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Optimizing nutrient management to improve tobacco (*Nicotiana tabacum*) production while reducing nutrient losses in tobacco fields

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KEYWORDS

Erhai Lake, leaching, nutrient loss, organic fertilizer, runoff flue-cured tobacco

HIGHLIGHTS

- Implement optimized organic-mineral fertilizer application to balance economic and environmental goals.
- Characteristics of nutrient loss under different fertilizer application treatments were examined.
- Soil organic matter and alkaline hydrolyzed nitrogen significantly affected nitrogen and phosphorus nutrient losses.
- Nutrient loss peaks were driven by the interaction of management and climate.

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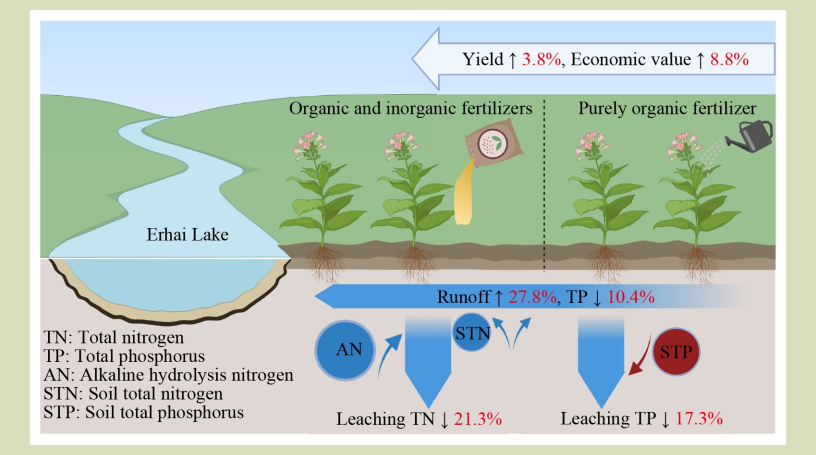
GRAPHICAL ABSTRACT



ABSTRACT

Efficient nutrient management is essential for mitigating nutrient losses from farmland in the Erhai Lake Basin (ELB). This 2-year field study (2021–2022) in the northern ELB investigated the effects of different fertilizer application methods on nitrogen and phosphorus losses. The four fertilizer treatments included: no fertilizer, farmer practice of solely organic fertilizer application (FP), mineral fertilizer, and a combination of organic and mineral fertilizers (OMC). Over the study period, total N (TN) losses ranged from 17 to 34 $kg\cdot ha^{-1}$ and total P (TP) losses from 1.0 to 1.4 $kg\cdot ha^{-1}$. Peak N and P losses occurred

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during June and July, with N lost primarily as nitrate and P lost primarily in dissolved forms. Compared with the FP treatment, the OMC treatment significantly reduced nutrient losses throughout the tobacco season; TN runoff decreased by 2.7 kg·ha^{-1}, TP runoff by 0.1 kg·ha^{-1}, TN leaching by 21% and TP leaching by 17%. Also, the OMC treatment increased the average tobacco yield by 3.8% (to 2.55 t·ha^{-1}) compared to the FP treatment, which in turn enhanced the gross value. Fertilizer treatments significantly affected soil properties. These altered soil properties, particularly alkaline hydrolysis N and soil organic matter levels, subsequently regulated N and P loss dynamics. These results provide a scientific basis for mitigating nutrient loss from farmland in the ELB through optimized fertilizer application.

1 Introduction

Farmland is critical for sustaining human societies, but it is also a major source for nutrient flows and their associated environmental impacts. In 2019, the global extent of farmland reached 1.2 × 10^{10} ha, marking a 9% increase since 2003[1]. Global fertilizer consumption has increased steadily by 2% annually, reaching 1.9 × 10^6 t by 2020, reflecting its perceived agronomic value. Although fertilizer application can boost crop yields by up to 31%[2], the constant increase in farmland coupled with the pervasive use of fertilizers raises issues of inefficient nutrient utilization and significant nutrient losses. Over half of the nitrogen applied to farmlands is lost to the atmosphere or water bodies[3,4]. Statistics indicate that the average Asian N surplus exceeds 90 kg·ha^{-1}·yr^{-1} N[5].

The Erhai Lake Basin (ELB) in China serves as an essential source of drinking and irrigation water for the surrounding region, particularly Dali City[6]. However, in recent years, the region has witnessed a significant deterioration in water quality, primarily due to excessive N and P loading. The western and northern areas of the ELB are the primary contributors to this pollution, which is largely attributed to the improper application of fertilizers as the main source of N and P contamination[7–9]. Studies have shown that around 30% of the total nitrogen (TN) entering the ELB is fertilizer-derived, with fertilizer loss from farmland being the primary contributor to mineral-N in the basin[10]. Tobacco (*Nicotiana tabacum*) production, a cornerstone of the ELB economy, occupied over 4.2 × 10^3 ha in 2025, representing approximately 10% of the total cultivated area (4.0 × 10^4 ha) of the basin. However, tobacco fields in the ELB are predominantly clustered in the western region, which is characterized by steep terrain. This topographic feature, combined with widespread suboptimal fertilizer application practices, elevates the risk of agricultural nutrient runoff. Despite these environmental challenges, tobacco farming remains a vital economic driver, contributing significantly to regional GDP and rural household incomes[11]. Therefore, balancing the goals of reducing nutrient loss from tobacco fields, ensuring high-quality crop production and supporting farmer incomes is critical for both environmental conservation and the sustainable development of agriculture in the ELB.

Optimized nutrient management is a viable strategy for small-scale farming in China because of its ability to balance farmer profitability with environmental protection[12–15]. Optimized nutrient management makes it feasible to achieve cost-effective benefits in nutrient utilization, stable yields and minimized nutrient losses[16–18]. Implementation of such management notably entails the optimization of fertilizer type, application rate, placement, and timing. The 4R nutrient management strategy has demonstrated positive results across various cropping systems when tailored to specific crop needs and soil nutrient contents[19,20].

The 4R framework, which includes strategies such as judicious fertilizer reduction and combining organic and mineral inputs, is widely recognized by both scholars and farmers for its potential to enhance crop quality. Research consistently indicates that this framework can enhance crop yields while simultaneously reducing nutrient losses from runoff and leaching[21–23]. However, significant spatial and seasonal variability in soil nutrient levels poses a challenge to the regional management of fertilizer pollution. Therefore, it is imperative to conduct detailed regional assessments of the impacts of optimized nutrient management on crop yields, farmer income, and nutrient losses. Such evaluations are essential to fostering the sustainable development of agriculture in China's ELB region and other similar regions.

A 2-year field experiment was conducted in Sanying Town, located in the northern region of the ELB, an area known as the source of Erhai Lake. The experiment consisted of four fertilizer treatments: no fertilizer (CK), farmer practice of solely organic fertilizer application (FP), mineral fertilizer (MF), and a combination of organic and mineral fertilizer (OMC). This study aimed to evaluate the effects of these nutrient management practices on N and P losses via runoff and leaching. The study also sought to understand the influence of various soil physicochemical properties on nutrient losses in this specific region. These findings are expected to provide valuable theoretical guidance for the promotion of sustainable agricultural practices in the ELB.

2 Materials and methods

2.1 Study area

Field experiments were conducted in 2021 and 2022 in Sanying Town, Eryuan County, Dali Bai Autonomous Prefecture (26°10′ N, 99°59′ E). The study area is located in the northern part of the ELB and has a monsoon climate, with an average annual temperature of 13.8 °C and an average annual precipitation of 732 mm. It is situated on the northern subtropical plateau of China. The precipitation and runoff and leaching volume during the 2021 and 2022 tobacco seasons are given in Fig. 1.

