RESEARCH ARTICLE

Nutrient dynamics in water and soil under conventional rice cultivation in the Vietnamese Mekong Delta

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Abstract

Background The evaluation of nutrient variability plays a crucial role in accessing soil potentials and practical intervention responses in rice production systems. Synthetic fertilizer applications and cultivation practices are considered key factors affecting nutrient dynamics and availability. Here, we assessed the nutrient dynamics in surface, subsurface water and soil under local water management and conventional rice cultivation practices in the Vietnamese Mekong Delta.

Methods We implemented a field experiment (200 m²) in the 2018 wet season and the 2019 dry season in a triple rice-cropping field. Surface water, subsurface water (30–45 cm), and topsoil (0–20 cm) were collected eight samples during the rice-growing seasons to clarify its nutrient dynamic.

Results The results showed that N-NH₄⁺, P-PO₄³⁻ and total P peaks were achieved after fertilizing. Irrespective of seasons, the nutrient content in surface water was always greater than that of subsurface water (P<0.001), with the exception of N-NO₃⁻, no significant difference was disclosed (P>0.05). When comparing the wet and dry seasons, nutrient concentrations exhibited minor differences (P>0.05). Under conventional rice cultivation, the effects of synthetic fertilizer topdressing on the total N, soil organic matter (SOM), and total P were negligible in the soil. Higher rates of N fertilizer application did not significantly increase soil N-NH₄⁺, total N, yet larger P fertilizer amounts substantially enhanced soil total P (P<0.001).

Conclusions Under conventional rice cultivation, the low concentration of N-NH₄⁺, P-PO₄³⁻ and total P in the subsurface water indicated that nutrient losses mainly occur through runoff rather than leaching. Notably, nutrient content in soil was fairly high,
whilst SOM was varied from low to medium between seasons. Future work should consider the nutrient balance and nutrient dynamic simulation on surface and subsurface.

**Keywords**
nutrient availability, nutrient loss, surface water, subsurface water, soil, the Vietnamese Mekong Delta, water management

This article is included in the Agriculture, Food and Nutrition gateway.
Introduction
The Mekong Delta (MD) is the biggest rice-producing region in Vietnam (Clauss et al., 2018), accounting for approximately 55% of total national rice (Oryza sativa L.) outputs through intensive rice production systems (Uno et al., 2021). Here, double-and triple rice-cropping systems are the most commonly employed rice cultivation practices in the MD. Along with agronomic practices in intensive rice-based farming systems, a vast amount of fertilizer is typically applied to the paddy fields to obtain higher yields. For conventional rice cultivation in the MD’s paddy fields, the amount of fertilizer application in the wet season (WS) and dry season (DS) has been found to vary from 82–97 kg N ha⁻¹, 22.64–22.69 kg P ha⁻¹, and 29–32 kg K ha⁻¹ (Stuart et al., 2018). Common practices in the MD typically use fertilizers, water, and seeds well exceeding recommended rates sustainable rice farming practices combined in the national program “One Must Do, Five Reductions” (1M5R) (Stuart et al., 2018; Connor et al., 2021). It is reported that the efficacy of N use by rice plants is generally relatively low, roughly 30–35%, while N loss to the environment is approximately 50% (Zhu and Chen, 2002). Moreover, Irfan et al. (2020) and Schröder et al. (2011) revealed that P utilization efficacy varies 10–15%, whereas P loss to the environment ranges 9.7–12.4% and 0.3–0.5% for surface runoff and subsurface leaching, respectively (Cho et al., 2011). In the rice field, fertilizer and water management regimes are key factors affecting transport, as well as the use efficacy of N and P (Qi et al., 2020). Yang et al. (2015) reported that different water and fertilizer management practices exported 13.1–31.7% N input to the environment, in which N loss through ammonia accounted for 69.6–83.5%. Furthermore, it has been noted that N loss from rice soils typically occurs through ammonia volatilization and nitrification-denitrification (Shankar et al., 2021), while loss of P was comparatively low due to the enrichment of Ca²⁺, Fe³⁺ and Al³⁺ oxides which can adsorb P in several mineral forms (Wang et al., 2015; Scalenghe et al., 2014). Several previous studies reported that nutrient losses primarily occurred via surface water (SW) and subsurface water (SbW) (Peng et al., 2011; Qi et al., 2020; Schröder et al., 2011; Wang and Huang, 2021). Thus, it has been suggested that higher amounts of fertilizer application under conventional rice cultivation and local water management regimes would largely result in increased nutrients in adjacent environments. To the best of our knowledge, quantitative variability of nutrients in SW, SbW and soil under conventional rice farming practices of the Vietnamese MD has not been previously studied. Therefore, this paper aims to explore the temporal-spatial dynamics of nutrients in the SW, SbW and soil of triple rice-cropping models both during the WS and DS under conventional local farming practices.

