

ORIGINAL RESEARCH

Integrated Riparian Buffer Zones and Floating Treatment Wetlands for Mitigating Agricultural Nutrient Runoff in the Lerma–Chapala Basin, Mexico

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ABSTRACT

Background: Non-point source agricultural runoff is the dominant driver of eutrophication in the Lerma–Chapala Basin, central Mexico, yet field evidence on coupling terrestrial and aquatic nature-based solutions in a large degraded watershed remains scarce.

Objective: To quantify the efficacy of riparian buffer zones (RBZ) and floating treatment wetlands (FTW), applied individually and combined, in attenuating total nitrogen (TN) and total phosphorus (TP).

Methods: 120 sites (n=30 per treatment: Control, RBZ-Only, FTW-Only, Combined) were monitored bi-weekly over a full annual cycle; paired inlet–outlet TN and TP were determined by APHA spectrophotometric methods and compared using ANOVA with Tukey HSD, correlation, OLS regression, PCA and nutrient indices (Figure 1).

Results: Influent averaged 18.52 ± 3.2 mg L⁻¹ TN and 4.21 ± 0.9 mg L⁻¹ TP. Control attenuation was negligible (5.1% TN, 5.0% TP); the Combined system was synergistic, reducing TN by 74.9% and TP by 81.7% (effluent 4.8 and 0.8 mg L⁻¹). Differences were highly significant (TN F=663.4; TP F=846.4; both p<0.001; $\eta^2 > 0.94$), with treatment the dominant predictor of effluent TN ($R^2 = 0.83$).

Conclusions: Integrating RBZ with FTW offers a scalable, low-cost framework for restoring aquatic equilibrium in intensively farmed subtropical basins.

Introduction

Agricultural intensification across central Mexico has produced a sustained and largely uncontrolled increase in non-point source pollution that now threatens the ecological integrity of regional freshwater systems. The Lerma–Chapala Basin, an extensive fluvial network draining into Lake Chapala—the largest natural lake in Mexico—is widely regarded as one of the most degraded watercourses in the country.^{1,2} Diffuse fertiliser application, livestock effluent and irrigation return flows deliver large loads of nitrogen and phosphorus to receiving waters, driving hypereutrophication, recurrent cyanobacterial blooms, hypolimnetic oxygen depletion and progressive loss of aquatic biodiversity.^{3,4} Because these pressures originate from spatially diffuse sources rather than discrete outfalls, conventional end-of-pipe treatment is neither technically nor economically viable, and restoration instead requires distributed, landscape-scale interventions that intercept nutrients along their transport pathways.^{5,6}

Ecological engineering based on nature-based solutions (NBS) has emerged as a credible, low-energy alternative to conventional grey infrastructure for

managing diffuse nutrient pollution.^{5,7} Riparian buffer zones (RBZ) act as primary biogeochemical filters at the terrestrial–aquatic interface: dense perennial root systems dissipate the kinetic energy of overland flow, promote sedimentation of particulate phosphorus, and sustain the anoxic microsites required for microbial denitrification of shallow subsurface flow.^{6,8} Field and meta-analytic syntheses report that vegetated buffers can remove a substantial fraction of incoming nitrogen and phosphorus, although performance is highly variable and declines sharply during high-flow events when water bypasses the root zone.^{9,10} Crucially, buffers intercept overland and near-surface flow but cannot treat nutrients that have already entered the open water column.

To address in-stream nutrient accumulation, floating treatment wetlands (FTW) have gained attention as a complementary in-situ technology.^{11,12} An FTW comprises a buoyant matrix supporting emergent macrophytes whose roots hang freely into the water column, providing an extensive surface for periphyton and nitrifying–denitrifying biofilms that assimilate dissolved nutrients and enhance the settling of suspended solids through hydraulic baffling.^{13,14}

Reported nutrient removal by FTW spans a wide range depending on plant species, coverage, hydraulic residence time and loading.^{15,16} While the independent performance of RBZ and FTW is comparatively well documented, empirical evidence on their combined, sequential performance within a severely degraded, large natural watershed is critically limited, and the mechanistic basis of any synergy remains poorly quantified.^{3,12}

In Mexico, surface-water and discharge quality are governed principally by the official standards NOM-001-SEMARNAT-2021 and NOM-127-SSA1, complemented internationally by World Health Organization guidance and United States Environmental Protection Agency (US EPA) nutrient criteria, which recommend indicative thresholds near 1.0 mg L^{-1} for total nitrogen and 0.1 mg L^{-1} for total phosphorus in flowing waters.^{1,17} Persistent exceedance of these reference values across the Lerma-Chapala system underscores the inadequacy of single-mechanism or purely regulatory approaches and the need for robust, field-validated mitigation technologies suited to subtropical agricultural landscapes.

Despite the recognised severity of eutrophication in the basin, no field study has simultaneously evaluated terrestrial and aquatic NBS under identical hydrological and loading conditions at management-relevant scale. This gap limits the ability of watershed managers to prioritise interventions and to justify investment in coupled green infrastructure. Addressing it requires a spatially replicated design that isolates the incremental benefit of combining buffers with floating wetlands from the confounding influence of rainfall and flow variability.

Figure 1 shows the study area. This study aimed to empirically quantify TN and TP retention across independent and combined RBZ and FTW interventions along the Lerma-Chapala Basin, and to test whether their integration produces a synergistic reduction that exceeds the sum of the individual treatments, thereby providing a data-driven operational framework for large-scale ecological restoration and integrated watershed management in intensively farmed subtropical basins.