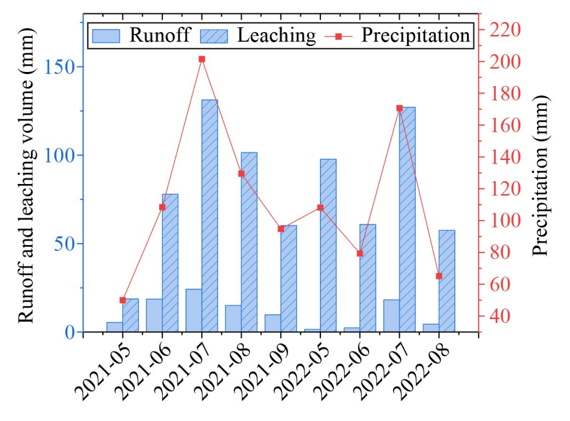

Fig. 1 Monthly precipitation and runoff and leaching volume during the 2021 and 2022 tobacco seasons.

Four fertilizer treatments were set up in this experiment. The experiment was a single-season flue-cured tobacco farmlands with a planting density of 16,500 plants ha^{-1}. The area of the trial site was 949 m^2, and the test cultivar was Honghuadajinyuan, the crop was transplanted on 16 May, and the top leaves matured on 8 September, for a total life span of 115 days. In 2022, the crop was transplanted on 20 May, and the top leaves matured on 10 September, for a life span of 113 days. Each treatment in the experiment was set up with three replicates and arranged in randomized blocks. The soil type of the test field was yellow loam with 3.9% clay, 46.5% silt and 49.6% sand, and the soil texture was sandy loam. Soil water content before transplanting flue-cured tobacco was 7.3%. The basic physical and chemical properties of the surface soil in the plot are given in Table 1.

Soil organic matter, total nitrogen and total phosphorus were determined by potassium dichromate oxidation-spectrophotometry. Alkaline hydrolysis nitrogen was determined by alkaline diffusion method. Available phosphorus was determined by sodium bicarbonate extraction and molybdenum-antimony spectrophotometry, and available potassium was determined by neutral ammonium acetate solution extraction and flame photometry[24].

Table 1 Basic properties of soil in an experimental tobacco field

pH	Soil Organic matter (g·kg^{-1})	Total nitrogen (g·kg^{-1})	Total phosphorus (g·kg^{-1})	Total potassium (g·kg^{-1})	Alkaline hydrolysis nitrogen (mg·kg^{-1})	Available phosphorus (mg·kg^{-1})	Available potassium (mg·kg^{-1})
8.0	70 ± 5.8	4.4 ± 0.8	1.8 ± 0.2	11.6 ± 0.5	232 ± 21	128 ± 24	502 ± 52

2.2 Experimental design

This experiment investigated the effects of different fertilizer treatments on the growth of and nutrient loss from flue-cured tobacco. The experiment included four treatments: CK, FP, MF and OMC. The treatments were arranged in a randomized complete block design with three replicates of each treatment. Each plot was 55.2 m^2 with seven rows of 13 plants each. Detailed information on the fertilizer management for each treatment is given in Table 2. The flue-cured tobacco cv. Honghuadajinyuan was provided by the Sanying Town tobacco workstation of the Dali Prefecture Tobacco Company. The solid and liquid organic fertilizers used in the experiment were both sourced from the same tobacco workstation. The solid organic fertilizer was produced by composting raw materials including cow dung, tobacco dust and fermentation bacteria. The resulting compost was then blended with decomposed coal and rapeseed cake. In contrast, the liquid organic fertilizer was produced by extracting nutrients from these raw materials through liquid fermentation, followed by solid-liquid separation. The resulting liquid extract was then fortified with seaweed extract, an approved organic nutrient source, to meet the target nutrient grade. Compound and formula fertilizers were provided by the Sanying Jinqiu Flue-Cured Tobacco Integrated Service Cooperative. Compound fertilizers had 12:3:20 NPK, with all N as nitrate. The tobacco fertilizers had 15:4:18 NPK with N as equal nitrate and ammonium, the phosphate fertilizer was calcium superphosphate (7% P) and the potassium fertilizer was potassium sulfate (43% K).

Nutrient grade of the organic fertilizers refers to total nutrients. The basal fertilizer was surface-applied in bands before planting according to local custom, while the topdressing was applied by placing a fixed amount of fertilizer directly into each planting hole after the tobacco had been transplanted.

2.3 Sampling and measurements

2.3.1 Yield measurement and grading

Tobacco leaves were harvested in batches by plots at maturity. Tobacco quality was classified into three major grades according to seven appearance grade factors[24]. Yield and the proportion of upper-medium grade tobacco were counted, and the gross value of each treatment was calculated according to the 2021 and 2022 tobacco purchase price tables of Eryuan County.

2.3.2 Soil sample collection and measurement

Before transplanting and after harvest, soil samples were collected using a soil auger. In each plot, five cores were taken from the area between two plants in the center row. For each depth, the five cores were combined and thoroughly mixed to create a single composite sample. This process was repeated for three depth increments: 0–20, 20–40 and 40–60 cm. This study focused on the 0–20 cm soil layer. A portion of each soil sample was air-dried and sieved through a 2-mm sieve for chemical analysis. Soil pH was measured using a pH meter (S2-Meter, Mettler Toledo, Shanghai, China) in a 1:2.5 soil-to-water suspension. Methods detailed by Lu[25] were used to determine soil organic matter (SOM) by potassium dichromate oxidation-spectrophotometry and soil total nitrogen (STN) using the Kjeldahl method[25]. Alkaline hydrolysis nitrogen (AN) was determined by the alkaline dissolution diffusion

Table 2 Scheme of fertilizer application and nutrient inputs for different fertilizer treatments

Treatments	Scheme of fertilizer application		Total NPK (kg·ha^{-1})
	Base fertilizer	Topdressing fertilizer	
CK	No fertilizer	No fertilizer	0
FP	Solid organic fertilizer (2:2:3 NPK) 1500 kg·ha^{-1}	Apply liquid organic fertilizer (6:1:10 NPK) 225 kg·ha^{-1} immediately after transplanting, followed by liquid organic fertilizer (6:1:10 NPK) 525 kg·ha^{-1} at 15 days after transplanting, and potassium sulfate 162 kg·ha^{-1} K 45 days after transplanting	75:33:286
MF	Compound fertilizer (12:3:20 NPK) 500 kg·ha^{-1}	Apply potassium sulfate 50 kg·ha^{-1} K at 45 days after transplanting	60:13:149
OMC	Tobacco formula fertilizer (15:4:18 NPK) 200 kg·ha^{-1}, solid organic fertilizer (2:2:3 NPK) 300 kg·ha^{-1}	Apply liquid organic fertilizer (6:1:10 NPK) 400 kg·ha^{-1} at 25 days after transplanting, followed potassium sulfate 63 kg·ha^{-1} K at 45 days after transplanting	60:17:149

method[26]. Several other parameters were determined following established procedures[26]: nitrate nitrogen (NO_3^--N) and ammonium nitrogen (NH_4^+-N) were extracted using potassium chloride solution and determined spectrophotometrically, available phosphorus (AP) was determined using sodium bicarbonate extraction followed by the molybdenum-antimony spectrophotometric method, soil total potassium (STK) was determined following hydrofluoric acid-perchloric acid digestion, and available potassium (AK) was determined by ammonium acetate extraction and flame photometry[25]. Soil total phosphorus (STP) was determined following alkali fusion with NaOH[27].

2.3.3 Runoff and leaching

Runoff water collection: each runoff plot (8.4 m^2) was equipped with a collection system. A ditch at the lower end of the plot directed surface runoff through a PVC pipe into a collection barrel installed adjacent to the plot. The collection barrel was attached to the soil surface through a pipe and the runoff water was then pumped out using a vacuum pump. After each rainfall event, the total volume of runoff in each barrel was measured. The water was then agitated, and a 250-mL subsample was immediately collected for analysis. Subsamples were stored at −18 °C until they could be analyzed for TN, nitrate N (NO_3^--N), ammonia N (NH_4^+-N), total P (TP) and total dissolved P (TDP). The area of each treatment runoff plot was 8.4 m^2.