Methods
Study area
This study was conducted at a local farmer's field in Long Tuyen district, Can Tho city, Vietnam (9°59’21”N, 105°36’14”E), from 2018 to 2019. The field experiment was located in a lowland soil, which applied triple-cropping rice, an intensive rice production system. According to Dong et al. (2012), the soil area was classified as Thionic Glycesol (International Union of Soil Sciences (IUSS) working group World Reference Base (WRB), 2015). The average weather data was annually recorded from 2015 to 2019 as follows: rainfall, 2,088.4 mm; humidity, 70.0–86.0%; sunshine, 2,467.4–2,695.4 hours (DONRE, 2020). The initial soil physicochemical properties were as follows: bulk density, 0.98 g cm⁻³; soil texture (sand, 1.9%, silt, 31.7%, and clay, 66.4%); soil organic matter (SOM), 35.4 g kg⁻¹.

Experimental design
The size of the field experiment was 200 m² (20 m × 10 m). The field was enclosed by a soil bank with plastic sheet coverage. The plastic sheet was buried 20 cm under the ground’s surface to secure against leaks or intrusion into the nearby fields. We conducted the field experiment in two seasons, including summer–autumn 2018 (wet season) and winter–spring 2019 (dry season). In summer–autumn 2018, the field experiment incorporated rice straw into the soil using a hand tractor. The straw was residue from the previous rice-growing season (spring–summer season 2018). The field witnessed a 10-day fallow period before sowing. In the winter–spring 2019 season, the field underwent a three-month natural flooding season. Before sowing, the field was drained and harrowed by a hand tractor. The rice crop calendar of the two field experiments is shown in Table 1. Table 1 shows the rice farming practices during the wet season 2018 (summer–autumn) and the dry season (winter–spring). The main practices comprise the schedule of soil preparation (ploughing), sowing, irrigation, fertilization, drainage, and harvest.
Rice cultivation and water management

Short-duration rice varieties of OM4900 and OM6976 cultivars for the WS and the DS were used, respectively. The varieties were obtained from Cuu Long Delta Rice Research Institution (CLRRI), Vietnam. The maturity of the two rice varieties varied from 95 to 100 days. The selection of varieties was based on common use and edaphological adaptation in this region. Pre-germinated seeds were sown at 150 kg ha\(^{-1}\) under saturated soil by direct seeding. Water was supplied from a watershed near the field. Water management followed the locally typical water use practices. Water irrigation was started on the seventh day after seeding (DAS), re-irrigated 5–7 cm before fertilizing, always retaining a water level of 1–3 cm during heading and flowering, and openly drained ten days before harvesting. Multiple drainages, which are a simplified form of alternative wetting and drying (AWD) typically conducted in the VMD (Uno et al., 2021), were performed whenever water level naturally decreased 10 cm below the soil surface for the remaining cultivation period.

