogen and phosphorus, and in changing pH, using plants and animal experiment, expert evaluation, and fuzzy set qualitative comparative analysis (FsQCA). The results demonstrated a significant reduction in pollutants in water through the combination of flora and fauna: *Hygrophila salicifolia, Vallisneria natans, Bischofia javanica, Cipangopaludina cathayensis and Macropodus opercularis*. The findings highlight the importance of integrating wetland communities into urban planning as a nature-based solution for future environmental management.
Keywords: *wetland management, landscape, health, sustainability, great bay area*

Introduction

Wetlands are among the most important ecosystems on Earth, providing indispensable ecosystem services (regulating, provisioning, and cultural), such as flood control, water purification, climate adjustment, food supply, educational function, and recreational opportunities (Huang et al., 2024). They also offer significant economic value, with a global estimate of $26.4 trillion per year (Kundu et al., 2024). However, wetland resources are also experiencing severe degradation, such as being drained, converted, or degraded due to human activities. According to a wetland survey, since 1970, global inland, marine, and coastal wetland areas have decreased by 35%, a rate three times faster than that of forests. This decline has impacted ecological security worldwide, threatening bird habitats and carbon sequestration (Fennessy and Lei, 2018;

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RAMSAR, 2021). Especially in Asia, the developing countries like China are affected by these ecological issues. Between 2003 and 2013, the natural wetlands in China decreased by 3.37 million hectares, a 9.33% reduction, due to urban expansion, agricultural development, climate change, industrial pollution, and invasive species (Zhou et al., 2020). Many countries are actively addressing these problems. For example, the USA's "no net loss" policy requires compensation for wetland loss through restoration or creation (Fennessy and Lei, 2018). China has implemented various wetland protection policies, aiming for a protection rate of over 50%. Large-scale restoration projects are underway, including reconnecting wetlands to the Yangtze River to mitigate related disasters (Jiang et al., 2023).

Among all the strategies, Nature-based Solutions (NbS) are gaining increasing attention as effective ways to address wetland loss and other ecological issues. Involving the actions to protect, conserve, restore, and sustainably manage natural, terrestrial, freshwater, coastal, and marine ecosystems, NbS simultaneously provides social well-being, ecosystem services, resilience and so on (UN, 2022). The World Water Development Report (WWDR) highlighted the potential of NbS to address water crisis while supporting sustainable development (UN, 2018). As is seen, the benefits of Nbs are multiple: they can save costs by reducing the need for expensive gray infrastructure, reduce the intensity of climate hazards, reverse biodiversity loss, and support species conservation (IUCN, 2025). Many regions are incorporating NbS into their climate and biodiversity targets, with over 92% of countries referencing NbS in their Nationally Determined Contributions (NDCs). Constructing artificial wetlands in the form of wetland parks is a typical NbS, which can help purify polluted water bodies, create beneficial habitats, increase treatment efficiency, regulate local microclimates, control atmospheric components, and achieve the goal of carbon neutrality (Shutes, 2001; Passeport et al., 2010; Jung et al., 2014; Rajpar et al., 2022; Jiao et al., 2024).

China has been actively implementing NbS as part of its national strategy to address the challenges, to enhance water security and improve climate resilience. Aligned with the concept of Chinese Ecological Civilization (CEE), NbS have been integrated into many projects, particularly in climate change adaptation and ecological restoration (Luo et al., 2024), such as the "Sponge City Initiative," which aims to enhance resilience through permeable surfaces and wetland infrastructure (Chan et al., 2018; Guan et al., 2021). Large-scale reforestation projects, including the "Three-North Shelter Forest Program", have significantly increased Chinese forest cover, combating desertification and enhancing carbon sequestration (Zhai et al., 2023). China is also contributing to proposing unified policy frameworks to upscale NbS solutions, calling for comprehensive approaches to coordinating these policies, regulations, and financing NbS projects (Hu et al., 2020). Some activities, supported by NGOs, effectively link governments and citizens. For example, the landscape company "Pandscape" proposed the initiative "Gardening Together" during COVID-19, which encouraged the public to participate widely in local NbS practices (Hardiman et al., 2024).

However, there are still some obstacles for the implement of the NbS, such as governance structures, decision-making system, information transparency, public acceptance, and execution and maintenance (Zhang et al., 2016; Guo and Bai, 2019; Hardiman et al., 2024). Additionally, wetlands are vulnerable to external impacts, such as rainfall, rising temperatures, and other extreme weather events. Wetlands need to be designed to be resilient to these challenges, which requires a deep understanding

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of their biogeochemical processes under rapidly changing conditions. The efficiency of water purification also depends on various factors such as pollutant type, community structure, and geographic conditions. More research and projects are needed to optimize urban wetland functions for better environmental and social services (Ferreira et al., 2023; Agaton et al., 2024). Based on the discussions above, this research aims to design a comprehensive methodology for low-cost wetland construction and maintenance as NbS that combines flora and fauna experiments, expert evaluation (analytic hierarchy process, AHP), and public participation (through questionnaires) to test and improve wetland purification effects from both environmental and social perspectives.

Methodology

Study area

Foshan City, located in the south of China, is historical city with rich culture heritage and dynamic economic situations. As a key component of the Chinese Greater Bay Area (GBA) and an important economic and cultural hub in the Pearl River Delta region (one of the most populated and highly urbanized area in China), it has been actively promoting sustainable development. The city is recognized for its efforts to integrate traditional culture with modern industries while preserving ecological balance. Foshan's modern infrastructure, including transportation networks, supports its sustainability goals. The city's land use plan (2022-2035) prioritizes wetland protection. Currently, Foshan has one national wetland park and several provincial wetlands. Using landscape ecological risk assessment, Chen and Ma (2023) identified significant wetland patches and corridors in the area to enhance local ecological security. However, frequent human and agricultural activities pose ecological risks to Foshan's wetlands, such as landscape fragmentation and isolation (Cao et al., 2018).

The selected wetland park is located in Daqitou County, Foshan (113° 0' 51.65" E, 23° 16' 50.70" N), covering an area of 35,000 m² (*Fig. 1*). Named one of the "National Historical and Cultural Villages" in China, the area preserves a rare ancient residential area from the 19th century in the Pearl River Delta. It includes one provincial cultural heritage site and four municipal intangible heritage sites. The wetland is situated in the north of the county. The construction project, completed in 2016, cost nearly three million US dollars. Due to its high historical and landscape value, a landscape improvement project was undertaken, incorporating various wetland communities (*Fig. 2*).

To achieve low-cost purification for the wetland park, this research follows the IUCN Global Standard for NbSs (IUCN, 2020). The methodology includes a literature review, index selection, weight determination, purification experiments, user questionnaires, and fuzzy set qualitative comparative analysis (FsQCA). Based on previous case studies (Li and Li, 2021; Fang et al., 2021; Ždero et al., 2024) and expert opinions, a comprehensive evaluation system was developed to optimize wetland aquatic flora and fauna, identifying low-maintenance and long-lasting community combinations. The experimental process involves preparing water bodies, cultivating selected aquatic plants and animals, testing water quality indicators, and applying these to the wetland park, followed by obtaining user feedback in Daqitou County. The details of applying AHP and FsQCA are listed as below.