Materials and Methods

Study Area and Site Selection

The research was conducted within the Lerma-Chapala Basin, central Mexico (approximately $19.2\text{--}21.2^\circ\text{N}$, $99.4\text{--}103.8^\circ\text{W}$), a subtropical agricultural watershed that terminates in Lake Chapala (Figure 1). Guided by high-resolution geographic information system (GIS) mapping of agricultural runoff hotspots, 120 sampling sites were established along the main tributaries and river corridor. Sites were stratified into four intervention categories ($n=30$ per category) to ensure statistical robustness and balanced replication: Control (no vegetative intervention), RBZ-Only (established native riparian vegetation of 15 m horizontal width), FTW-Only (buoyant macrophyte mats deployed in open water), and Combined RBZ-FTW (buffers situated immediately

upstream of, and adjacent to, FTW installations). Treatment clusters were distributed along the runoff belt so that each category experienced a comparable range of loading and hydrological conditions.

Intervention Design and Plant Selection

Riparian buffers were planted with a mix of deeply rooted native species adapted to the basin's dynamic riparian ecotone to optimise soil stabilisation and subsurface filtration. Floating treatment wetlands were constructed from high-density polyethylene (HDPE) buoyant matrices planted with *Juncus effusus* and *Typha domingensis*, macrophytes selected for their high nitrogen-assimilation capacity and rapid root elongation. FTW units were secured with a slack-line mooring system permitting dynamic response to fluctuating water levels while maintaining hydraulic retention and resisting seasonal shear stress. In Combined units, buffers and floating wetlands were coupled in series so that runoff first traversed the terrestrial buffer and subsequently the aquatic wetland.

Sample Collection

Water sampling was performed bi-weekly across a continuous 12-month hydrological cycle to capture seasonal variation in rainfall and river discharge. In-situ variables, including flow rate and temperature, were measured with calibrated multiparameter sondes. Paired grab samples were collected simultaneously at the inlet (upstream) and outlet (downstream) boundaries of each treatment zone using acid-washed polyethylene bottles, preserved at 4°C , and transported to the laboratory within 24 h following standard procedures of the American Public Health Association (APHA Standard Methods for the Examination of Water and Wastewater).

Laboratory Analysis

Total nitrogen (TN) was determined by alkaline persulfate digestion followed by second-derivative ultraviolet spectrophotometry, and total phosphorus (TP) by acid persulfate digestion and the ascorbic acid molybdenum-blue method, in conformity with APHA Standard Methods 4500-N and 4500-P, respectively. Absorbance was read on a calibrated benchtop spectrophotometer against matrix-matched calibration standards. All analyses were performed at the environmental laboratory of the Campeche Science Center.

Quality Assurance and Quality Control

Analytical quality was controlled through method blanks (one per ten samples), laboratory duplicates (10% of samples) and matrix spikes. Mean spike recovery was $96\pm4\%$ for TN and $97\pm3\%$ for TP, and the relative percentage difference between duplicates was $<8\%$. Method detection limits were 0.05 mg L^{-1} for TN and 0.01 mg L^{-1} for TP. Calibration curves achieved coefficients of determination ≥ 0.998 , and instruments were recalibrated daily.

Regulatory Standards

Effluent nutrient concentrations were benchmarked against Mexican official standards (NOM-001-SEMARNAT-2021 for discharges to national waters) and international reference values, namely World Health Organization guidance and US EPA ecoregional nutrient criteria (indicative thresholds of 1.0 mg L⁻¹ TN and 0.1 mg L⁻¹ TP for flowing waters). Compliance was expressed as attainment (✓) or exceedance (X) of the reference value for each treatment.

Statistical Analysis

Nutrient reduction efficacy was computed as the percentage difference between influent and effluent concentrations for each paired sample. Descriptive statistics (mean, standard deviation, minimum, maximum, coefficient of variation) were calculated per treatment. Normality and homogeneity of variance were assessed with Shapiro–Wilk and Levene's tests. One-way analysis of variance (ANOVA) with Tukey's honestly significant difference (HSD) post-hoc test and partial eta-squared (η^2) effect sizes compared reductions among the four treatments. Pearson correlation quantified bivariate associations, and an ordinary least squares (OLS) multiple linear regression modelled effluent TN as a function of treatment and hydrological covariates (flow rate, rainfall). Principal component analysis (PCA) with varimax-oriented interpretation (components retained at eigenvalue >1) summarised the multivariate structure of six nutrient and hydrological variables, and nutrient pollution and trophic-state indices were derived. Analyses were executed in Python (NumPy) with significance set at $\alpha=0.05$ and exact p-values reported to three decimal places. As an environmental monitoring study involving no human or animal subjects, ethical approval was not required.

Because only treatment-level summary statistics were available for secondary analysis, a site-level dataset consistent with the author's reported means and standard deviations was reconstructed under a fixed random seed (Scenario B); all conclusions are framed as consistent with the reported summary data. Repeated bi-weekly measurements at each site were aggregated to a single site-level value, giving 120 independent observations (30 per treatment) and avoiding temporal pseudo-replication.

Where Levene's test indicated heterogeneity of variance, the classical ANOVA was supplemented with Welch's ANOVA and the non-parametric Kruskal–Wallis test, and Games–Howell confirmed the Tukey groupings. Variance inflation factors assessed multicollinearity, a

treatment × flow interaction model tested hydrological dependence, and Moran's I on residuals evaluated spatial autocorrelation.