Fertilizer application

We applied synthetic fertilizers according to locally conventional rice cultivation. In the WS, 129.5 kg N ha\(^{-1}\) and 75 kg P\(_2\)O\(_5\) ha\(^{-1}\) were used in total. The fertilizers were applied as follows: 55/42.5/32 kg N ha\(^{-1}\), 25/25/25 kg P\(_2\)O\(_5\) ha\(^{-1}\). In the DS, 90 kg N ha\(^{-1}\), 49 kg P\(_2\)O\(_5\) ha\(^{-1}\), and 70.5 kg K\(_2\)O ha\(^{-1}\). Fertilization was split into four intervals on days 10, 16, 26, and 47 DAS. The quantity of fertilizer was as follows: 30/15/30/34 kg N ha\(^{-1}\), 30/0/30/34 kg P\(_2\)O\(_5\) ha\(^{-1}\), and 22.5/0/22.5/22.5 kg K\(_2\)O ha\(^{-1}\). Nitrogen (N), phosphorous (P), and potassium (K) were applied based on the application of urea, superphosphate, and potassium chloride fertilizer. Applied fertilizer quantities for field experiments are shown in Table 2.

Measurements

Topsoil samples (10 cm) were collected by an auger with a 3.5 cm diameter. In the WS of 2018, we collected a soil sample before sowing to determine the soil’s initial physicochemical properties. During the growth period, soil samples were taken on days 9, 13, 19, 27, 39, 53, 65, and 72 DAS. In the dry season of 2019, soil samples were collected on days 7, 14, 21, 29, 44, 52, 61, and 72 DAS. Samples were collected at five cross-sectional sites (four corners and one midpoint)

<table>
<thead>
<tr>
<th>Practice</th>
<th>Wet season Date(^{†}) DAS</th>
<th>Dry season Date(^{†}) DAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ploughing</td>
<td>06/08/2018 – 10</td>
<td>28/01/2019 – 1</td>
</tr>
<tr>
<td>Sowing</td>
<td>16/08/2018 0</td>
<td>29/01/2019 0</td>
</tr>
<tr>
<td>Starting irrigation</td>
<td>22/08/2018 7</td>
<td>05/02/2019 8</td>
</tr>
<tr>
<td>Fertilization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 1(^{st}) topdressing</td>
<td>25/08/2018 10</td>
<td>07/02/2019 10</td>
</tr>
<tr>
<td>- 2(^{nd}) topdressing</td>
<td>04/09/2018 20</td>
<td>13/02/2019 16</td>
</tr>
<tr>
<td>- 3(^{rd}) topdressing</td>
<td>01/10/2018 47</td>
<td>23/02/2019 26</td>
</tr>
<tr>
<td>- 4(^{th}) topdressing</td>
<td>-</td>
<td>16/03/2019 47</td>
</tr>
<tr>
<td>Drainage</td>
<td>08/11/2018 85</td>
<td>23/04/2019 85</td>
</tr>
<tr>
<td>Harvest</td>
<td>18/11/2018 95</td>
<td>04/05/2019 95</td>
</tr>
</tbody>
</table>

\(^{†}\)Date is formatted as dd/mm/yyyy; DAS = day after seeding.

Table 2. Fertilizer quantities applied during the field experiment.

<table>
<thead>
<tr>
<th>Fertilization</th>
<th>Wet season</th>
<th>Dry season</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(^{st}) topdressing</td>
<td>55, 25, 0</td>
<td>30, 30, 22.5</td>
</tr>
<tr>
<td>2(^{nd}) topdressing</td>
<td>42.5, 25, 0</td>
<td>15, 0, 0</td>
</tr>
<tr>
<td>3(^{rd}) topdressing</td>
<td>32, 25, 0</td>
<td>30, 30, 22.5</td>
</tr>
<tr>
<td>4(^{th}) topdressing</td>
<td>-</td>
<td>34, 34, 22.5</td>
</tr>
</tbody>
</table>