Leachate collection: to collect leachate, a collection pit was excavated in the center of each plot prior to the 2021 growing season. The pit was excavated to a depth of 80 cm, with surface dimensions of 1.2 m × 1 m. The soil was carefully removed in 20 cm layers and set aside to preserve the original soil horizons. A custom-built, open-bottom leachate collector, constructed from PVC plastic sheeting, was then placed at the bottom of the pit. The excavated soil was subsequently backfilled into the pit, layer by layer, to reconstruct the original soil profile. The floor and sides of this hole were lined with a plastic sheet barrier with the only outlet into the collection barrel which was covered with two layers of 80 mesh nylon net and 3 cm of quartz sand. The hole was then refilled with originally excavated layers, in order, and compacted to the original bulk density. A connecting pipe from the bottom of the collection barrel extends to the soil surface, where a vacuum pump is used to extract and record the volume of leaching water in the barrel. Subsamples are collected and stored as for surface water. TN in water samples was digested by alkaline potassium persulfate, ultraviolet spectrophotometry, NO_3^--N was determined by phenol sulfonic acid spectrophotometry, NH_4^+-N was determined by Nessler reagent spectrophotometry[28]. TP was determined using the ammonium molybdate spectrophotometric method, following digestion using potassium persulfate as an oxidant. TDP was filtered through a 0.45 μm membrane and determined using the ammonium molybdate spectrophotometric method, following digestion using potassium persulfate as an oxidant[27].

2.4 Data processing

The economic analysis includes both cost inputs and output values. The cost input in this study is the cost of fertilizer input, including the cost of the fertilizer itself and labor cost. The prices of solid organic fertilizer, liquid organic fertilizer, compound fertilizer, tobacco formula fertilizer and potassium sulfate were 0.25, 0.22, 0.56, 0.60 and 0.70 USD·kg⁻¹, respectively, which were based on the subsidized price from the Dali Tobacco Company and the 2021 China Fertilizer Network Annual Report. The labor cost for a single application of fertilizer was 421 USD·ha⁻¹, which was converted from a compilation of agricultural cost and benefit information for China as a whole combined with the local information. To account for labor costs accurately, two field operations were assumed for the CK treatment. This reflects the local practice where fertilizer application is often combined with other tasks like weeding and pesticide application. The calculation formula was as follows:

$$\begin{aligned}&\text{Cost of fertilizer application }(\text{USD}\cdot\text{ha}^{-1}) = \\ &\text{Fertilizer cost }(\text{USD}\cdot\text{ha}^{-1}) + \text{Labor cost }(\text{USD}\cdot\text{ha}^{-1})\end{aligned} \quad (1)$$

$$\begin{aligned}&\text{Net value}\left(\text{USD}\cdot\text{ha}^{-1}\right) = \text{Gross value}\left(\text{USD}\cdot\text{ha}^{-1}\right) - \\ &\text{Cost of fertilizer application }(\text{USD}\cdot\text{ha}^{-1})\end{aligned} \quad (2)$$

N and P nutrient losses were calculated as follows:

$$\text{N runoff/Leaching losses }(\text{kg}\cdot\text{ha}^{-1}), \text{N} = \sum_{i=1}^{n}(CNi \times Vi) \quad (3)$$

where, *CNi* is the N concentration in the *i*-th runoff or leachate and V*i* is the volume of the *i*-th runoff or leachate;

$$\text{P runoff/Leaching losses }(\text{kg}\cdot\text{ha}^{-1}), \text{P} = \sum_{i=1}^{n}(CPi \times Vi) \quad (4)$$

where, *CPi* is the P concentration in the *i*-th runoff/leachate and *Vi* is the volume of the *i*-th runoff/leachate.

2.5 Statistical analysis

The data were processed in Excel 2016 (Microsoft Corp., Seattle, WA, USA) and statistically analyzed using IBM SPSS 25 (SPSS Inc., Armonk, NY, USA) software. Economic traits, loss amount was analyzed using a one-way analysis of variance (ANOVA). Multiple comparisons were performed using Duncan's test at $\alpha = 0.05$. The timing and total amount of nutrient loss were plotted by Origin 2023 (Origin Laboratory., Northampton, MA, USA).

3 Results

3.1 Yield and economic traits

Yield and gross value were significantly affected by fertilizer treatment and year ($p < 0.001$, Table 3), whereas average price and the proportion of high-quality tobacco were not significantly affected. The interaction effect between treatment and year was not significant for economic traits of tobacco. Fertilizer application significantly increased the yield and gross value of flue-cured tobacco compared with CK treatments, in which the FP and OMC treatments also significantly increased the average price and the proportion of upper-medium tobacco (Table 3). For yield, no significant differences were observed among the fertilized treatments, although the numerical values were ordered MF > OMC > FP, and MF and OMC treatments were 3.8% and 2.6% higher than the FP treatment. Compared with the FP treatment, the OMC treatment significantly increased the gross value and the proportion of upper-medium tobacco by 8.8% and 9.1%, respectively. In parallel, we examined the fertilizer costs and labor costs required for the different treatments in order to better explain the economic traits between the different treatments. The results show that the MF treatment had the highest net value of production with a significant increase of 26.8% over the FP treatment, followed by the OMC treatment with an increase of 19.0% over the FP treatment.

The results of this 2-year trial show that the gross value and the proportion of high-quality tobacco leaves in the OMC treatment were significantly higher than those in the FP treatment, but there were no significant differences between them and the MF treatment. Overall yield and net value in 2022 decreased by 15.7% and 17.9%, respectively, compared with 2021, but did not change average price and the proportion of upper-medium tobacco.

3.2 N loss characteristics

3.2.1 Total N loss

This study examined the loss characteristics of TN through

Table 3 Economic traits of flue-cured tobacco in different fertilizer treatments

Treatments (T)	Yield ($t\cdot ha^{-1}$)	Gross value ($USD\cdot ha^{-1}$)	Average price ($USD\cdot kg^{-1}$)	Proportion of upper-medium tobacco (%)	Net value ($USD\cdot ha^{-1}$)
CK	2.12 b	6750 c	3.20 b	74.5 b	5907 c
FP	2.51 a	8831 b	3.54 a	76.5 b	6334 b
MF	2.60 a	9081 ab	3.49 ab	80.4 ab	8031 a
OMC	2.57 a	9612 a	3.74 a	83.4 a	7540 ab
Year (Y)					
2021	2.66	9251	3.47	79.3	7636
2022	2.24	7885	3.51	78.1	6270
Source of variation					
T	***	***	ns	ns	***
Y	***	***	*	*	***
T×Y	ns	ns	ns	ns	ns

Note: Means followed by the same letter are not significantly different between treatments ($p < 0.05$) according to repeated-measures ANOVA, followed by Duncan's multiple comparison test. ns, not significant; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$; CK, no fertilizer; FP, farmer practice of solely organic fertilizer application; MF, mineral fertilizer; and OMC, combination of organic and mineral fertilizer.

environmental pathways (Fig. 2). Over the 2-year period, the cumulative TN loss ranged from 4.59 to 9.65 kg·ha^{-1} via surface runoff and a more substantial 12.4–25.4 kg·ha^{-1} via leaching. These results indicate that leaching was the predominant pathway for TN loss in this system. All fertilizer applications significantly increased TN losses through both pathways compared to CK, with significant differences also observed among the various fertilizer treatments.