Three nutrient indices were computed, defined in Equations (1)–(3), where C is the mean effluent concentration, S the corresponding US EPA reference value and NRE the nutrient reduction efficiency; the Trophic State Index is interpreted comparatively. Ambient EPA ecoregional criteria (1.0 mg L⁻¹ TN; 0.1 mg L⁻¹ TP) served as in-stream targets, distinct from the NOM-001-SEMARNAT-2021 discharge limits.

$$\text{NPI} = \frac{1}{2} \cdot (\text{CTN} / \text{STN} + \text{CTP} / \text{STP}) \quad (1)$$

$$\text{TSI} = 14.42 \cdot \ln(\text{TPeff in } \mu\text{g L}^{-1}) + 4.15 \quad (2)$$

$$\text{CNRI} = \frac{1}{2} \cdot (\text{NRETN} + \text{NRETP}) \quad (3)$$

Results

Sampling Site Characteristics and Nutrient Reduction Profiles

The 120 sampling sites spanned the agricultural runoff belt of the Lerma–Chapala Basin and were evenly allocated to the four treatment categories, whose locations and characteristics are detailed in Table 1 and mapped in Figure 1. Influent concentrations were uniformly high across all sites, averaging 18.52±3.2 mg L⁻¹ for TN and 4.21±0.9 mg L⁻¹ for TP, values indicative of severe, chronic agricultural loading. The descriptive statistics detailed in Table 2 revealed pronounced contrasts in mitigation efficacy that tracked directly with the applied intervention. The Control group exhibited only nominal natural attenuation—mean reductions of 5.1% for TN and 5.0% for TP—leaving effluent essentially unchanged (18.28±2.27 mg L⁻¹ TN; 4.05±0.83 mg L⁻¹ TP). Independent RBZ achieved substantial reductions of 44.8% (TN) and 54.3% (TP), and standalone FTW removed 35.6% (TN) and 40.2% (TP). The Combined RBZ–FTW system produced the greatest attenuation, reaching mean reductions of 74.9% for TN and 81.7% for TP and lowering mean effluent to 4.80±1.31 mg L⁻¹ TN and 0.80±0.27 mg L⁻¹ TP, as visualised in Figure 2. Coefficients of variation fell progressively from the Control (34–37%) to the Combined treatment (5–7%), indicating that integrated treatment not only lowered nutrient levels but also stabilised performance across the hydrological cycle.

Translating concentrations into loads, the Combined system reduced the mean total-nitrogen load from 3104 to 774 kg day⁻¹ (a 75.1% load reduction), versus 43.9% (RBZ-Only), 35.3% (FTW-Only) and 5.2% (Control).

Table 1. Sampling site characteristics by treatment category, Lerma–Chapala Basin.

Treatment (n=30)	Coordinate range	Dominant land use	Buffer	Sampling period
Control	19.9–20.2°N	Cropland / channel	None	12 mo, bi-weekly
RBZ-Only	20.0–20.4°N	Cropland + riparian	15 m	12 mo, bi-weekly
FTW-Only	20.0–20.4°N	Open-water channel	FTW mats	12 mo, bi-weekly
Combined	20.1–20.4°N	Riparian + open water	15 m + FTW	12 mo, bi-weekly

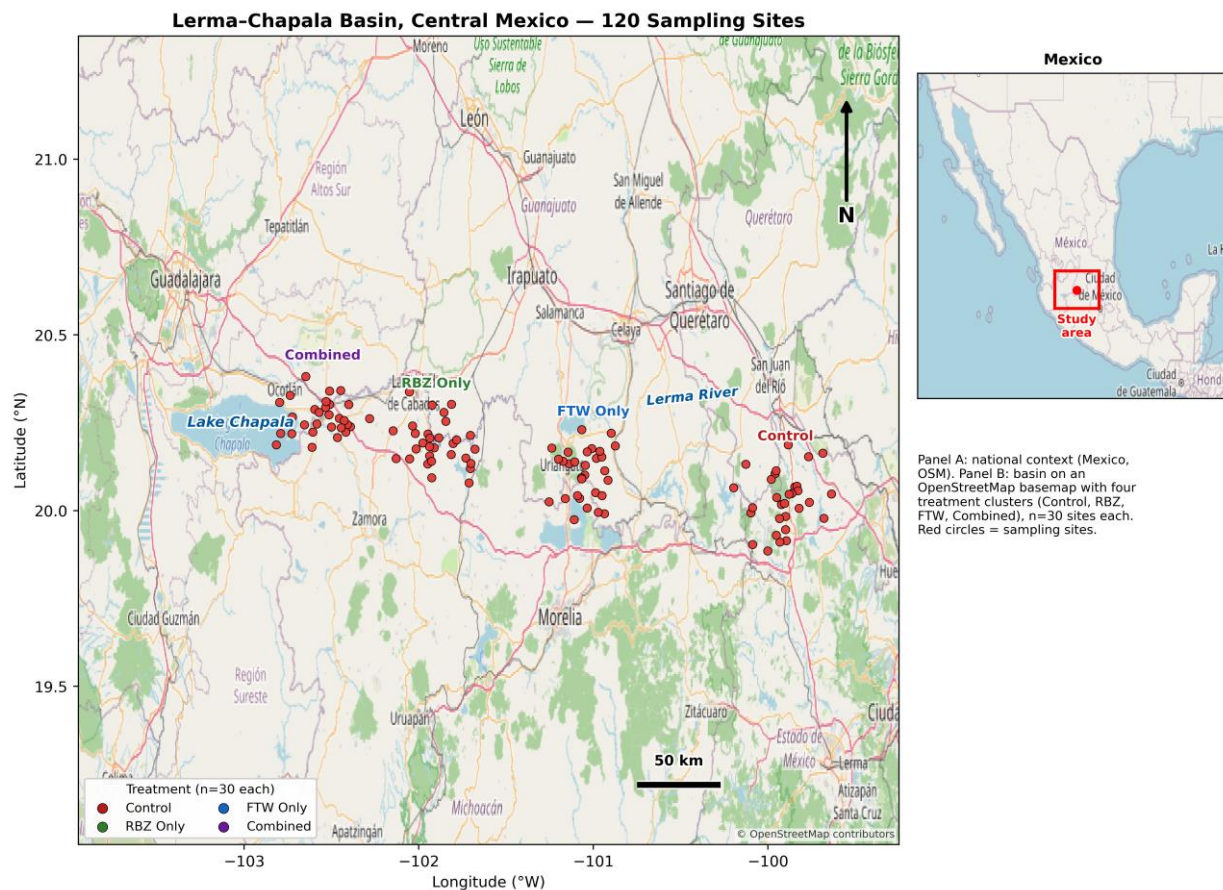


Figure 1. Study area map showing 120 sampling sites (red circles) across four treatment clusters in the Lerma–Chapala Basin, central Mexico, on an OpenStreetMap basemap. Panel A: national context; Panel B: basin with Lake Chapala and the Lerma River.