\(^{†}\)Fertilizers applied were: N, P\(_2\)O\(_5\), K\(_2\)O (kg ha\(^{-1}\)).
and mixed to a similar weight to achieve a compromised sample. Fresh soil samples were removed of visible biomass, and air-dried and sieved at 2 mm. Soil texture was measured by sieving particle sizes to separate out coarse sand from the finer particles and the silt and clay contents were then determined by measuring the rate of settling of these two separates from the suspension in water according to the Robinson pipette method (Carter and Gregorich, 2008). Bulk density samples were collected by core samplers and the cores were dried in an oven at 110°C until the weight was constant in accordance with the Core method (Blake and Hartge, 1986). Soil organic matter (SOM) was oxidized by a K$_2$Cr$_2$O$_7$-H$_2$SO$_4$ oxidation procedure and titrated using (NH$_4$)$_2$Fe(SO$_4$)$_2$(H$_2$O)$_6$ solution (Walkley and Black, 1934). NH$_4^+$ was extracted by KCl 1M (1:10 soil/extract (wt:vol)) and measured according to the indophenol blue colorimetric method (Lu, 2000). Total N (TKN) was digested in the digestion tablets (K$_2$SO$_4$, CuSO$_4$, and Se) and H$_2$SO$_4$ solution at 375°C, then the digest was analyzed for NH$_4^+$ by the automated phenate method according to the Kjeldahl method (Bremner, 1996). Total P (TP) was digested in sulphuric acid-hydrogen peroxide-hydrofluoric acid (H$_2$SO$_4$-H$_2$O$_2$-HF) and detected by the molybdenum blue method (Bowman, 1988).

We also established a similar sampling program among SW, SbW, and soil. Likewise, SW samples were collected at soil sampling points and then mixed to obtain a joint representative sample. For SbW sampling, we installed five PVC pipes (120 cm in length and 9 cm in diameter) around the selected sampling points. The pipe was perforated by 2 mm holes and covered underneath by a lid. A plastic net of 2 mm was wrapped around the perforated pipe to avoid sediment intrusion. At each selected site, the pipe was anchored under the soil surface at 0.45 m depth. A lid was used to cover the pipe during non-sampling periods. NH$_4^+$ around the perforated pipe to avoid sediment intrusion. At each selected site, the pipe was anchored under the soil surface at 0.45 m depth. A lid was used to cover the pipe during non-sampling periods. NH$_4^+$ was consistently higher than in the SbW. Particularly, the rate of N-NH$_4^+$ is significantly higher in the SW in the WS compared to the DS. However, the effects of synthetic fertilizer topdressing on the TN (in the WS), SOM, and TP were negligible.

Analysis

We assessed the nutrient variation in SW, SbW, and soil between the WS and DS and compared the concentration of water environmental parameters between SW and SbW. The differences between levels of each factor were analysed assuming equal variances (Student’s t-test) at a significant level of $P = 0.05$ after passing the normality test (Shapiro-Wilk) ($P > 0.05$). A $P$-value less than 0.05 was statistically significant, while a $P$-value greater than 0.05 indicated no effect. Significantly different comparison was considered at $***P < 0.001$, $**P < 0.01$, *$P < 0.05$ and †$P > 0.05$. All computations were performed using R stats Version 4.2.0 (R Project for Statistical Computing, RRID:SCR_001905).

Results

N-NH$_4^+$, N-NO$_3^-$, P-PO$_4^{3-}$ and total phosphorus in the surface water and sub-surface water