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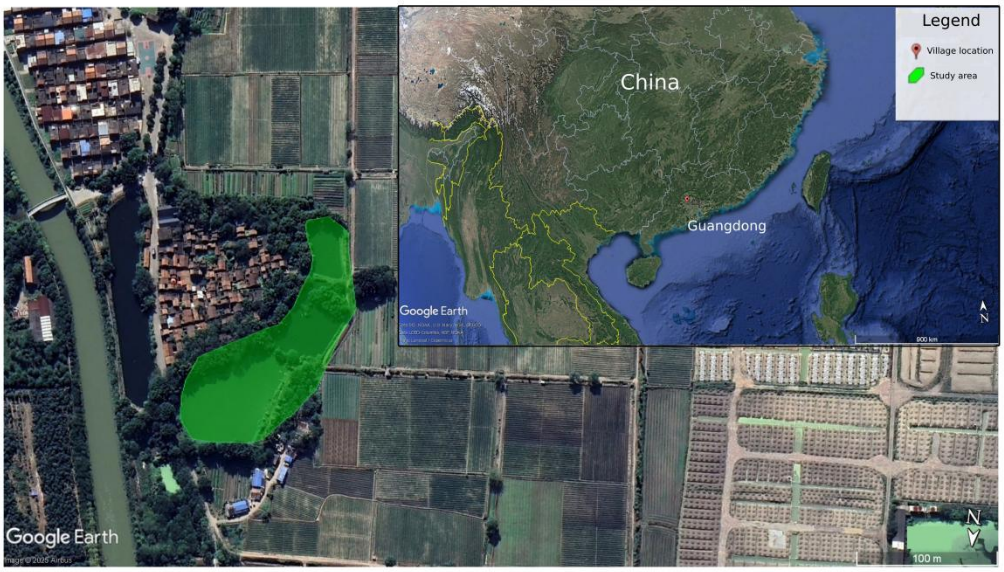

Figure 1. *Study area*

Figure 2. *Daqitou wetland. (Photo by authors)*

AHP

AHP is an effective weight calculation method used to systematically evaluate and prioritize multiple factors, leading to informed strategies. It saves time by gathering expert opinions. In this study, a hierarchical approach was used to determine the weight of selected indices through experts' opinions and comparisons. Eight experts from agriculture, landscape architecture, geography, ecology, and environmental science fields participated the survey (three full professors from the Zhongkai University of Agriculture and Engineering, three full professors from the South China Agricultural University, one professor from Guangdong Forestry Survey and Planning Institute, and one engineer from Guangdong Forestry Survey and Planning Institute). They compared the significance of each factor pairwise, assigning values according to the AHP scale (1/9, 1/7, 1/5, 1/3, 1/1, 3/1, 5/1, 7/1, and 9/1). For instance, a 1-1 value indicates equal importance, 9-1 suggests the first index is significantly more important, and 1-9 means the first index is much less

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important (Saaty, 2004). The ranking and consistency of the indices were determined using an AHP calculator (https://bpmsg.com/ahp-online-calculator/).

FsQCA

FsQCA is a method using fuzzy set theory to do qualitative comparisons. It is designed to analyze complex relationships by examining interactions among multiple factors, making it particularly useful for studying non-linear relationships and identifying configurations of conditions that lead to specific outcomes (Li et al., 2025). FsQCA has been increasingly applied in ecology and environmental science to understand the drivers of ecosystem services, analyze interactions between ecosystems and humans, and identify how different factor combinations lead to specific ecological outcomes. For example, Gao and Zhu (2024) used FsQCA to analyze the mechanisms of ecological product value realization, which requires conditions such as property rights systems, capital investment, value-added manifestation, and supply-demand matching. Liu et al. (2025) found that digital innovation is a core factor for eco-efficiency using FsQCA. According to Wang et al. (2025), the FsQCA process involves several key steps: collecting data samples, identifying cases, calibrating fuzzy sets, creating truth tables, listing all combinations of conditions, finding configurations that lead to the outcome, and interpreting the results. In this research, FsQCA was used to test the purification effect based on user understanding.

A questionnaire survey was conducted in the Daqitou Wetland in Foshan, Guangdong Province, China. Variables were selected based on discussions with experts (independent variables: C1: color, C2: ornament, C3: harmony, C4: hierarchy, C5: management cost, and C6: plant growth; the outcome measured was the purification effect). One variable (C7: health condition) was included in AHP but not included in public surveys, as the health of wetlands is difficult for the general public to evaluate. For example, respondents were asked if they felt the wetland environment quality had improved (purification effect). Questionnaires were issued using the Likert scale (1-5) to measure public perception of the wetland landscape after the improvement project, conducted from September 2024 to November 2024. Ethical standards such as anonymity, volunteerism, and academic purpose were upheld. Convenience sampling was used to survey local residents in Daqitou Village. A total of 120 questionnaires were collected, and after data cleaning and filtering (removing invalid responses such as empty or repeated answers), 102 valid questionnaires remained for analysis (an 85% validity rate). The required sample size is twice the number of variables, so the sample met this requirement (Farrugia, 2019).

Experiment

The figure out the water purification effect, three rounds of tests/experiments are included: plant measurement and selection in the sampling sites, aquatic animal experiment, and flora and fauna combination test in the lab. In the aquatic animal experiment. Four animals are included (Yan et al., 2009; Li et al., 2015; Wang et al., 2016; Zhang et al., 2020): Freshwater snail (*Cipangopaludina cathayensis*) was obtained from the wetland park (heights from 1.6 cm to 2.2 cm, lengths from 2.3 cm to 3.5 cm). Paradise fish (*Macropodus opercularis*) were collected from the wetland field (sizes 4 cm to 5 cm); Silver carp (*Hypophthalmichthys molitrix*) and mosquito fish (*Gambusia affinis*) with size of 4 cm to 5 cm were purchased from the local market (size 2 cm to 3.5 cm).

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Mosquito larvae, one of the biological index for wetland quality (Diemont, 2006), were added to each group to observe the animals' influences in the water.

The experimental water is prepared in the lab, with initial quality parameters: total nitrogen (TN: 3.78 ± 0.22 mg/L), total phosphorus (TP: 3.86 ± 0.02 mg/L), Chemical Oxygen Demand (COD: 137.43 ± 6.30 mg/L), ammonium-nitrogen (NH4 + -N: 1.413 ± 0.06 mg/L), Nitrite Nitrogen (NO2-N: 0.033 ± 0.002 mg/L), pH 7.83 ± 0.05, and color degree 152 ± 0.58 (Xu, 2005). The experimental glass bottles are 20 cm in height and 10 cm in diameter. Group 1 served as the control group (only mosquito larvae), Group 2 has paradise fish, Group 3 hads silver carp, Group 4 contains mosquito fish, and Group 5 has the freshwater snails. The experiment is conducted in the laboratory at Zhongkai University of Agriculture for 15 days, with indicators monitoring every three days. The water volume keeps constant throughout the experiment.