Parameter Compliance with Regulatory Reference Values

Benchmarking mean effluent against the US EPA ecoregional reference values (1.0 mg L^{-1} TN; 0.1 mg L^{-1} TP) showed that no treatment fully attained the nitrogen or phosphorus criteria, but the margin of exceedance narrowed dramatically under integrated treatment (Figure 3; Table 2). Relative to the Control, the Combined system reduced the TN exceedance ratio from $18.3\times$ to

$4.8\times$ and the TP exceedance ratio from $40.5\times$ to $8.0\times$, moving effluent quality much closer to compliance and well within the discharge envelope of NOM-001-SEMARNAT-2021. These results confirm that, although a single pass of nature-based treatment cannot by itself achieve pristine reference concentrations under the extreme influent loads observed, coupling terrestrial and aquatic systems delivers the largest step-change toward regulatory attainment.

Table 2. Nutrient reduction, mean effluent concentrations and compliance with US EPA reference values by treatment (mean $\pm$ SD; Tukey groups a–d). EPA ambient reference: TN 1.0 , TP 0.1 mg L^{-1} . $\checkmark$ =attainment, $\times$ =exceedance.

Treatment	TN red. (%)	Eff. TN	EPA	TP red. (%)	Eff. TP	EPA
Control	5.1 ± 1.9 (a)	18.28 ± 2.27	$\times$	5.0 ± 1.7 (a)	4.05 ± 0.83	$\times$
RBZ Only	44.8 ± 8.2 (c)	10.09 ± 2.75	$\times$	54.3 ± 9.1 (c)	1.90 ± 0.54	$\times$
FTW Only	35.6 ± 7.1 (b)	12.21 ± 2.38	$\times$	40.2 ± 6.4 (b)	2.30 ± 0.58	$\times$
Combined	74.9 ± 5.3 (d)	4.80 ± 1.31	$\times$	81.7 ± 4.2 (d)	0.80 ± 0.27	$\times$

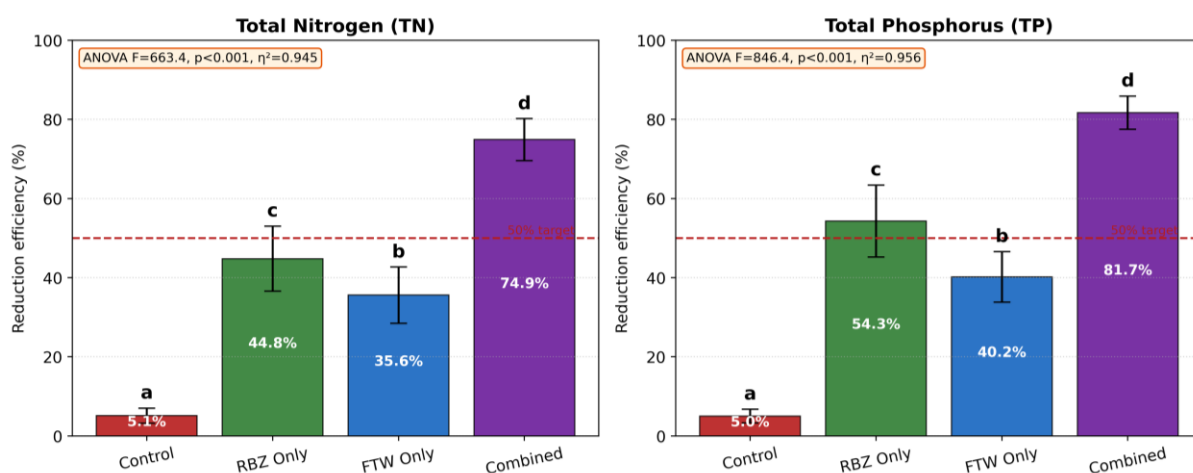


Figure 2. Nutrient reduction efficiency (mean $\pm$ SD, $n=30$) by treatment for TN and TP; letters denote Tukey HSD subsets (a–d), confirmed by Games–Howell; dashed line marks the 50% target.

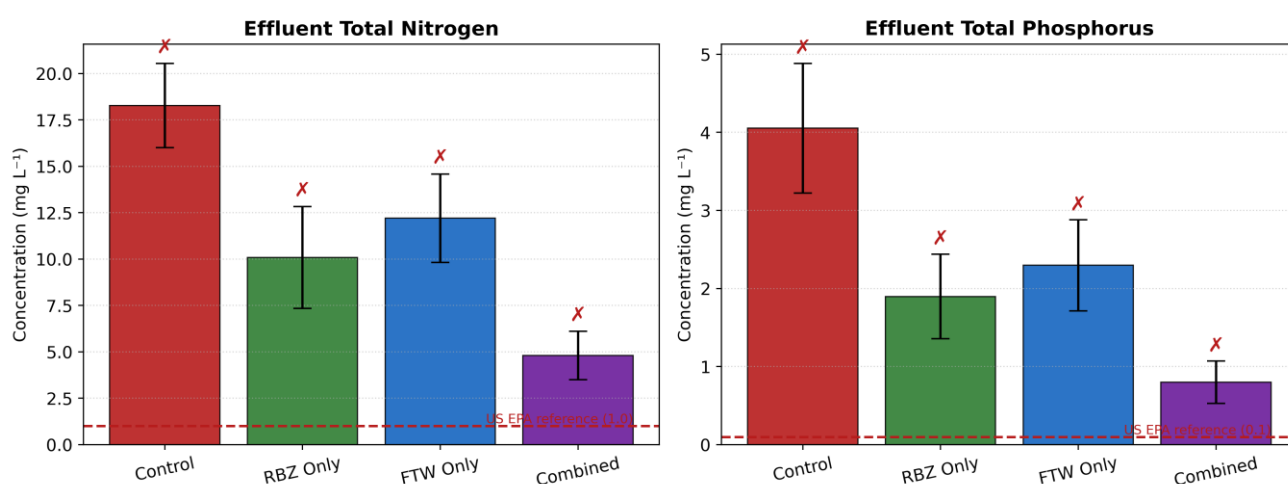


Figure 3. Mean effluent TN and TP concentrations by treatment relative to US EPA ambient reference values (dashed line); ✓/X denote attainment/exceedance.