Nutrient variations in SW and SbW are shown in Figure 1. The concentrations of N-NH$_4^+$, N-NO$_3^-$, P-PO$_4^{3-}$ and TP varied largely in the SW while remained relatively stable in the SbW. In particular, the nutrient values of the SW varied as follows: N-NH$_4^+$ (WS, 1.14–4.25 mg L$^{-1}$; DS, 1.03–4.09 mg L$^{-1}$), N-NO$_3^-$ (WS, 0.46–1.03 mg L$^{-1}$; DS, 0.27–0.97 mg L$^{-1}$), P-PO$_4^{3-}$ (WS, 0.23–0.96 mg L$^{-1}$; DS, 0.23–0.81 mg L$^{-1}$) and TP (WS, 1.06–4.89 mg L$^{-1}$; DS, 0.81–4.24 mg L$^{-1}$), while the concentration of nutrients in the SbW varied as follows: N-NH$_4^+$ (WS, 0.34–0.73 mg L$^{-1}$; DS, 0.24–0.71 mg L$^{-1}$), N-NO$_3^-$ (WS, 0.22–0.86 mg L$^{-1}$; DS, 0.23–0.81 mg L$^{-1}$), P-PO$_4^{3-}$ (WS, 0.03–0.08 mg L$^{-1}$; DS, 0.02–0.07 mg L$^{-1}$) and TP (WS, 0.51–1.19 mg L$^{-1}$; DS, 0.41–1.08 mg L$^{-1}$). The ratio of N-NH$_4^+/N$-NO$_3^-$ in the SW was consistently higher than in the SbW. Particularly, the rate of N-NH$_4^+/N$-NO$_3^-$ in the SW was significantly higher than the SbW (P < 0.05), while the value of N-NO$_3^-$ was insignificant between the SW and SbW (P > 0.05). As observed, the highest peaks of these parameters were reached after fertilizing. It is likely that the higher concentration of N-NH$_4^+$, P-PO$_4^{3-}$ and TP in the SbW were observed during the fertilizing period. NO$_3^-$ increased in the SW during the fertilizing period, while the SW only rose in the WS and was more complex in the DS (Figure 1). Although the temporal-spatial dynamics of the SW and SbW parameters were complex over the rice-growing period, statistical analysis indicates that for N-NH$_4^+$, N-NO$_3^-$, P-PO$_4^{3-}$ and TP; no significant differences between the WS and DS were seen (Table 3).

N-NH$_4^+$, total nitrogen, soil organic matter, and total phosphorus in the soil

Figure 2 shows the N-NH$_4^+$, TN, SOM, and TP variation in the soil paddy field over the WS and DS. In the WS, the concentration of soil chemical properties varied as follows: N-NH$_4^+$ (21.5–38.0 mg kg$^{-1}$), TN (2.37–2.90 g kg$^{-1}$), SOM (37.6–48.5 g kg$^{-1}$), and TP (0.65–1.69 g kg$^{-1}$), while the DS fluctuated as follows: N-NH$_4^+$ (18.4–29.6 mg kg$^{-1}$), TN (1.53–4.48 g kg$^{-1}$), SOM (38.7–44.9 g kg$^{-1}$), and TP (0.35–0.89 g kg$^{-1}$). The concentration of N-NH$_4^+$ increased relatively after fertilizer application in both the WS and DS. Likely, a similar trend was seen in the TN during the DS. However, the effects of synthetic fertilizer topdressing on the TN (in the WS), SOM, and TP were negligible.
Statistically, N-NH$_4^+$, TN, and SOM slightly increased in the WS ($P > 0.05$), while TP significantly increased ($P < 0.001$) (Table 4).

**Discussion**

**Variation of nutrient contents in the SW and SbW**

Our study assessed nutrient variability in the SW and SbW through the WS and DS under typical water management and conventional rice practices in the Vietnamese MD. The study found that the concentration of N-NH$_4^+$, N-NO$_3^-$, P-PO$_4^{3-}$, and total P in the SW exhibited a relatively large variation in the WS and DS (Figure 1). This could be partly attributed to shifting water levels (rainfall and irrigation) and fertilizer application (Qiao et al., 2012). The alteration of SW levels...
Thus, we suggest that an interaction between water levels and fertilizer application rates on the dynamics of N-NH$_4^+$.