The loss pathway for TN varied by fertilizer application strategy. Runoff losses of TN were highest for FP, whereas the MF treatment resulted in the highest loss via leaching. Compared to the FP and MF treatments, the OMC treatment resulted in a 27.8% and 19.3% reduction in TN runoff loss, respectively (Fig. 2(b)). Similarly, it decreased TN leaching loss by 21.3% and 28.0% relative to the FP and MF treatments. The temporal dynamics of N loss were closely associated with fertilizer application timing and rainfall events. Runoff losses of TN followed the pattern of precipitation, peaking during July with the highest rainfall volumes and declined as rainfall volumes declined (Fig. 2(a)). Overall TN loss and its variability were higher in the 2021 growing season. Among the fertilized treatments, the OMC treatment consistently maintained the lowest mean monthly TN loss throughout the study. However, statistically significant differences in TN loss between the OMC treatment and others were primarily confined to the early and middle stages of the 2021 season.

Means with the same lowercase letter are not significantly different for runoff and leaching separately between treatments ($p < 0.05$) according to repeated-measures ANOVA, followed by Duncan's multiple comparison test. Means with the same uppercase letter are not significantly different for aggregate TN loss between treatments ($p < 0.05$) according to repeated-measures ANOVA, followed by Duncan's multiple comparison test. Error bars represent SE. CK, no fertilizer; FP, farmer practice of solely organic fertilizer application; MF, mineral fertilizer; and OMC, combination of organic and mineral fertilizer.

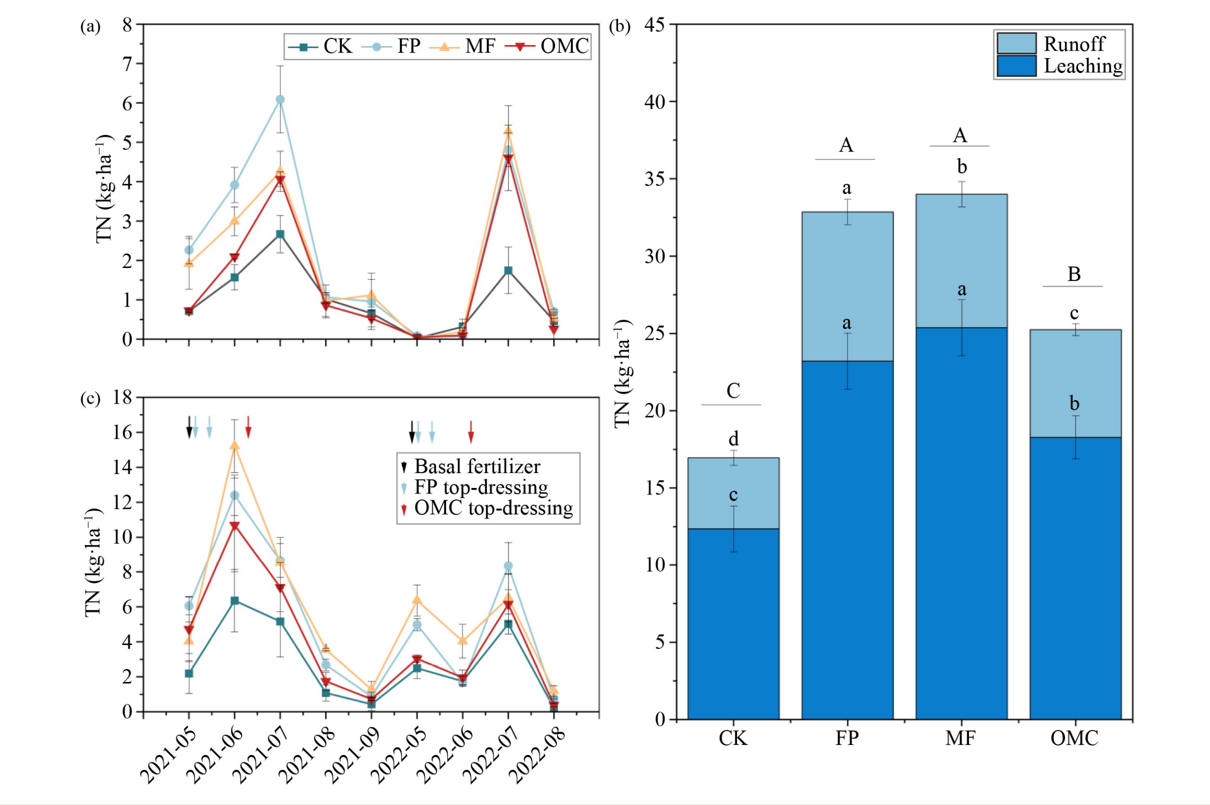

Fig. 2 Runoff (a) and leaching (c) losses of total N (TN) (b) during the 2021 and 2022 tobacco seasons.

3.2.2 NO_3^--N loss

The cumulative loss of NO_3^--N over the 2-year period ranged from 2.69 to 4.72 kg·ha^{-1} via runoff and a higher 8.00–16.0 kg·ha^{-1} via leaching, establishing leaching as the predominant loss pathway for this mobile anion (Fig. 3). Regarding runoff loss, a trend was observed with NO_3^--N losses in the order of FP > MF > OMC > CK; however, these differences among treatments were not statistically significant. In contrast, for leaching loss, the MF and FP treatments resulted in significantly higher NO_3^--N losses than the OMC and CK treatments. The OMC treatment reducing NO_3^--N leaching by 24.5% and 36.9% compared to the FP and MF treatments, respectively. Mineral-N loss accounted for 47.6% to 62.9% of TN runoff loss and accounted for 58.7% to 70.5% of TN leaching loss; NO_3^--N was the main form of mineral-N loss (Fig. 3(b)). The temporal dynamics of NO_3^--N loss had seasonal peaks corresponding to periods of high rainfall. In runoff, NO_3^--N losses peaked in July of both years (Fig. 3(a)). For leaching, the peak loss occurred in June of 2021 but shifted to July in 2022 (Fig. 3(c)). This earlier peak in 2021 corresponded with a high-intensity rainfall event that occurred in June of that year, shortly after fertilizer application.

Means with the same letter are not significantly different between treatments ($p < 0.05$) for runoff and leaching separately according to repeated-measures ANOVA, followed by Duncan’s multiple comparison test. Error bars represent SE. CK, no fertilizer; FP, farmer practice of solely organic fertilizer application; MF, mineral fertilizer; and OMC, combination of organic and mineral fertilizer.

3.2.3 NH_4^+-N loss

The cumulative loss of NH_4^+-N over the 2-year period was relatively low, ranging from 0.11 to 0.14 kg·ha^{-1} via surface runoff and from 0.64 to 0.71 kg·ha^{-1}via subsurface leaching (Fig. 4). Although both pathways contributed to NH_4^+-N loss, leaching was quantitatively the more significant route. For both runoff and leaching, only the FP treatment resulted in a significantly higher NH_4^+-N loss compared to the CK; the MF