In the combination test, the aquatic animals include 30 freshwater snails (2.3 cm to 3.5 cm) and paradise 18 fishes (4 cm to 5 cm). The selected plants include *Hygrophila salicifolia, Vallisneria natans, and Bischofia javanica*, with 18, 36, and 12 individuals. The test device is a translucent plastic box (51 cm × 38 cm × 31 cm) containing 40 L of water. The test water is simulated eutrophic wetland park water, with initial water quality parameters as follows: TN (3.42 ± 0.20 mg/L), TP (1.72 ± 0.01 mg/L), COD (90.30 ± 1.2 mg/L), $NH4^{+}$-N (1.56 ± 0.05 mg/L), $NO2^{-}$-N (0.023 ± 0.001 mg/L), pH (8.00 ± 0.04), and color degree (135 ± 1). The authors designs two parallel groups: Group 1 (control group with only mosquito larvae) and Group 2 (combination of aquatic plants and animals). The experiment is conducted in the laboratory at Zhongkai University of Agriculture from October 2023 to November 2023 (30 days). The lab temperature ranges from 23.4°C to 27.6°C. Water quality indicators are measured every three days between 8:30 am-9:00 am. The measurement tools are shown in *Table 1*.

Table 1. *Water quality test methods*

ID	Indicator	Measuring method	Devices
1	TN	Spectrophotometry	Shengaohua SH6600
2	TP	Spectrophotometry	Shengaohua SH6600
3	$NH4^{+}$-N	Nessler's reagent colorimetric method	GDZX Power Equipment: PC-6320
4	COD	Potassium dichromate method	Yihua CODmax-II
5	$NO2^{-}$-N	Spectrophotometric method	Tiandishouhe - TDYN-230
6	pH	pH test paper	Apure GRT1120
7	Color	Colorimetric method	CHE Colorimetric Water Analysis Test Kits

At last, the data from the experiments are processed using Excel 2016 version and the Statistical Package for the Social Sciences (SPSS 26.0) to analyze the changing patterns over the experiment period. It mainly included descriptive and inferential analysis, such as mean value, change rate, t-test, and charts drawing.

Results

Site survey

To figure out the local wetland situations, random sampling method was used to select 11 wetlands in the GBA (including inland wetlands 36%, mangroves 36% and

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costal wetland 28%) (*Table 2*; *Fig. 3*). A field survey conducted from May 2023 to June 2023 identified 128 species belonging to 42 families and 83 genera. The most common wetland wild woody plants belong to the families of Moraceae, Euphorbiaceae, Myrsinaceae, Rubiaceae, Verbenaceae, Melastomataceae and Myrtaceae. In coastal areas, 28 species of wild woody plants were found, belonging to 14 families and 22 genera. Freshwater artificial wetlands in Guangdong host 37 woody plant species from 19 families and 28 genera. The use of Taxodium distichum and Salix babylonica is prevalent in Guangdong wetlands, with occurrences of 86% and 76%, respectively, followed by Glyptostrobus pensilis, Syzygium jambos and Syzygium nervosum. During fieldwork, 11 herbaceous plant samples were collected to measure their height, diameter, density, coverage rate, and growth (*Table 3*). The criteria about selecting plants were according to: low biomass (total dry matter), long growth cycle, upright and not prone to lodging based on Wang et al. (2018). After evaluating the plants and consulting with experts, the authors selected Hygrophila salicifolia, Alternanthera philoxeroides, and Hydrocotyle vulgaris for further studies. Because for low-cost NbS, local species with low growth rates are crucial parameters that influence maintenance and management costs in wetland parks (Shelef et al., 2017; Wang et al., 2018).

Table 2. *Wetland samples*

ID	Type	Longitude (E)	Latitude (N)	Elevation (m)	Area（m^2）
1	Inland	114.528050009	22.735985657	3.218	800
2	Inland	114.531590525	22.740813633	5.860	800
3	Inland	114.533382241	22.738195797	4.503	800
4	Inland	114.532931629	22.736307522	4.052	800
5	Mangrove	114.542930905	22.731543919	2.061	800
6	Mangrove	114.548402611	22.729677101	1.668	800
7	Mangrove	114.554196182	22.727767369	0.127	800
8	Mangrove	114.554566506	22.725068389	1.854	800
9	Coastal area	114.557989005	22.724338828	0.000	800
10	Coastal area	114.563954238	22.722793876	0.680	800
11	Coastal area	114.567784432	22.718888580	0.000	800

Table 3. *Plant samples*

Plants	Density (plant/m2)	Height (m^2)	Maximum H (m^2)	Coverage (%)	Dry weight underground (g/m^2)	Total dry matter (g/m^2)
1. Cyperus papyrus	5.3 ± 1.6	3.0 ± 0.6	3.5 ± 0.8	56.8 ± 11.1	1548.2 ± 204.3	1975.8 ± 224.5
2. Thalia geniculata	9.1 ± 3.3	1.3 ± 0.3	1.5 ± 0.2	37.6 ± 9.3	220.7 ± 36.8	426.3 ± 50.7
3. Scirpus trifoliatus	40.5 ± 8.9	2.2 ± 0.8	2.4 ± 0.4	56.4 ± 7.7	1548.5 ± 193.7	2577.0 ± 297.4
4. Iris tectorum	18.6 ± 0.8	1.0 ± 0.1	1.4 ± 0.4	12.6 ± 3.4	2109.0 ± 244.1	2608.2 ± 202.1
5. Typha orientalis	32.8 ± 14.6	1.8 ± 0.4	2.0 ± 0.6	36.4 ± 7.9	1204.2 ± 105.5	3341.5 ± 281.4
6. Ampelopteris prolifera	44.7 ± 22.6	0.9 ± 0.4	1.2 ± 0.2	28.3 ± 7.1	123.6 ± 3.3	158.8 ± 12.4
7. Hydrocotyle vulgaris	98.4 ± 17.9	0.4 ± 0.1	0.47 ± 0.2	64.1 ± 11.8	124.1 ± 9.0	436.6 ± 61.8
8. Eichhornia crassipes	34.7 ± 9.3	0.8 ± 0.3	0.89 ± 0.3	85.6 ± 20.7	295.3 ± 21.7	1078.0 ± 103.5
9. Alternanthera philoxeroides	92.7 ± 15.1	0.4 ± 0.09	0.47 ± 0.2	82.9 ± 15.5	86.2 ± 5.7	266.3 ± 32.7
10. Ipomoea aquatica	62.3 ± 3.6	0.4 ± 0.03	0.46 ± 0.1	83.6 ± 6.6	287.5 ± 12.2	510.9 ± 42.1
11. Hygrophila salicifolia	23.2 ± 17.2	0.9 ± 0.3	1.37 ± 0.4	91.7 ± 27.9	151.9 ± 13.8	371.0 ± 20.6