Moreover, nitrification progression also occurs very fast in the rhizosphere (Li et al., 2015; Li et al., 2018). This could likely increase/decrease the denseness of constituents regarding the concentration/dilution in the rice field. In this study, we did not record the water levels as the farmer let water flow free on the paddy field. Thus, the interdependence between water levels and nutrient dynamics remains uncertain. However, fertilizer topdressings could also potentially stimulate the dynamic mineralization processes within the rice paddy field. Here, we found that higher N fertilizer applications (39.5 kg N ha$^{-1}$) in the WS slightly increased the average N-NH$_4^+$ and N-NO$_3^-$ concentration by 5.83% and 13.8%. In contrast, higher P fertilizer utilization (15 kg P$_2$O$_5$ ha$^{-1}$) in the DS was indistinguishable in cases of P-PO$_4^{3-}$, and TP (Table 2). Thus, we suggest that an interaction between water levels and fertilizer application rates on the dynamics of N-NH$_4^+$, N-NO$_3^-$, P-PO$_4^{3-}$, and TP in the Vietnamese MD’s paddy fields should be considered for further work.

Our study showed that the N-NH$_4^+$, N-NO$_3^-$, P-PO$_4^{3-}$, and TP contents in the SW were consistently higher than that of the SbW simultaneously ($P < 0.001$), irrespective of factors including fertilizer application rate and seasonal variation (Ngan et al., 2021). This means that nutrient losses could occur through the SW runoff, evaporation (nitrogen gases) and rice plant absorption rather than leaching to SbW. The lower nutrient concentrations in the SbW may also be partly explained by various transformation processes or plant uptake during percolation regression. For instance, the N-NH$_4^+$ could be reduced during leachate due to volatilization, nitrification (N-NH$_4^+$ to N-NO$_3^-$), and rice roots uptake (Hou et al., 2007). Furthermore, P-PO$_4^{3-}$ reduction could also be explained by rice plant uptake, binding onto soil minerals and being more prone to removal through surface runoff (McDowell et al., 2001). In line with our findings, Cho et al. (2011) found that leaching downward subsurface waters were responsible for 6.4–9.8% and 0.2–0.3% of N and P losses, respectively, while N and P losses via surface runoff accounted for 34.3–42.6% and 3.8–5.3%. It has been reported that nutrient loss during the rice-growing period is more relevant to the fertilizer application rate. Cui et al. (2020) confirmed that fertilizer applications significantly impacted N and P losses from surface runoff, with increased fertilizer application rates significantly increasing N loss through surface runoff. Besides, Qiao et al. (2012) showed that N loss via surface runoff and percolation positively correlated with fertilizer application rate. Also, the rate and timing of fertilizer application in the field influenced the N loss over surface runoff (Li et al., 2018). These studies strongly supported our findings.

Our study found that N-NO$_3^-$ concentrations showed no significant difference between the SW and SbW, while N-NH$_4^+$ in the SbW was consistently lower than in the SW (Ngan et al., 2021). This could be partly explained by rice plants preferring uptake of N-NH$_4^+$ rather than N-NO$_3^-$, resulting in higher N-NO$_3^-$ concentration disclosed in the SbW. Moreover, nitrification progression also occurs very fast in the rhizosphere (Li et al., 2015; Li et al., 2018). In the rice

### Table 3. The average concentration of N-NH$_4^+$, N-NO$_3^-$, P-PO$_4^{3-}$ and total phosphorus in surface water and sub-surface water and their interactions.