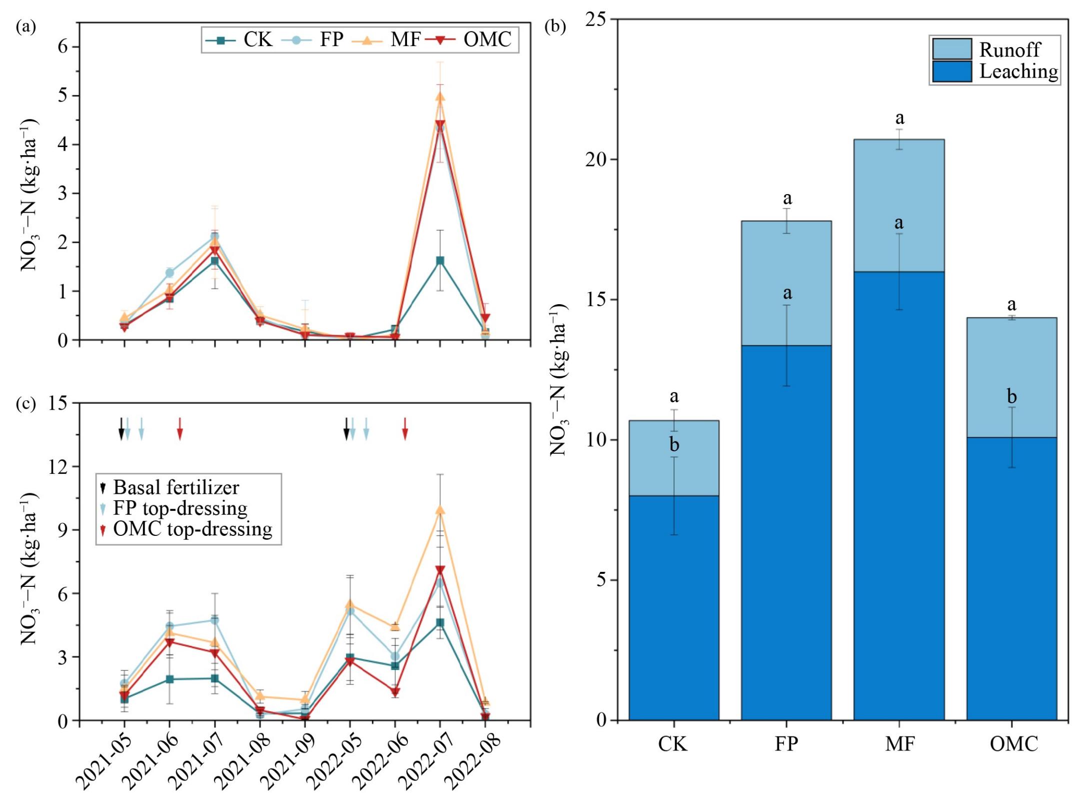

Fig. 3 Runoff (a) and leaching (c) losses of nitrate nitrogen (NO_3^--N) (b) during the 2021 and 2022 tobacco seasons.

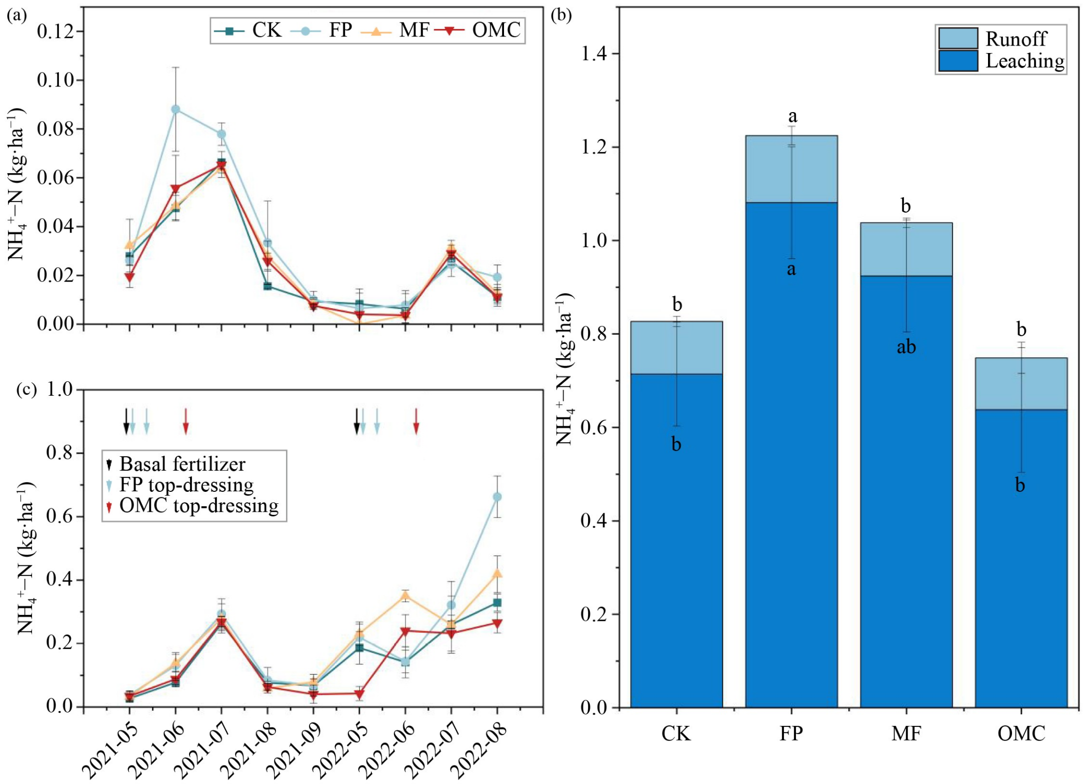

Fig. 4 Runoff (a) and leaching (c) losses of ammonium nitrogen (NH_4^+-N) (b) during the 2021 and 2022 tobacco seasons.

and OMC treatments were not significantly different from CK for NH_4^+-N loss. When comparing among the fertilizer treatments, NH_4^+-N runoff loss from the OMC treatment was significantly lower (by 22.6%) than from the FP treatment. For leaching, NH_4^+-N loss from the OMC treatment was 41.0% and 31.0% lower than from the FP and MF treatments, respectively, although these differences were not statistically significant (Fig. 4(b)). The temporal dynamics of NH_4^+-N loss differed notably between the two pathways and across the two study-years. Runoff loss declined from the 2021 to 2022 season, whereas leaching loss increased from the 2021 to 2022 season (Fig. 4(a)). A distinct trend emerged late in the 2022 growing season, as NH_4^+-N leaching began to increase across all treatments (Fig. 4(c)). This increase was most pronounced in the FP treatment, followed by the MF treatment.

Means with the same letter are not significantly different between treatments ($p < 0.05$) for runoff and leaching separately according to repeated-measures ANOVA, followed by Duncan's multiple comparison test. Error bars represent SE. CK, no fertilizer; FP, farmer practice of solely organic fertilizer application; MF, mineral fertilizer; and OMC, combination of organic and mineral fertilizer.

3.3 P loss characteristics

3.3.1 Total P loss

The cumulative loss of TP over the 2-year study ranged from 0.29 to 0.41 kg·ha^{-1} via runoff and 0.69–0.96 kg·ha^{-1} via leaching (Fig. 5). Therefore, leaching represented the primary pathway for TP loss in this system. For runoff loss, the FP treatment was significantly higher than the MF and CK treatments, but no significant difference was observed between the OMC and the other treatments. Regarding leaching loss, a clear trend of FP = MF > OMC = CK was observed. Compared with the FP and MF treatments, the OMC treatment significantly reduced TP leaching by 17.3% and 17.1%, respectively (Fig. 5(b)). The monthly dynamics of TP runoff loss exhibited distinct patterns between the two years