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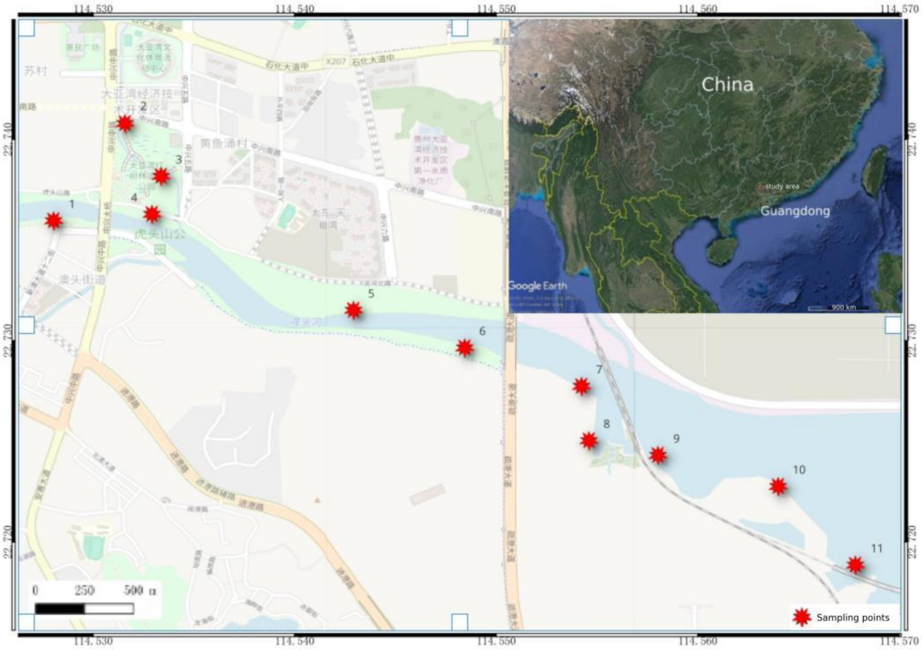

Figure 3. *Sampling points*

Index selection for plant communities

To evaluate plant combinations for water purification in wetlands, AHP method was used. Based on relevant studies and case analyses, the evaluation system included three main indicators: aesthetics (B1), growth characteristics (B2), and adaptability (B3). Each indicator was further divided into several factors for measurement (C1-C8). The related references are listed in *Table 4*.

Table 4. *Evaluation system and explanation*

Indicator	Factors	References
Aesthetics (B1)	Color (C1) Ornament (C2) Harmony (C3) Hierarchy (C4)	Zhang et al., 2022; Wang et al., 2023; Lyu et al., 2024
Growth characteristics (B2)	Management cost (C5) Growth rate (C6)	Li and Yu, 2013; Wang et al., 2018
Adaptability (B3)	Health condition (C7) Purification (C8)	Xu, 2005; Chen et al., 2019; Fang et al., 2021; Ajloon et al., 2024

Weight calculation

Using the AHP method, the importance of each indicator was measured on a 1-9 scale. After collecting expert scores, a consistency test for each constructed matrix was performed using the AHP online calculator. The hierarchical single factor weights obtained for C1-C8 were: 2.77%, 1.49%, 5.17%, 2.77%, 21.31%, 10.65%, 37.23%, and 18.61% (Consistency Ratio < 0.1) (Saaty et al., 2012). Eight experts from Guangdong

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province were also invited to evaluate the selected 12 plant communities according to the criteria explained in *Table 5*. Each community was rated on a Likert scale (1-5) to determine their suitability for a low-cost NbS wetland (Saaty et al., 2012), as is shown in *Table 6*. After weighting, the top group (*Bischofia javanica* + *Hygrophila salicifolia* + *Vallisneria natans*) was selected for further experiment (*Table 7*).

Table 5. *Scores explanation*

Factors	Explanations and scores
Color (C1)	5. Excellent: rich colors, obvious seasonal changes, appealing 4. Good: different colors can be seen also with changes in season 3. Medium: color and seasonal changes are less, with little regularity 2. Less good: less colors can be observed 1. Poor: monotonous color or too much, no obvious seasonal change
Ornament (C2)	5. Excellent: beautiful shapes, ornamental features such as flowers, fruits, leaves, and plant shapes 4. Good: shapes and features looks okay with the flowers, fruits and leaves 3. Medium: plant morphology is general, the ornamental characteristics are not strong, certain differences between species 2. Less good: the flowers, fruits, leaves are not clear to observe the ornamental features 1. Poor: No obvious differences in plant morphology, single ornamental features, little variation
Harmony (C3)	5. Excellent: balanced light and heavy configuration, natural and coordinated changes 4. Good: the light and heavy configurations look good 3. Medium: average balance of light and heavy configurations, with certain changes 2. Less good: the light and heavy configurations is not good to observe 1. Poor: unbalanced light and heavy configuration, almost no change
Hierarchy (C4)	5. Excellent: plants arranged in different heights and with a certain regularity 4. Good: plants arrangement is good 3. Medium: plants are scattered and have some variation, but not very regular 2. Less good: plants arrangement is not good to observe 1. Poor: no obvious changes in layers, no regularity
Management cost (C5)	5. High: no need extra maintenance and management cost 4. Good: less maintenance and management cost 3. Medium: normal maintenance and management requirements 2. Less good: maintenance and management cost is needed 1. Low: high maintenance and management cost
Growth rate (C6)	5. High: The growth rate is slow 4. Good: relative low growth rate 3. Medium: The growth extension is relatively suitable 2. Less good: high growth rate 1. Low: Rapid natural growth and spread
Health condition (C7)	5. Strong: no obvious diseases or insect pests 4. Good: few diseases or insect pests 3. Medium: a small amount of pests and diseases 2. Less good: some pests and diseases 1. Weak: pests and diseases have a serious impact on the community
Purification (C8)	5. Strong: strong purification ability, can effectively control weeds 4. Good: good purification ability 3. Medium: a certain purification ability and has a certain inhibitory effect on weeds 2. Less good: less purification ability 1. Weak: purification ability is not obvious and cannot inhibit the growth of weeds

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Table 6. *Plant composition*