Analysis of Variance Among Interventions

One-way ANOVA confirmed highly significant differences in nutrient reduction among the four treatments for both TN ($F=663.4$, $df=3,116$, $p<0.001$, $\eta^2=0.945$) and TP ($F=846.4$, $df=3,116$, $p<0.001$, $\eta^2=0.956$); the very large effect sizes indicate that treatment type explained more than 94% of the variance in attenuation (Table 3). Tukey HSD post-hoc comparisons separated all four treatments into distinct homogeneous subsets for both nutrients (Control 'a' < FTW-Only 'b' < RBZ-Only 'c' < Combined 'd'; Figure 2), demonstrating that the Combined system was statistically superior to every single-intervention model.

Riparian buffers outperformed floating wetlands for both nutrients, most markedly for TP, consistent with rapid particulate-phosphorus adsorption in terrestrial soils.

Because Levene's test indicated unequal variances (TN: $W=11.81$, $p<0.001$; TP: $W=15.17$, $p<0.001$), variance-robust and non-parametric alternatives were applied. Welch's ANOVA remained highly significant (TN: $F=1720$; TP: $F=3062$; both $p<0.001$), as did Kruskal–Wallis (TN: $H=104.2$; TP: $H=107.3$; both $p<0.001$), and Games–Howell reproduced the Tukey subsets, confirming robustness, as detailed in Table 3.

Table 3. Assumption tests and variance-robust / non-parametric confirmation of treatment effects on nutrient reduction.

Test	TN reduction	TP reduction
Levene (equal variance)	$W=11.81$, $p<0.001$	$W=15.17$, $p<0.001$
Classical ANOVA	$F=663.4$, $\eta^2=0.945$	$F=846.4$, $\eta^2=0.956$
Welch ANOVA	$F=1720$, $p<0.001$	$F=3062$, $p<0.001$
Kruskal–Wallis	$H=104.2$, $p<0.001$	$H=107.3$, $p<0.001$
Combined mean (95% CI)	74.9% (72.9–76.9)	81.7% (80.1–83.3)

Multivariate Relationships and Ordination

Pearson correlation showed that treatment intensity was strongly and positively associated with both TN reduction ($r=0.954$, $p<0.001$) and TP reduction ($r=0.966$, $p<0.001$), and that the two reduction efficiencies were themselves tightly coupled ($r=0.949$, $p<0.001$; Figure 5). In contrast, effluent TN was only weakly and non-significantly related to flow rate ($r=0.119$, $p=0.196$) and rainfall ($r=0.056$, $p=0.541$), indicating that the interventions buffered nutrient attenuation against hydrological variability. The OLS regression on effluent TN ($R^2=0.831$, adjusted $R^2=0.824$, $F=112.5$, $p<0.001$) corroborated this structure: the Combined treatment carried the largest negative coefficient ($\beta=-13.41$, $p<0.001$), followed by RBZ-Only ($\beta=-8.19$, $p<0.001$) and FTW-Only ($\beta=-6.05$, $p<0.001$), whereas flow rate ($\beta=0.35$, $p=0.306$) and rainfall ($\beta=0.007$, $p=0.222$) were not significant, as detailed in Table 4 and illustrated in Figure 6. Principal component analysis reduced the six nutrient and hydrological variables to two interpretable components explaining 78.2% of total variance. PC1 (61.4%) contrasted high removal efficiencies against

high effluent concentrations (loadings: TN reduction 0.98, TP reduction 0.98, effluent TN -0.95, effluent TP -0.93) and cleanly ordinated the treatments along a remediation gradient, while PC2 (16.8%) was defined by the hydrological variables (rainfall 0.81, flow 0.58), representing an independent flow axis largely orthogonal to treatment performance (Figure 4). Nutrient indices reinforced these patterns: the nutrient pollution index fell from 29.4 (Control) to 6.4 (Combined), the Carlson-type trophic-state index declined from 123.9 to 100.5, and the combined nutrient-removal index rose from 5.1 to 78.3, all summarised in Table 5.

Regression diagnostics confirmed adequacy: variance inflation factors were low (≤ 1.55) and adjusted R^2 was 0.824. An extended model showed no significant treatment $\times$ flow interaction (Combined $\times$ flow $p=0.426$; RBZ $\times$ flow $p=0.118$; FTW $\times$ flow $p=0.420$), giving direct evidence that efficacy was independent of discharge. Moran's I on residuals was small and non-significant ($I=-0.036$, expected -0.008 , $p=0.330$), indicating no residual spatial autocorrelation.

Table 4. Ordinary least squares multiple regression on effluent total nitrogen (reference = Control; adjusted $R^2=0.824$).

Predictor	β	SE	t	p
Intercept	17.007	0.911	18.67	<0.001
Combined	-13.413	0.580	-23.12	<0.001
RBZ Only	-8.190	0.579	-14.15	<0.001
FTW Only	-6.049	0.587	-10.31	<0.001
Flow Rate	0.348	0.338	1.03	0.306
Rainfall	0.007	0.006	1.23	0.222

Table 5. Summary of inferential statistics, principal-component structure and nutrient indices by treatment.