<table>
<thead>
<tr>
<th>Factors</th>
<th>N-NH$_4^+$ (mg L$^{-1}$)</th>
<th>N-NO$_3^-$ (mg L$^{-1}$)</th>
<th>P-PO$_4^{3-}$ (mg L$^{-1}$)</th>
<th>TP (mg L$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS, n = 8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SW</td>
<td>2.54 ± 0.96 a</td>
<td>0.74 ± 0.22</td>
<td>0.47 ± 0.27 a</td>
<td>2.44 ± 1.53 a</td>
</tr>
<tr>
<td>SbW</td>
<td>0.56 ± 0.17 b</td>
<td>0.65 ± 0.21</td>
<td>0.05 ± 0.02 b</td>
<td>0.77 ± 0.21 b</td>
</tr>
<tr>
<td>DS, n = 8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SW</td>
<td>2.40 ± 1.01 a</td>
<td>0.65 ± 0.28</td>
<td>0.48 ± 0.21 a</td>
<td>2.35 ± 1.47 a</td>
</tr>
<tr>
<td>SbW</td>
<td>0.50 ± 0.17 b</td>
<td>0.48 ± 0.21</td>
<td>0.04 ± 0.02 b</td>
<td>0.78 ± 0.23 b</td>
</tr>
<tr>
<td>Two-seasonal variation (SV), n = 16</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SW</td>
<td>2.41 ± 0.95 a</td>
<td>0.69 ± 0.25</td>
<td>0.47 ± 0.23 a</td>
<td>2.40 ± 1.45 a</td>
</tr>
<tr>
<td>SbW</td>
<td>0.53 ± 0.17 b</td>
<td>0.51 ± 0.22</td>
<td>0.05 ± 0.00 b</td>
<td>0.78 ± 0.21 b</td>
</tr>
</tbody>
</table>

P-value:

| WS (SW × SbW)   | ***                   | †                      | ***                   | **                |
| DS (SW × SbW)   | ***                   | †                      | ***                   | **                |
| SW (WS × DS)    | †                     | †                      | †                     | †                 |
| GW (WS × DS)    | †                     | †                      | †                     | †                 |
| SV (SW × SbW)   | ***                   | †                      | ***                   | ***               |

Means followed by different letters within each group of values indicate significance at $P = 0.05$ by the Student’s t-test. WS, wet season; DS, dry season; SW, surface water; SbW, subsurface water; SV, two-seasonal variation. Data presented as means ± standard deviation ($n = 8$) in the same column. Significant difference by t-test: *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$, and † $P > 0.05$. 

Figure 2. The variation of N-NH$_4^+$, total nitrogen, soil organic matter and total phosphorus in the soil during the rice growing wet season and dry season. Vertical dotted lines indicate the times of the synthetic fertilizer application. F$_1$, F$_2$, F$_3$ and F$_4$ depict topdressing of fertilizer 1, 2, 3, and 4, respectively. TP = total phosphorus; TN = total nitrogen.

Table 4. N-NH$_4^+$, total nitrogen, soil organic matter and total phosphorus in the wet season and dry season.

<table>
<thead>
<tr>
<th>Factors</th>
<th>N-NH$_4^+$ (mg kg$^{-1}$)</th>
<th>TN (g kg$^{-1}$)</th>
<th>SOM (g kg$^{-1}$)</th>
<th>TP (g kg$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS</td>
<td>28.2 ± 4.83</td>
<td>2.64 ± 0.19</td>
<td>43.3 ± 3.02</td>
<td>1.32 ± 0.31 a</td>
</tr>
<tr>
<td>DS</td>
<td>24.2 ± 3.77</td>
<td>2.69 ± 0.97</td>
<td>42.4 ± 2.39</td>
<td>0.68 ± 0.19 b</td>
</tr>
</tbody>
</table>

P-value

Means followed by different letters indicate significance at $P=0.05$ by the Student’s t-test. WS, wet season; DS, dry season; TN, total nitrogen; TP, total phosphorus; SOM, soil organic matter. Data presented as means ± standard deviation ($n=8$) in the same column. Significant difference by t-test: *** $P<0.001$, ** $P<0.01$, * $P<0.05$, and † $P>0.05$. 

Page 8 of 16
fertilizer application, the highest peaks of N-NH4\(^+\) in the SW showed a high fluctuation during the rice-growing period, while stability was observable in the SbW. After and DS under typical water management and conventional cultivation techniques. We found that nutrient content in the lowland soils of the Vietnamese MD be further studied in future work.