ID	Plant composition
1	*Bischofia javanica + Hygrophila salicifolia + Vallisneria natans*
2	*Taxodium distichum + Bischofia javanica + Triadica sebifera + Erythrina variegata + Barringtonia racemosa + Rhodamnia dumetorum + Glochidion puberum + Thalia dealbata + Hydrocotyle vulgaris + Hydrilla verticillata*
3	*Rhodamnia dumetorum + Glochidion zeylanicum + Glochidion puberum + Hydrocotyle vulgaris*
4	*Rhodamnia dumetorum + Phyllanthus flexuosus + Hydrocotyle vulgaris*
5	*Kandelia obovata + Acorus gramineus + Schoenoplectus tabernaemontani + Hygrophila salicifolia*
6	*Sonneratia apetala + Kandelia obovata + Laguncularia racemosa + Acanthus ilicifolius*
7	*Glyptostrobus pensilis + Camptotheca acuminata + Glochidion puberum + Cyperus papyrus + Iris pseudacorus*
8	*Barringtonia racemosa + Echinodorus macrophyllus + Alisma plantago-aquatica + Vallisneria natans*
9	*Sonneratia apetala + Aegiceras corniculatum + Kandelia obovata + Acanthus ilicifolius + Typha orientalis + Echinodorus macrophyllus + Hydrilla verticillata*
10	*Kandelia obovata*
11	*Sonneratia apetala + Kandelia obovata + Aegiceras corniculatum + Acanthus ilicifolius*
12	*Kandelia obovata + Glochidion puberum + Acanthus ilicifolius*

Table 7. *Comprehensive scores results*

ID	C1	C2	C3	C4	C5	C6	C7	C8	Final score
1	5	5	5	5	4	4	4	5	4.31
2	5	4	5	4	4	4	4	5	4.26
3	4	3	4	3	4	3	5	4	4.22
4	4	4	4	3	3	3	5	4	4.02
5	4	3	4	3	4	4	4	4	3.95
6	4	4	3	4	4	4	4	4	3.95
7	3	3	4	3	4	4	4	3	3.74
8	4	4	4	3	4	4	3	4	3.60
9	4	4	4	3	3	4	4	3	3.57
10	4	4	4	2	2	3	4	4	3.41
11	4	3	4	2	4	4	3	3	3.37
12	2	2	3	1	4	4	3	2	3.03

FSQCA results

Following the data interpretation method (Cangialosi, 2023), the FsQCA showed both parsimonious (simple) and intermediate solutions to achieve a good purification (*Table 8*). Among all the solutions, the core factors (most frequent one in both parsimonious and intermediate results) to lead a better purification effect according to public views were the presence of management cost (C5) plants growth (C6). The condition C5*C6 also had the highest coverage (41.6%) and consistency rate (99.8%), which meant that 41.6% of memberships in the outcome explained by each term of the

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solution and the combination led to an outcome to the extent of 99.8%. Thus, basically, the public views were consistent with the experts' opinions. They both valued the variable of growth characteristics of wetland.

Table 8. *FsQCA solutions*

PARSIMONIOUS SOLUTIONS (solution coverage: 0.574; solution consistency: 0.821)			
Conditions	**Raw coverage**	**Unique coverage**	**Consistency**
C5*C6	0.416	0.13	0.998
C2*C4	0.279	0.001	0.828
C3*C4	0.278	0.001	0.891
C2*C5	0.321	0.001	0.917
C3*C5	0.313	0.002	0.947
C2*C6	0.325	0.005	0.903
~C1*~C5*C6	0.032	0.001	0.926
INTERMEDIATE SOLUTIONS (solution coverage: 0.535; solution consistency: 0.989)			
Conditions	**Raw coverage**	**Unique coverage**	**Consistency**
C1*C4*C5*C6	0.322	0.152	0.998
C1*~C2*~C3*C5*C6	0.135	0.049	0.995
C1*C2*C3*C5*C6	0.129	0.031	0.999
C2*C3*C4*C5*C6	0.193	0.098	0.980
~C1*~C2*~C3*~C4*~C5*C6	0.031	0.031	0.960

Aquatic animal selection

The results (*Table 9*) showed that the survival rates of the four aquatic animals in eutrophic water bodies varied, significantly impacting water quality. All silver carp and mosquito fish died by the end of the experiment, while individuals in the paradise fish and freshwater snail groups survived. As the silver carp and mosquito fish groups gradually died, the values of TN, TP, and $NH4^{+}$-N in the water increased rapidly. At the end of the experiment, TN and $NH4^{+}$-N levels were 16.37-18.35 mg/L and 17.19-19.65 mg/L, respectively, higher than the initial values. However, the dead bodies may release nutrients, which can cause some measurement errors. Mosquito larvae were still present in the control group and the freshwater snail group, indicating that freshwater snails do not effectively remove mosquito larvae. However, freshwater snails were effective in reducing the pH and color of the water and had a good removal effect on COD (removal rate of 36.5%). In both the silver carp and mosquito fish groups, the larvae died during the experiment. Paradise fish demonstrated strong adaptability to sewage and effectively removed mosquito larvae from the water. They also significantly reduced TP, COD, and NH4 + -N, with removal rates of 15.5%, 37%, and 40.8%, respectively. Based on the experiment results, paradise fish and freshwater snails were selected for further community research due to their good cleaning rates.

Flora and fauna combination

In a wetland system, aquatic plants provide food for aquatic animals, while the excrement or corpses of these animals serve as fertilizer for the plants. Biological interactions between animals, plants, and benthic compartments can positively affect water

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quality (Taguchi and Nakata, 2009). Previous studies have shown that healthy aquatic communities are better able to resist external disturbances, such as pollution and climate change, thereby maintaining water quality stability. In some restoration projects, artificially constructed communities, like ecological floating islands, have been widely used. These islands utilize the absorption and microbial degradation capabilities of aquatic plants to effectively improve eutrophic water bodies (Yao et al., 2011). To test a better combination of aquatic plants and animals in the Greater Bay Area, China, this research conducted an experiment with the selected plants and animals from previous steps.