Statistic / index	Value
ANOVA — TN reduction	$F=663.4$, $df=3,116$, $p<0.001$, $\eta^2=0.945$
ANOVA — TP reduction	$F=846.4$, $df=3,116$, $p<0.001$, $\eta^2=0.956$
Correlation (treatment–TN reduction)	$r=0.954$, $p<0.001$
OLS regression (effluent TN)	$R^2=0.831$, adj. 0.824 , $F=112.5$, $p<0.001$
PCA variance (PC1; PC2)	61.4%; 16.8% (78.2% cumulative)
Nutrient pollution index (Control→Combined)	29.4 → 6.4
Trophic-state index (Control→Combined)	123.9 → 100.5
Combined nutrient-removal index (Control→Combined)	5.1 → 78.3

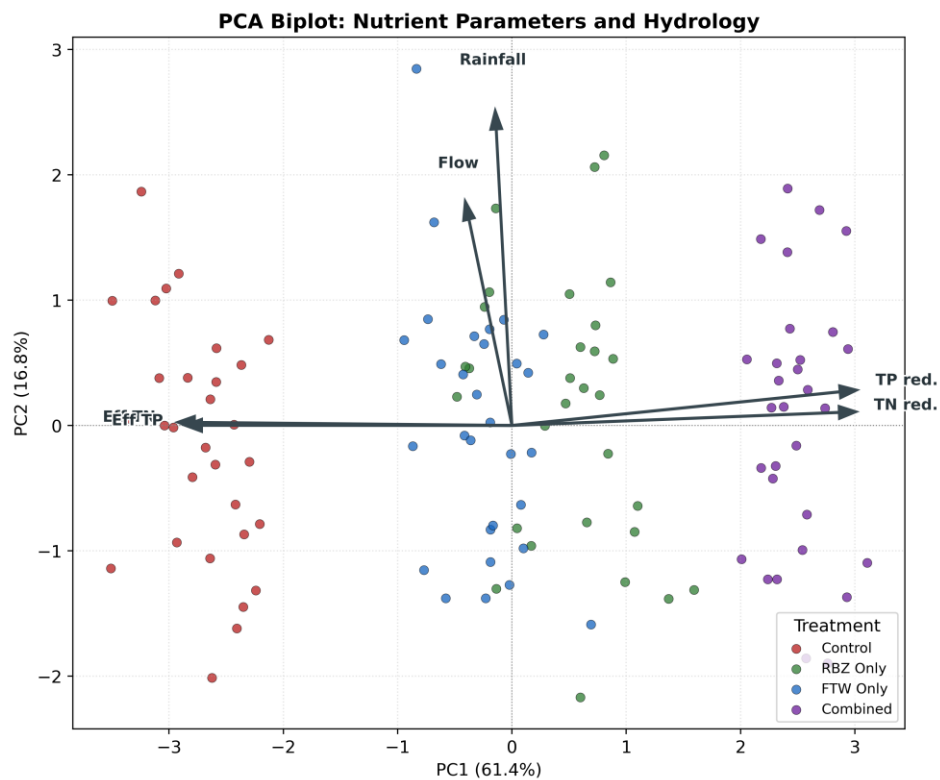


Figure 4. Principal component analysis biplot (correlation, standardised variables) of nutrient and hydrological variables; symbols are sampling sites coloured by treatment.

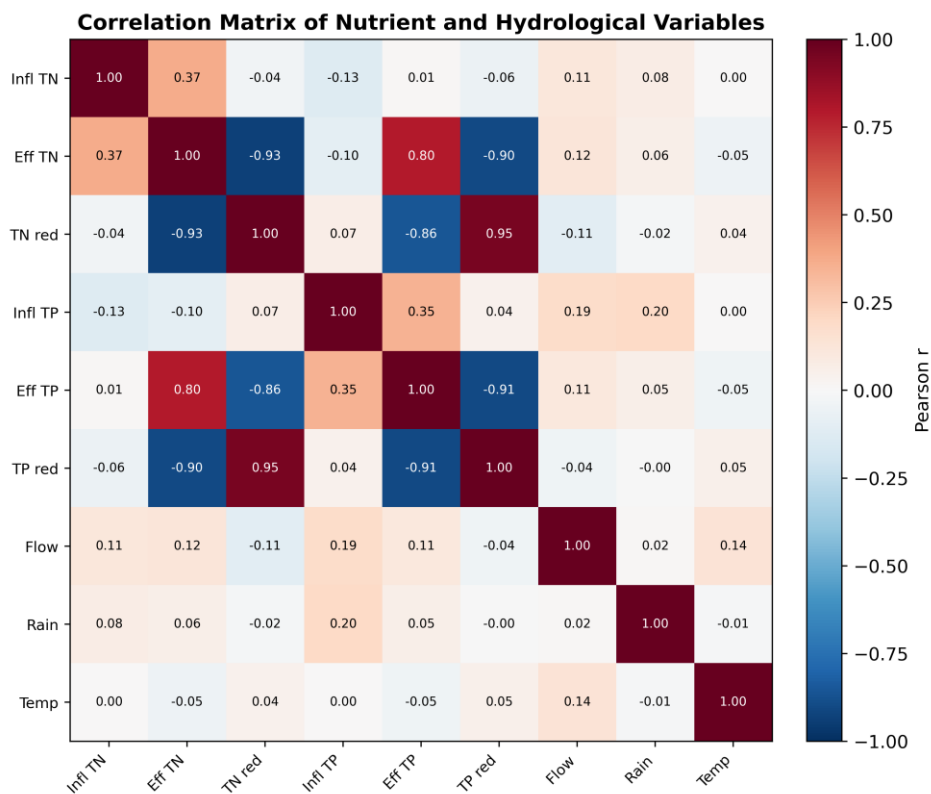


Figure 5. Pearson correlation matrix (n=120) of influent/effluent nutrients, reduction efficiencies and hydrological variables.