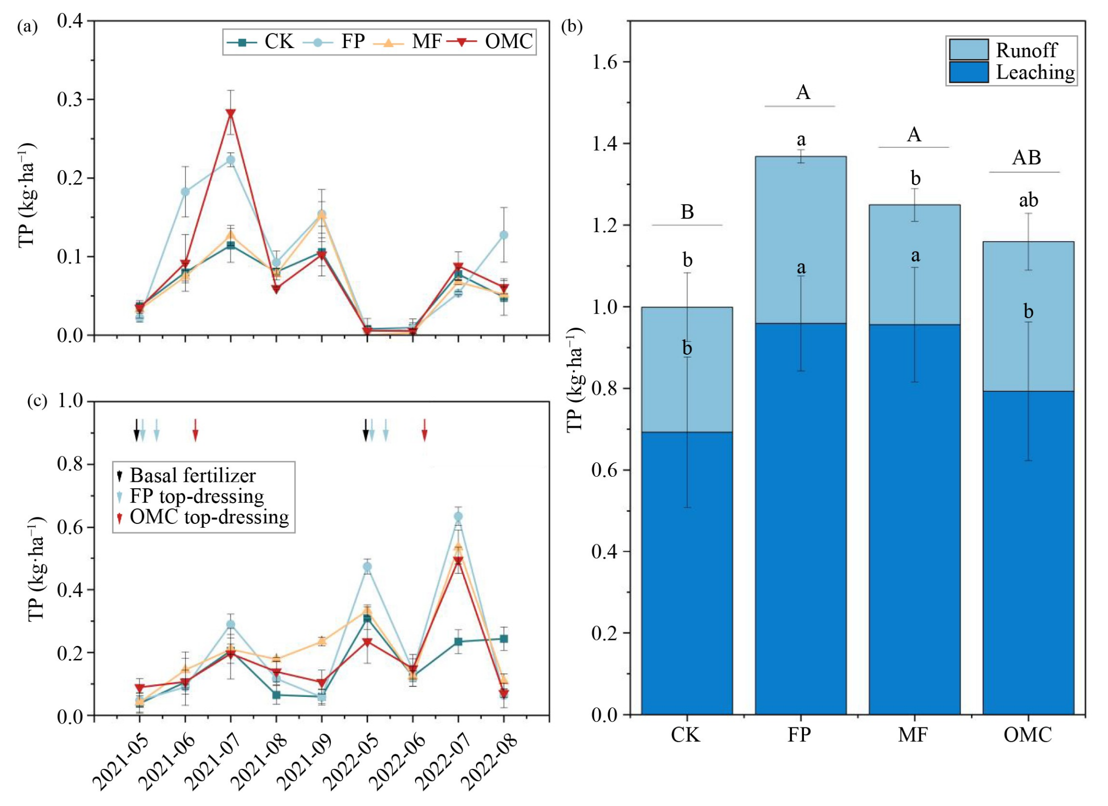

Fig. 5 Runoff (a) and leaching (c) losses of total phosphorus (TP) (b) during the 2021 and 2022 tobacco seasons. Means with the same lowercase letter are not significantly different for runoff and leaching separately among treatments ($p < 0.05$) according to repeated-measures ANOVA, followed by Duncan's multiple comparison test. Means with the same uppercase letter are not significantly different for aggregate TP loss among treatments ($p < 0.05$) according to repeated-measures ANOVA, followed by Duncan's multiple comparison test. Error bars represent SE. CK, no fertilizer; FP, farmer practice of solely organic fertilizer application; MF, mineral fertilizer; and OMC, combination of organic and mineral fertilizer.

(Fig. 5(a)). In 2021, after fertilizer application in May, TP runoff losses tracked the seasonal rainfall pattern, increasing to a peak in July before declining. Notably, despite decreasing rainfall in September 2021, a secondary peak in TP loss occurred, with the FP and MF treatments recording the highest losses. In 2022, TP runoff remained relatively stable from May to June before again peaking in July. However, between July and August 2022, while TP losses in most treatments declined along with rainfall, those from the FP treatment continued to rise.

3.3.2 Total dissolved P loss

Cumulative TDP losses ranged from 0.18 to 0.25 kg·ha^{-1} via runoff and from 0.14 to 0.27 kg·ha^{-1} via leaching (Fig. 6). However, the proportion of TP loss that occurred as TDP differed significantly between pathways. In runoff, TDP was the predominant form of P, accounting for 53.6% to 67.7% of the total TP loss. In stark contrast, TDP represented a much smaller fraction of leached TP, comprising only 19.6%–28.5% of the total (Fig. 6(b)).

The effects of the treatments on TDP loss were also pathway-dependent. For runoff, the OMC treatment resulted in the highest TDP loss, followed by the FP treatment. For leaching loss, all fertilizer treatments significantly increased TDP loss compared with the CK treatment. Among the treatments, the OMC treatment significantly reduced TDP leaching by 29.1% compared with the FP treatment, but was not significantly different from the MF treatment. Regarding temporal patterns, the loss characteristics of TDP were similar to those of TP, with

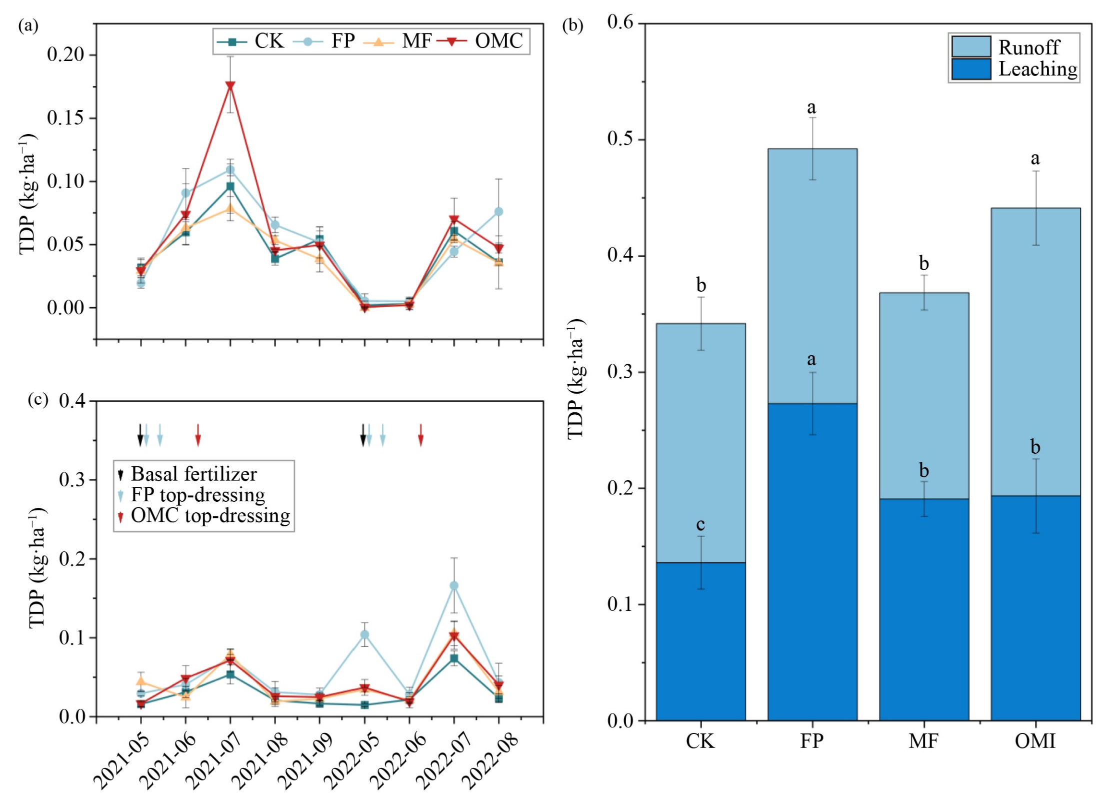

Fig. 6 Runoff (a) and leaching (c) losses of total dissolved phosphorus (TDP) (b) during the 2021 and 2022 tobacco seasons. Means with the same letter are not significantly different between treatments ($p < 0.05$) for runoff and leaching separately according to repeated-measures ANOVA, followed by Duncan's multiple comparison test. Error bars represent SE. CK, no fertilizer; FP, farmer practice of solely organic fertilizer application; MF, mineral fertilizer; and OMC, combination of organic and mineral fertilizer.

peak losses for both pathways consistently occurring in July of each year (Fig. 6(a, c)).

3.4 Correlation of soil properties with N and P loss

3.4.1 Post treatment soil properties

Although a net decline in most soil nutrients was observed across all treatments relative to initial values, the treatments differed in their relative effects on mitigating this decline (Table 4). After the 2-year experimental period, the soil properties varied among the treatments. For SOM, the highest concentration was observed in the FP treatment, followed in descending order by OMC, MF and CK, with significant differences among all treatments. Similarly, the FP and OMC treatments maintained higher STN concentrations compared to the CK and MF treatments. For STP, the OMC treatment maintained the highest final concentration, which was significantly greater than the concentrations in the MF and CK treatments. For available nutrients, no significant differences were observed among the fertilized treatments for AN, AP, AK and NO_3^--N. However, for NH_4^+-N, all three fertilized treatments had significantly higher residual concentrations than the CK treatment.