Table 9. *Indicator changes*

Type	**TN change (mg/L)**				
	3 d	**6 d**	**9 d**	**12 d**	**15 d**
Group 1: Control group	2.740 ± 0.08	2.515 ± 0.03	2.982 ± 0.15d	2.402 ± 0.08	2.708 ± 0.05
Group 2: Paradise fish	3.761 ± 0.16	5.683 ± 0.02	6.673 ± 0.11c	7.029 ± 0.09	7.588 ± 0.09
Group 3: Silver Carp	4.654 ± 0.19	10.065 ± 0.29	12.430 ± 0.19	20.438 ± 1.42	20.150 ± 1.19
Group 4: Mosquito fish	13.601 ± 1.04	18.864 ± 1.39	22.761 ± 0.84	25.420 ± 0.93	22.133 ± 0.47
Group 5: Freshwater snail	3.427 ± 0.06	4.876 ± 0.04	6.208 ± 0.24	6.613 ± 0.14	7.185 ± 0.18
Type	**TP change (mg/L)**				
	3 d	**6 d**	**9 d**	**12 d**	**15 d**
Group 1: Control group	4.549 ± 0.17	4.573 ± 0.09	4.641 ± 0.11	4.997 ± 0.11	4.659 ± 0.10
Group 2: Paradise fish	4.472 ± 0.03	4.555 ± 0.07	3.555 ± 0.15	3.389 ± 0.12	3.260 ± 0.16
Group 3: Silver Carp	4.403 ± 0.12	4.997 ± 0.12	4.616 ± 0.08	4.987 ± 0.04	5.876 ± 0.07
Group 4: Mosquito fish	5.297 ± 0.05	5.971 ± 0.03	6.339 ± 0.02	6.437 ± 0.14	6.321 ± 0.15
Group 5: Freshwater snail	4.567 ± 0.07	4.975 ± 0.03	4.038 ± 0.11	3.818 ± 0.12	3.742 ± 0.03
Type	**COD change (mg/L)**				
	3 d	**6 d**	**9 d**	**12 d**	**15 d**
Group 1: Control group	114.40 ± 1.50	100.81 ± 1.48	105.80 ± 0.87	112.93 ± 3.07	105.37 ± 1.46
Group 2: Paradise fish	113.90 ± 0.87	103.30 ± 2.29	81.76 ± 1.36	80.23 ± 2.28	86.61 ± 0.77
Group 3: Silver Carp	124.40 ± 5.68	108.50 ± 1.80	102.31 ± 1.51	121.70 ± 3.34	138.40 ± 2.05
Group 4: Mosquito fish	120.63 ± 2.19	125.93 ± 2.55	131.27 ± 2.07	123.20 ± 1.06	119.70 ± 0.75
Group 5: Freshwater snail	115.15 ± 3.75	114.40 ± 1.50	96.19 ± 1.46	91.52 ± 0.92	87.23 ± 0.43
Type	**NH_4^+-N change (mg/L)**				
	3 d	**6 d**	**9 d**	**12 d**	**15 d**
Group 1: Control group	1.547 ± 0.11	1.424 ± 0.01	1.185 ± 0.10	1.092 ± 0.03	1.068 ± 0.01
Group 2: Paradise fish	2.548 ± 0.08	4.122 ± 0.12	3.295 ± 0.03	0.863 ± 0.14	0.837 ± 0.13
Group 3: Silver Carp	4.678 ± 0.16	8.178 ± 0.38	9.980 ± 0.34	13.215 ± 1.09	18.328 ± 1.08
Group 4: Mosquito fish	9.453 ± 0.70	18.662 ± 1.89	22.448 ± 2.17	21.445 ± 1.75	21.063 ± 1.79
Group 5: Freshwater snail	2.265 ± 0.05	3.584 ± 0.13	3.745 ± 0.02	3.251 ± 0.08	2.513 ± 0.11
Type	**NO_2^--N change (mg/L)**				
	3 d	**6 d**	**9 d**	**12 d**	**15 d**
Group 1: Control group	0.025 ± 0.003	0.039 ± 0.001	0.045 ± 0.003	0.033 ± 0.001	0.022 ± 0.004
Group 2: Paradise fish	0.022 ± 0.002	0.050 ± 0.012	1.153 ± 0.072	1.408 ± 0.002	1.328 ± 0.010
Group 3: Silver Carp	0.027 ± 0.001	0.029 ± 0.002	0.040 ± 0.001	0.044 ± 0.002	0.028 ± 0.003
Group 4: Mosquito fish	0.037 ± 0.014	0.042 ± 0.005	0.029 ± 0.003	0.074 ± 0.006	1.215 ± 0.166
Group 5: Freshwater snail	0.020 ± 0.002	0.078 ± 0.003	0.320 ± 0.007	0.667 ± 0.097	0.785 ± 0.058
Type	**pH Changes**				
	3 d	**6 d**	**9 d**	**12 d**	**15 d**
Group 1: Control group	7.97 ± 0.06	8.10 ± 0.10	8.13 ± 0.06	8.20 ± 0.10	8.40 ± 0.10
Group 2: Paradise fish	7.63 ± 0.06	7.50 ± 0.10	8.20 ± 0.10	8.10 ± 0.10	7.53 ± 0.06
Group 3: Silver Carp	7.70 ± 0.10	7.63 ± 0.06	7.63 ± 0.06	7.80 ± 0.10	7.90 ± 0.10
Group 4: Mosquito fish	7.70 ± 0.10	7.53 ± 0.06	7.67 ± 0.06	7.77 ± 0.06	7.97 ± 0.15
Group 5: Freshwater snail	7.76 ± 0.06	7.53 ± 0.06	7.43 ± 0.06	7.40 ± 0.10	7.40 ± 0.10
Type	**Color change (degrees)**				
	3 d	**6 d**	**9 d**	**12 d**	**15 d**
Group 1: Control group	136 ± 1.53	137 ± 1.15	135 ± 1.53	133 ± 5.69	130 ± 4.04
Group 2: Paradise fish	135 ± 0.58	137 ± 3.06	132 ± 1.53	127 ± 1.00	124 ± 1.53
Group 3: Silver Carp	146 ± 1.00	146 ± 0.58	136 ± 3.00	146 ± 3.06	154 ± 2.52
Group 4: Mosquito fish	162 ± 1.53	165 ± 4.00	146 ± 3.06	144 ± 5.29	133 ± 3.51
Group 5: Freshwater snail	134 ± 2.52	134 ± 1.53	132 ± 1.00b	127 ± 4.16	123 ± 2.00

During the experiment, the paradise fish thrived, primarily consuming waste and mosquito larvae, with a survival rate of about 93.4%. The water became more transparent. The snails also grew well, with a survival rate of 95%. The three aquatic plants had a 100% survival rate, with a root growth from 5-6 cm to 15-16 cm, especially in *Vallisneria natans* (*Figs. 4-5*). The water quality changes are shown in *Fig. 6a-g*. The results indicated that the combined effect of aquatic plants and animals was superior to that of single species. *Vallisneria natans* effectively intercepted floating dust and absorbed phosphorus from the water. *Bischofia javanica and Hygrophila salicifolia* were capable of degrading nitrogen and phosphorus. Compared to the control group, the combined treatment significantly removed nutrients such as TN, TP, and COD from the water, meeting the requirements for industrial water use or higher standard.

Observations also revealed that the paradise fish consumed approximately 40 mosquito larvae within the initial 10 min (*Fig. 7a-f*). Compared to the control group, paradise fish played a significant role in controlling mosquitoes in eutrophic water. The freshwater snail fed on organic detritus and algae in the water. Through its metabolic processes, the snail can increase the concentration of nutrients in the water, which can promote plant growth to some extent.