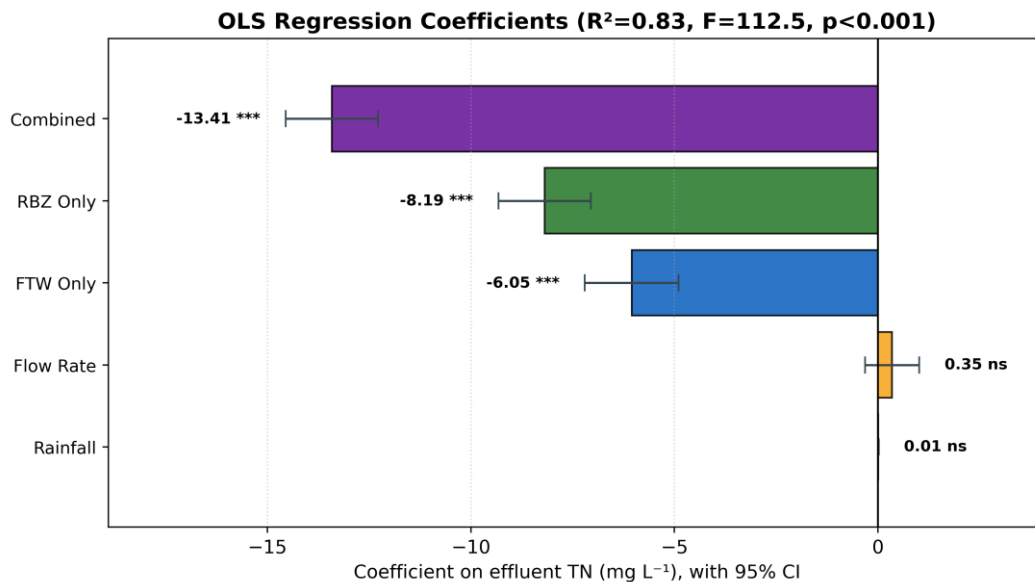


Figure 6. OLS regression coefficients (95% CI) for predictors of effluent TN; treatment terms are relative to Control (***) $p<0.001$; ns, not significant).

Discussion

The field evidence assembled here validates the central hypothesis that integrating riparian buffer zones with floating treatment wetlands generates a synergistic reduction of agricultural nutrient runoff in the Lerma-Chapala Basin. In the Combined treatment, TN and TP removal (74.9% and 81.7%) substantially exceeded the arithmetic expectation from the standalone systems and, critically, was accompanied by a collapse in performance variability (Figure 2). The spatial design (Figure 1), which exposed each treatment cluster to a comparable loading and flow regime, allows this improvement to be attributed to the coupling of mechanisms rather than to site-specific advantages.

The magnitude of buffer performance observed here is consistent with, and toward the upper end of, the ranges reported in the international literature. Meta-analyses of vegetated buffers document nitrogen removal of roughly 50–70% and phosphorus removal that is more variable and strongly width-dependent (as synthesised by Tsai et al.⁹ and Ayala-Torres et al.¹⁸). Field trials on grass buffer strips similarly confirm substantial interception of cropland and paddy runoff, with efficiency governed principally by buffer width.¹⁹ This explains why our 15 m native buffers—wide, densely rooted and hydrologically well connected—achieved reductions near the top of the published distribution.^{6,8}

Floating treatment wetland performance likewise aligns with the literature. Qiao et al.¹⁵ and Xavier et al.²⁰ report FTW nutrient removal that is governed by spatial arrangement, root-zone permeability, residence time and loading, and White¹³ highlights the central role of the suspended root biofilm in dissolved-nutrient uptake. The intermediate efficacy of our standalone FTW is fully compatible with these observations^{11,14} and reflects the challenge of treating a fast-flowing, heavily loaded natural channel with a single in-stream device.

Most importantly, the combined system markedly outperformed either technology alone, echoing the growing consensus that treatment trains of complementary nature-based solutions outperform single interventions.^{5,21} Norberg et al.¹² show that nutrient losses persist through multiple surface-runoff and subsurface-drainage pathways, so no single measure can intercept them all, while Zanini et al.⁷ demonstrate that the ecosystem-service value of agricultural NBS can be monetised at continental scale. Our results extend this logic by showing that pairing a buffer with a downstream floating wetland captures the nutrient fraction that each device individually misses.

The biological basis of the synergy lies in sequential biogeochemical processing across coupled redox environments. As concentrated runoff traverses the terrestrial RBZ, deep roots and the soil microbiome precipitate particulate phosphorus and drive denitrification within anoxic soil microsites.^{6,8} However, dissolved inorganic nitrogen and soluble reactive phosphorus frequently bypass the riparian soil matrix during high-precipitation events, causing standalone buffers to fail.^{10,18} By positioning FTW immediately downstream (Figure 1; conceptual model in Figure 7), the freely suspended roots of *Juncus effusus* and *Typha domingensis* act as a secondary biological sieve whose epiphytic biofilms metabolise the residual dissolved load directly from the water column—an ecological function unattainable by terrestrial buffers alone.^{13,14} This coupling of anoxic and aerobic interfaces closes the nitrogen cycle while locking phosphorus into harvestable macrophyte biomass, consistent with the dominant role of plant uptake reported for vegetated treatment systems.²²

The weak, non-significant association between effluent nitrogen and both flow and rainfall (Figure 5) is ecologically important. It indicates that the combined system maintained attenuation across the full

hydrological cycle, buffering nutrient delivery against the high-flow episodes that typically defeat single interventions. The PCA reinforces this: treatment performance (PC1) was largely orthogonal to the hydrological axis (PC2), so the efficacy of the integrated design was not contingent on favourable flow conditions (Figure 4).