3.4.2 N and P loss correlation

In this study, runoff and leaching data for TN and TP were compared with soil physicochemical properties to investigate the factors influencing nutrient losses in the study area. Nutrient losses were strongly related to several indicators (Fig. 7). For runoff TN losses (Fig. 7(a)), positive correlations were observed with SOM, STN, AN and NO_3^--N (all $p < 0.05$), and AN had the strongest correlation with TN runoff loss. For

Table 4 Post treatment soil properties of tobacco fields in different fertilizer treatments

Physicochemical property	CK	FP	MF	OMC
SOM ($g \cdot kg^{-1}$)	51.8 d	58.9 a	53.7 c	56.5 b
STN ($g \cdot kg^{-1}$)	2.95 b	3.50 a	3.0 b	3.6 a
STP ($g \cdot kg^{-1}$)	1.39 c	1.59 ab	1.45 bc	1.67 a
STK ($g \cdot kg^{-1}$)	12.0 a	11.7 a	11.7 a	11.5 a
AN ($mg \cdot kg^{-1}$)	174 b	192 a	195 a	182 ab
AP ($mg \cdot kg^{-1}$)	68.6 b	76.9 a	71.9 ab	77.1 a
AK ($mg \cdot kg^{-1}$)	398 a	395 a	381 a	404 a
NO_3^--N ($mg \cdot kg^{-1}$)	18.7 a	22.1 a	20.4 a	22.0 a
NH_4^+-N ($mg \cdot kg^{-1}$)	0.36 b	0.57 a	0.58 a	0.57 a

Note: Means with the same letter are not significantly different between treatments ($p < 0.05$) according to repeated-measures ANOVA, followed by Duncan's multiple comparison test. ns, not significant. CK, no fertilizer; FP, farmer practice of solely organic fertilizer application; MF, mineral fertilizer; OMC, combination of organic and mineral fertilizer. SOM, soil organic matter content; STN, soil total nitrogen; STP, soil total phosphorus; STK, soil total potassium; AN, Alkaline hydrolysis nitrogen; AP, soil available phosphorus; AK, soil available potassium; NO_3^--N, nitrate nitrogen; NH_4^+-N, ammonium nitrogen.

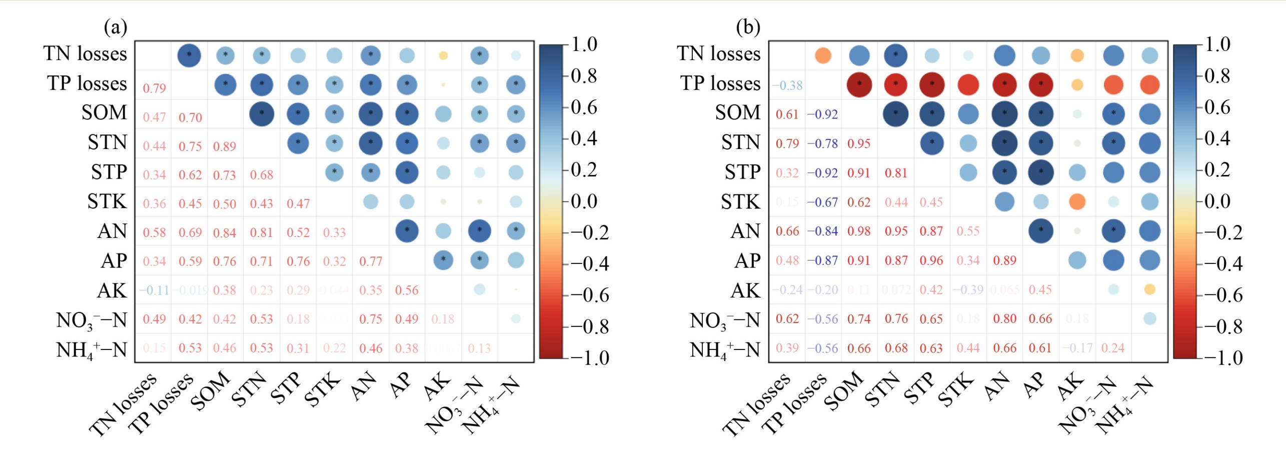

Fig. 7 Correlation coefficient matrix between nutrient loss and various factors for runoff loss (a) and leaching loss (b). The size and color of the circle indicate the strength of the correlation. *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$; SOM, soil organic matter content; STN, soil total nitrogen; STP, soil total phosphorus; STK, soil total potassium; AN, alkaline hydrolysis nitrogen; AP, soil available phosphorus; AK, soil available potassium; NO_3^--N, nitrate nitrogen; and NH_4^+-N, ammonium nitrogen.

runoff TP losses, a negative correlation was found with AK, whereas positive correlations were observed with all other measured physicochemical properties ($p < 0.05$). STN had the strongest correlation with TP runoff loss. In addition, a positive correlation was observed between runoff TN and TP losses ($p < 0.05$). For leaching TN losses (Fig. 7(b)), a positive correlation was observed only with STN ($p < 0.05$). For leaching TP losses, negative correlations were observed with SOM as well as with STN, STP, AN, and AP (all $p < 0.05$). No significant correlation was observed between TN and TP losses in the leaching process.

4 Discussion

4.1 Economic traits

The application of mineral nutrients via fertilizers is crucial for optimal plant growth and has become a standard practice in modern agriculture. Growing global demand for food and high-quality agricultural products has driven the widespread use of fertilizers to maximize productivity on existing farmland[29]. In this study, the use of fertilizers significantly increased the yield and gross value of flue-cured tobacco so that it could effectively meet the social needs (Table 3). However, the high fertilizer inputs of the FP did not significantly enhance the proportion of high-quality tobacco and focusing primarily on maximizing yield can lead to significant nutrient losses[30]. The OMC treatment produced an optimum balance between productivity and environmental losses. Although the yield of the OMC treatment did not exhibit a statistically significant difference compared to the MF treatment, the long-term effects of organic substitution necessitate further observation and validation.

This study also analyzed the input costs of different treatments. To ensure the economic evaluation was representative of local farming practices, all agronomic operations were conducted following standardized local protocols. The cost assessment focused on fertilizer prices and labor expenses, as other inputs, such as pesticides or machinery, were kept constant across treatments and were therefore excluded. To ensure a realistic economic comparison, standard labor costs for weeding and pesticide application, tasks that local farmers typically perform concurrently with fertilizer application, were calculated across all treatments, including the CK. The analysis revealed that the MF and the OMC treatment achieved the highest net value indicating the most favorable balance between input costs and economic returns. The cost advantage of the MF treatment was primarily due to its lower fertilizer application frequency and the high nutrient content of mineral fertilizers, which reduced the required labor expense for application. However, the fertilizer application strategy in the MF treatment is not synchronized with the pattern of crop nutrient uptake. Although this method can achieve high yields in the short-term, it results in an overall higher nutrient loss, which is similar to the findings of Zhu et al.[31] and can have a greater impact on the environment in the long-term.

4.2 N loss

The results demonstrate that the OMC treatment markedly reduced N runoff and leaching loss in both seasons, compared to the FP treatment (Fig. 3), which is consistent with previous research[32]. In contrast, the MF treatment exacerbated the runoff loss of NO_3^--N, as it is likely due to the rapid nutrient release from soluble fertilizers[33]. Monthly variations in N loss displayed a peak in July for both years, attributable to the overlap of fertilizer application and rainfall. This concurrent activity strongly influenced nutrient dynamics, with the resulting runoff driving both the transport of dissolved N and causing splash and surface erosion, which may contribute to particulate N loss[34]. Concerning the form of N loss, the predominance of NO_3^--N in losses from tobacco fields in the ELB is primarily determined by the proportion of mineral N, especially nitrate, in the farmland soil, which in turn is heavily influenced by fertilizer use. A particularly noteworthy finding was the TN and NO_3^--N losses through leaching were higher in June than July of 2021, when every other loss peaked in July. We attribute this phenomenon to the interaction between underlying N transformation and transport and rainfall. Specifically, our rainfall data show that a high-intensity rainfall event occurred in June 2021. After fertilizer application in May, a large amount of highly mobile nitrate accumulated in the surface soil, and rainfall caused large-scale downward transport of nitrate, resulting in an early leaching peak. At the same time, the heavy rainfall during this period may have caused soil saturation, forming temporary anaerobic conditions, inhibiting aerobic nitrification processes[35]. At the same time, NH_4^+-N produced by mineralization accumulated and adsorbed onto soil particles because it could not be nitrified. Subsequent large amounts of runoff led to increased NH_4^+-N loss by eroding these particles[36]. In contrast, rainfall in June 2022 was milder, resulting in the postponement of the main leaching event until the arrival of more intense monsoon rainfall in July. This highlights that the timing of the first major rainfall event after fertilizer application is a key factor controlling the temporal dynamics of nitrate leaching losses in this system.