Figure 4. *Root of Vallisneria natans*

Figure 5. *Roots of Vallisneria natans grow in soil*

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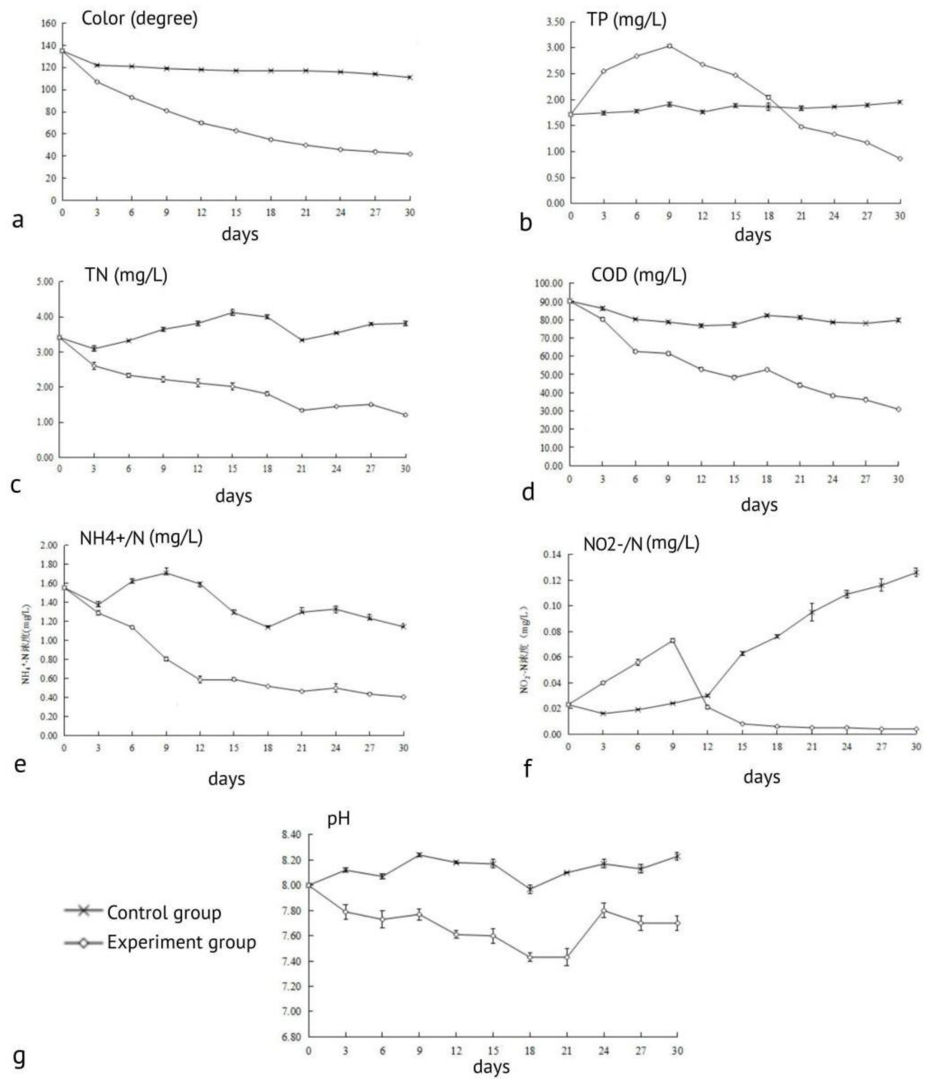

Figure 6. *Parameter changes*

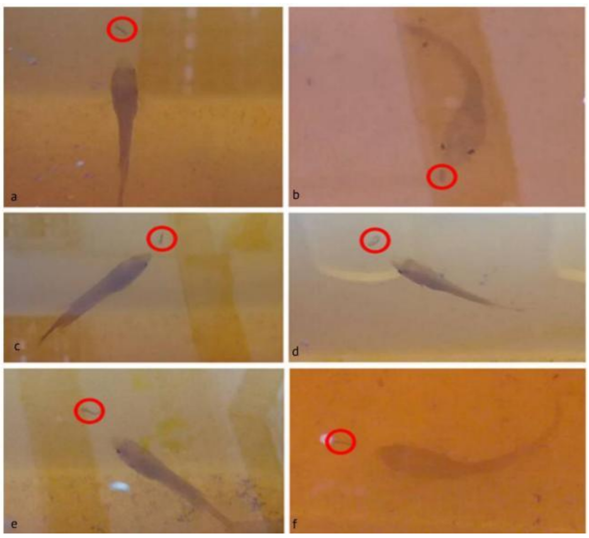

Figure 7. *Paradise fish in the water*

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By SPSS, the t-test was run to compare the means of changes in quantity (0-3 d, 3 d-6 d, 6 d-9 d, 9 d-12 d, 12 d-15 d, 15-18 d, 18-21 d, 21-24 d, 24-27 d, 27-30 d) between the experimental group with control group. The result (*Table 10*) showed that experiment groups (TN, COD, and color) had a significant difference with the control group. But for TP, NH_4^+ -N, NO_2^- -N, and pH, there was not a significant difference between the experiment group and the control group. However, an insignificant value does not mean no effect of the experiment group. Comparing the initial value with the end value, the authors observed clear changes: the change rate in TP experiment group was -51.2%, comparing with 14.6% in the control group; for NH_4^+-N, the change rate were -65.1% and 24.0% in experiment group and control group; for NO_2^- -N, the change rate were -0.52 and 454% in experiment group and control group; for pH, the change rate were -2.5% and 1.2%, respectively.

Table 10. *T-test for comparing experiment group with control group*

Type	Days	Changes in control group	Changes in experiment group
TN (mg/L)	0-3	-0.21	-0.81
	3-6	0.22	-0.3
	6-9	0.22	-0.1
	9-12	0.19	-0.13
	12-15	0.18	-0.06
	15-18	-0.11	-0.07
	18-21	-0.56	-0.52
	21-24	0.26	0.07
	24-27	0.1	0.02
	27-30	-0.01	-0.15
P-value			0.008**
TP (mg/L)	0-3	0.01	0.78
	3-6	0.01	0.2
	6-9	0.11	0.28
	9-12	-0.1	-0.42
	12-15	0.09	-0.13
	15-18	-0.03	-0.41
	18-21	0.01	-0.6
	21-24	0.03	-0.02
	24-27	0.04	-0.04
	27-30	0.07	-0.44
P-value			0.439
COD (mg/L)	0-3	-1.1	-10.2
	3-6	-6.0	-17.8
	6-9	-3.0	-1.1
	9-12	-0.7	-8.5
	12-15	1.0	-2.9
	15-18	7.1	3.8
	18-21	-1.1	-4.8
	21-24	-5.9	-6.6
	24-27	-0.5	-1.0
	27-30	1.10	-2.4
P-value			0.011**