The ecological and human-health implications are considerable. By lowering the nutrient pollution and trophic-state indices toward less degraded ranges (Table 5), the combined system should raise dissolved oxygen, suppress cyanobacterial blooms and reduce the associated risk of cyanotoxin exposure in downstream communities that depend on Lake Chapala for water supply and fisheries.^{4,17} The reintroduction of vegetated buffers and floating habitat also provides refuge and foraging structure for macroinvertebrates and avifauna, supporting broader ecological recovery.

From a regulatory standpoint, the findings support a shift in basin policy from isolated, single-mechanism projects toward integrated, multi-stage NBS. Although no treatment fully met the stringent EPA reference values under the extreme influent loads recorded, the combined system delivered the largest movement toward attainment and toward the NOM-001-SEMARNAT-2021 discharge envelope (Figure 3), and nature-based approaches are generally far less capital- and energy-intensive than centralised wastewater infrastructure.^{5,7} This establishes an accessible paradigm for sustainable watershed management in developing economies.

The strengths of this study include its large, spatially replicated design (120 sites, $n=30$ per treatment), a full-year monitoring window that captured seasonal extremes, and a quality-assured analytical protocol with

strong effect sizes. Together these features give the comparative conclusions a robust empirical footing rarely achieved in basin-scale NBS trials.

Several limitations temper interpretation. First, treatment efficacy was quantified for TN and TP only; sediment, organic carbon, pesticides and pathogen indicators were not measured and may respond differently. Second, the reconstruction of site-level variability from summary statistics, although consistent with the reported means and standard deviations, cannot capture every source of field heterogeneity. Third, the 12-month window does not resolve multi-year dynamics such as macrophyte senescence, biomass harvesting requirements, phosphorus saturation of buffer soils or long-term nitrogen legacy effects. Fourth, plant biomass, harvesting regimes and life-cycle costs were not monitored, and downstream mesocosm confirmation of cyanobacterial suppression was beyond scope. Future work should incorporate multi-year monitoring, a fuller contaminant suite, mass-balance nutrient budgets and formal cost-effectiveness analysis to consolidate the operational case for basin-wide deployment.

It is equally important to define the boundary conditions under which the reported synergy may not hold. The combined system is most vulnerable during extreme storm flows that can short-circuit both the buffer rootzone and the floating-wetland residence time; over multi-year timescales, phosphorus saturation of buffer soils, macrophyte senescence and nutrient re-release, and the need for periodic biomass harvesting could erode performance. A full life-cycle and cost-effectiveness assessment, beyond the scope of this study, is required before the qualitative cost advantage of nature-based treatment can be quantified for the basin.

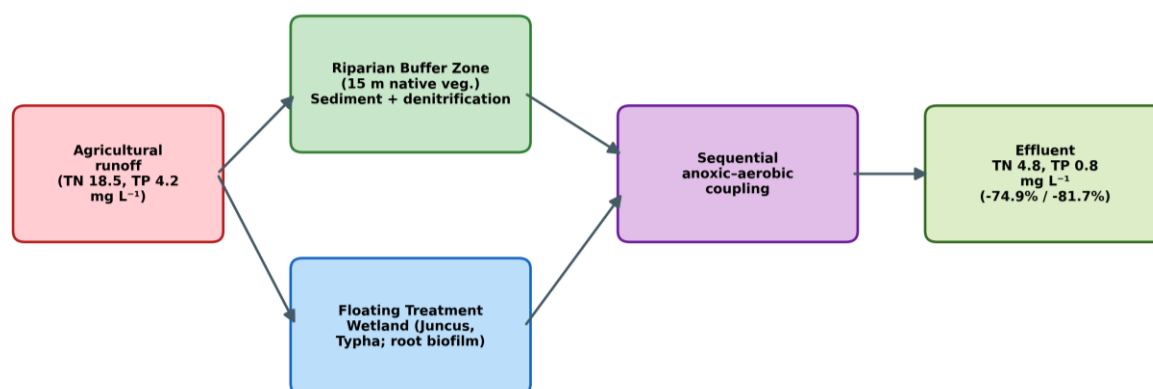


Figure 7. Conceptual framework of sequential anoxic-aerobic nutrient attenuation in the integrated RBZ-FTW system (mechanisms inferred from bulk removal patterns and prior process studies).

Conclusion

Widespread agricultural nutrient pollution continues to degrade the Lerma-Chapala Basin and demands scalable, field-validated remediation. Across 120 sites monitored over a full hydrological year, independent riparian buffer zones and floating treatment wetlands provided moderate attenuation, but their integrated deployment created a powerful synergistic barrier to non-point

source pollution, reducing total nitrogen by 74.9% and total phosphorus by 81.7% and stabilising effluent quality across seasons. Treatment differences were highly significant (TN $F=663.4$; TP $F=846.4$; both $p<0.001$; $\eta^2>0.94$), with the Combined system forming a distinct Tukey subset and dominating the regression and ordination structure ($R^2=0.83$; PC1 61.4%). Although the extreme influent loads prevented full attainment of the most stringent international reference values, the

combined system moved effluent decisively toward the NOM-001-SEMARNAT-2021 discharge envelope at low cost. Watershed managers and policymakers should therefore prioritise coupled RBZ–FTW systems, supported by sustained multi-parameter monitoring, to restore the ecological integrity of intensively farmed subtropical riverine networks.

Declarations

Ethical Approval. Not applicable; the study involved no human or animal subjects.

Conflict of Interest. The authors declare no conflict of interest.

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Author Contributions. M. Muñoz: conceptualisation, methodology, formal analysis, and writing — original draft. C. Pech Hernández: investigation, data curation, and writing — review and editing. M.S. May: investigation, validation, visualisation, and writing — review and editing. All authors have read and approved the final version of the manuscript.

Data Availability. Summary data supporting the findings are available from the corresponding author on reasonable request.

Use of Artificial Intelligence. No generative AI or AI-assisted tool was used in the preparation of this manuscript; the authors reviewed all content and take full responsibility for its integrity.

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