4.3 P loss

Our results demonstrate that both the MF and OMC treatments were effective in reducing TP loss relative to FP, which is in agreement with other studies conducted in the ELB[37]. The total amount of P applied in each treatment was FP (33 kg·ha^{-1}), OMC (17 kg·ha^{-1}) and MF (13 kg·ha^{-1}). While previous studies suggest applied P correlates with P loss, our results reveal a more complex relationship[38]. TDP runoff loss from the OMC treatment was not significantly different from the FP treatment, but it was significantly higher than from the MF treatment. This may be because the amount of P fertilizer applied in this study was different, and the forms of P fertilizer were also different. The OMC treatment contained 8.7 kg·ha^{-1} of fast-acting water-soluble P, which constituted a risk source that could be directly washed away when runoff occurred. Secondly, during the decomposition process, its organic components can compete with the soil for P adsorption sites by releasing organic acids, thereby inhibiting the soil from fixing the above-mentioned soluble P and improving its migration ability in the soil surface[39]. This result is notable because the OMC treatment had a lower input of readily available P (8.7 kg·ha^{-1} P from mineral fertilizer) than the MF treatment (13 kg·ha^{-1} P) yet still produced higher TDP runoff. This phenomenon strongly confirms our speculation: in the absence of organic material protection, the soluble P in the MF treatment is more easily adsorbed and fixed by the soil, thereby reducing its risk of migration and loss with runoff. The application of fertilizers can result in the formation of different types of P, each having a distinct level of environmental response[40]. Therefore, analyzing the impact of different organic fertilizer types and their substitution strategies on P forms is essential to elucidate the underlying mechanisms by which organic substitution management affects P loss.

Between years, runoff and leaching losses of P had different distribution patterns. Runoff losses of P were higher in 2021 than in 2022, but leaching losses were lower. In terms of runoff and leaching volumes, runoff was less than leaching in both 2021 and 2022, suggesting that most of the loss was through leaching. Therefore, it can be inferred that the interannual variability in P loss was likely driven by a combination of rainfall amount and intensity. 2021 had a greater variation in rainfall intensity; the greater the total rainfall, the greater the volume of runoff generated[41]. When rainfall intensity exceeds infiltration capacity, greater rainfall volumes typically produce greater volumes of surface runoff[42]. This will therefore increase the total runoff P loss.

At the same time, we found that in leaching loss, the proportion of TDP in TP loss was relatively small, and most P was lost in a particulate P form. Future research should focus on measures to control particulate P loss, targeting solutions to the problem of nutrient loss. Therefore, to ensure effective nutrient management, fertilizer application timing and techniques can be further optimized and in-field strategies guided by the 4R stewardship principles should be adopted to facilitate comprehensive management in focused areas[43].

4.4 Changes in post treatment soil properties and their relationship with nutrient loss

This study confirms that nutrient loss from farmland is a multifaceted process, influenced by a combination of factors including inherent soil properties, fertilizer application regimes, rainfall patterns and management practices. Building on this understanding, our study had two primary objectives: first, to evaluate the impact of different fertilizer application strategies on TN and TP losses; and second, to investigate how these strategies alter soil properties over a 2-year period and how these altered properties, in turn, regulate nutrient loss. Building on this understanding, our study had two primary objectives: first, to evaluate the impact of different fertilizer application strategies on TN and TP losses; and second, to investigate how these strategies alter soil properties over a 2-year period and how these altered properties, in turn, regulate nutrient loss. A critical finding was the net depletion of soil nutrients across all treatments, including those with fertilizer, relative to baseline levels. This indicates that total nutrient outputs from crop uptake and environmental losses surpassed nutrient inputs. This nutrient deficit was driven by the combination of substantial nutrient removal by the high-yielding tobacco crop and significant environmental losses via runoff and leaching[44,45]. Even the highest fertilizer inputs were insufficient to compensate for these combined losses, creating a potential vicious cycle of escalating fertilizer rates and environmental degradation. While the optimized OMC strategy in our study offers a step toward mitigating this cycle, future research must prioritize advanced practices that can achieve a true nutrient balance or surplus, rather than merely minimizing relative losses. The FP treatment had a high nutrient input, and most of it was organic fertilizer, so it significantly increased SOM, STN and STP compared to the CK treatment. The application of organic fertilizer directly inputs organic carbon sources into the soil and can promote the formation of humus to increase the SOM content[46,47]. Nutrients applied to the soil that are not immediately absorbed by crops or lost to the environment, particularly P and K, can be retained in the soil, creating a nutrient reserve for subsequent crops.

Of the post treatment soil properties measured, STN is a common factor affecting TN runoff and leaching, which is consistent with previous research results[48]. In addition, TN loss via runoff was positively correlated with SOM, AN and NO_3^--N. SOM is typically associated with improved soil structure and enhanced crop N uptake, which may help reduce nutrient loss. Notably, our correlation analysis revealed that TP loss was positively correlated with several key soil properties, including SOM, STN and AN. While this indicates a complex interplay, the most direct explanation for these concurrent correlations likely lies in a single confounding factor: our experimental design. The highest levels of SOM, STN and AN were all observed as a direct result of the FP treatment. This same treatment also involved the highest total P application rate. Therefore, these positive correlations are likely indirect artifacts rather than direct causal relationships. The plots with the highest organic matter and N status were also the plots that received the highest P loading, which was the primary driver of P loss. However, beyond this primary confounding effect, a secondary biogeochemical mechanism may also have contributed. The high inputs of carbon and N from the organic fertilizer could have stimulated overall microbial activity. This increased activity, in a system potentially limited by P, may have enhanced the microbial mineralization of soil organic P to meet stoichiometric demands, thereby converting a portion of the stable P pool into more mobile, loss-prone forms[49].

5 Conclusions

This study elucidates the impact of optimized nutrient management on N and P loss in tobacco fields within the ELB. Compared to the common farmer practice, the OMC treatment represents a more balanced approach, reducing nutrient runoff and leaching while also increasing the gross value of the tobacco. Nitrogen loss in tobacco fields primarily occurred through leaching, with mineral N mainly lost in the form of NO_3^--N. TDP is the main form of P runoff loss, but it accounts for a smaller proportion of the leaching loss. Therefore, future research should focus on reducing the leaching loss of different P forms based on existing practices. The peak loss of N and P in June and July reflects the interaction between high nutrient availability post-fertilizer application and the increased runoff and leaching driven by intense seasonal rainfall. The study also revealed complex correlations between key soil properties (SOM, STN and AN) and nutrient losses, highlighting region-specific factors that influence nutrient dynamics. This study was conducted at a single location, focusing on the influence of certain factors on nutrient loss. Future research should focus on validating these single-location findings across the diverse Erhai Lake Basin and further optimizing the OMC treatment, including application timing, rates and sources, to maximize its economic and environmental benefits.

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Compliance with ethics guidelines

Chen Wang, Qi Miao, Yingxin Guo, Lu Liu, Zhiyong Fan, Yanxia Hu, Dexun Wang, Junying Li, Junwei Sun, and Zhenling Cui declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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