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Type	Days	Changes in control group	Changes in experiment group
NH_4^+-N (mg/L)	0-3	-0.15	-0.29
	3-6	0.21	-0.12
	6-9	0.07	-0.26
	9-12	-0.08	-0.34
	12-15	-0.25	0.03
	15-18	-0.17	-0.06
	18-21	0.17	-0.04
	21-24	0.05	0.02
	24-27	-0.07	-0.05
	27-30	-0.06	-0.05
P-value			0.200
NO_2^--N (mg/L)	0-3	-0.004	0.018
	3-6	0.004	0.012
	6-9	0.001	0.024
	9-12	0.003	-0.059
	12-15	0.038	0.005
	15-18	0.011	-0.002
	18-21	0.009	-0.009
	21-24	0.028	-0.001
	24-27	0.005	0.000
	27-30	0.005	-0.001
P-value			0.204
pH	0-3	0.12	-0.20
	3-6	-0.01	-0.02
	6-9	0.1.0	0.02
	9-12	-0.02	-0.05
	12-15	-0.01	-0.29
	15-18	-0.20	0.01
	18-21	0.13	0.36
	21-24	0.07	-0.03
	24-27	-0.07	-0.04
	27-30	0.14	0.01
P-value			0.420
Color (degree)	0-3	-14.0	-26.0
	3-6	0.0	-18.0
	6-9	-1.0	9.0
	9-12	0.0	-15.0
	12-15	0.0	-17.0
	15-18	0.0	-9.0
	18-21	0.0	1.0
	21-24	0.0	-6.0
	24-27	-1.0	-4.0
	27-30	-1.0	-2.0
P-value			0.035**

**$P < 0.05$

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Discussion

Wetland and NbS

Wetlands are vital ecosystems with frequent energy and material exchanges, high biodiversity, and abundance. They provide important habitats for many birds, fish, and other wildlife, and have significant ecological, social, and economic value. However, the rapid expansion of urban construction in recent years has greatly reduced wetland areas. Industrial wastewater, urban sewage, and agricultural pollution have increased harmful pollutants in wetlands, degrading their natural purification functions. Additionally, invasive plants like *Mikania micrantha and Spartina alterniflora*, along with frequent pest outbreaks such as mosquitoes, pose significant challenges to wetland protection and ecosystem health.

Ecological restoration is urgently needed in urban areas like the GBA. NbS offer new theoretical guidance for wetland restoration and management by addressing multiple goals and interests. Wetland parks are an important form of NbS for wetland protection. This paper uses the Daqitou wetland park as a case study to explore wetland ecological restoration technology based on NbS, addressing local challenges in the GBA and proposing valuable technical means for wetland restoration. These actions are crucial for practicing ecological civilization and creating healthy communities with integrated natural landscapes.

In this research both expert opinions and public views were collected to evaluate the selection of wetland communities. Experts identified management cost, growth rate, health condition, and purification capacity as the most important factors. The FsQCA of public views showed similar results, with management cost and growth rate being core factors. Management cost is a key consideration for resource allocation and long-term viability, while a lower growth rate can reduce maintenance costs by limiting the expansion of wetland ecosystems. This research provides valuable insights into wetland community selection, highlighting the need for a comprehensive and balanced approach to wetland management and conservation. By considering cost-effectiveness, ecological quality, and enhancing public awareness and participation, future projects can better protect and sustain wetland ecosystems for future generations.

Based on AHP and FsQCA, a set of key processes for long-lasting purification and low-maintenance ecological wetland water restoration using aquatic plants and animals was proposed. This technology balances landscape value and maintenance needs, addressing issues such as high costs, poor purification efficiency, and lack of landscape characteristics in current water restoration projects. The multi-dimensional wetland water purification technology includes a comprehensive configuration of aquatic herbs, terrestrial woody plants, and aquatic animals. By utilizing specific plant communities (*Hygrophila salicifolia, Vallisneria natans, and Bischofia javanica*) and a combination of animals (*Cipangopaludina cathayensis and Macropodus opercularis*) to remove pollutants like TN, TP, and COD from eutrophic water bodies, the purification effect was clear.

Comparisons

Different combinations of communities show significant differences in water purification effects. Compared with previous studies, Zhao et al. (2021) found that *Hydrilla verticillata, Nymphaea, Viviparus malleatus, and Hypophthalmichthys molitrix* has shown good purification effects on eutrophic water bodies. The removal rates of TN and TP in the eutrophic group were 51.3% and 80.7%, respectively. The proposed

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system in our research showed better removal effects on TN but weaker effects on TP. This may be due to the individual deaths of paradise fish during the experiment, which led to an increase in TP concentration in the water due to the release of nutrients from their decomposing bodies. However, other water quality indicators still met the required standards.

Another study by Wang et al. (2013) used a combination of *Viviparus malleatus, Hypophthalmichthys molitrix, Myriophyllum spicatum, and Macrobrachium nipponense* in an experiment. The results showed that this combination failed to reduce TP concentration, also led to a slight increase of it. The purification effects on TN, TP, and COD were not significant, with concentrations decreasing from 1.92 mg/L, 9.47 mg/L, and 0.43 mg/L to 1.47 mg/L, 8.49 mg/L, and 0.42 mg/L. This indicated that the purification capacity of this combination was weak and not suitable for practices. Thus, the combination of aquatic plants and animals used in this study demonstrated significant purification effects to a certain extent compared to other studies.

Limitation and future research

The limitation of this research first lies in limited number of tested communities. According to FsQCA and AHP, only the top group was used for an experiment. Future research could delve deeper into more specific combinations of wetland communities that are most cost-effective in boosting purification performance. And investigating the particular species (animals, plants, and microorganisms) that contribute most significantly to pollutant removal could provide targeted strategies for wetland vegetation management (Xu et al., 2024). Then, in the experiment, there were some measurement errors that should be further considered, such as the dead body of animals. For example, Wenger et al. (2019) studied that bones and shells can provide TP in the water. Further research will be done to clean the dead animals during the experiment. Besides, economic index was not included in this research. For a more comprehensive study, more economic indexes for measuring wetland purification can be involved, such as energy utilization efficiency, etc. (Zhu et al., 2024). Understanding these will further refine our ability to design and maintain better wetlands that maximize ecological benefits.

Conclusion

Theoretically, this research reinforces the concept of wetlands as natural bioreactors, efficiently processing and reducing urban pollutants. It extends existing research by demonstrating the effectiveness of wetland parks through a combination of selected flora and fauna. Practically, the study provides empirical evidence for urban planners and environmental agencies in the Chinese GBA to prioritize the development and conservation of wetland parks. Implementing such green infrastructures can be a cost-effective strategy for water purification, aligning with Chinese broader goals of sustainable urbanization and ecological civilization. In conclusion, the selected communities from Daqitou Wetland, China significantly enhances its water quality by effectively removing pollutants. This underscores the role of wetland park in ecological sustainability and pollution mitigation. It highlights the necessity of integrating natural communities into urban environments to address the challenges of water pollution. Future research could explore long-term performance monitoring and the impact of different plant species on purification efficiency to enrich urban living, pave the way for healthier, more resilient cities.

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