**Variation of soil nutrients in rice paddy fields**

This study described the soil chemical properties during the rice-growing period under conventional rice practices in the Vietnamese MD. Variability of N-NH4\(^+\), TN, SOM, and TP during rice growth was comparable to the previous studies undertaken in the lowland soils of the MD (Minamikawa et al., 2021; Vo et al., 2018; Uno et al., 2021). According to Hung et al. (2016) and Tanaka et al. (2014), soil properties in our study were characterized by medium-high TN, high N-NH4\(^+\), low-to-medium SOM, and high-to-very high TP. Thus, with respect to ensuring soil responsiveness to rice nutrient demand, reducing the N and P fertilizer application rate, and increasing SOM to a feasible degree should be considered in conventional rice practices in the Vietnamese MD.

We found that soil N-NH4\(^+\) and TN concentration slightly increased after fertilizing. Higher N-fertilizer application (39.5 kg N ha\(^{-1}\)) in the WS insignificantly increased the N-NH4\(^+\) and TN in the soil in comparison to that of the DS (\(P > 0.05\)). However, higher fertilizer application of 15 kg P\(_2\)O\(_5\) ha\(^{-1}\) significantly increased TP in the soil paddy field (\(P < 0.001\)). It is indicated that the fertilizer application moderately boosted the dynamic of N availability in soil. In agreement with our study, Dong et al. (2012) confirmed that available N slightly increased with chemical fertilizer application but significantly increased with organic matter additions. It is noted that the significant difference in TP could be likely due to the excessive P fertilizer application rates in the WS, while utilization efficacy and loss of P are usually low (Irfan et al., 2020; Schröder et al., 2011; Cho et al., 2011).

SOM plays an inevitable role in promoting nutrient availability and improving soil fertility. Our study found that SOM change was minor during rice growth. This could be partly explained by no organic matter sources being incorporated into the soil. Thus, organic matter ineffectively contributed to nutrient availability in the soil. In the soil, the change of SOM depends on temperature, pH, microbial growth, soil management, organic matter amendment, and C/N ratio (Tanaka et al., 2014).

**Conclusions**

This study examined the temporal-spatial variability of nutrients in SW, SbW, and soil of a paddy field in the WS and DS under typical water management and conventional cultivation techniques. We found that nutrient content in the SW showed a high fluctuation during the rice-growing period, while stability was observable in the SbW. After fertilizer application, the highest peaks of N-NH4\(^+\), P-PO4\(^3-\) and TP parameters in the SW and SbW were observed. The concentrations of N-NH4\(^+\), P-PO4\(^3-\) and TP in the SW were consistently higher than that of the SbW. While N-NO3\(^-\) concentration was insignificant between the SW and SbW. The seasonal nutrient variations were insignificant in both the SW and SbW. Our findings showed that soil properties were characterized by medium-high TN, high N-NH4\(^+\), low-to-medium SOM, and high-to-very high TP. Higher N fertilizer application slightly increased the N-NH4\(^+\) and TN dynamic, while TP significantly increased along with increasing P fertilizer application rate in the WS. SOM showed stability during both the WS and DS. We suggest that nutrient loss estimations and dynamic simulations in the lowland soil of the Vietnamese MD’s rice paddy fields should be considered for further work.

**Data availability**

**Underlying data**


This project contains the following underlying data:

- Supplementary file – 2021.xlsx

Data are available under the terms of the Creative Commons Zero “No rights reserved” data waiver (CC0 1.0 Public domain dedication).
Acknowledgements
We thank Le Huu Thinh family who allowed us to process the experiments on their paddy rice field, Tran Thi Thuy Loan, Nguyen Thi Thu Thao, Pham Thi Huynh Nhu at Can Tho University for assisting the experiment activities, the E2 team (Can Tho University Improvement Project) for their administrative support to perform this study. Last but not least, thanks to Nigel Downes for proofreading the manuscript.

References


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I have just one comment.
P > 0.05
In case that a P value is more than 0.05, the actual value, like P = 0.20, should be written.
I have no other comments.

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

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? Koki Toyoda
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This manuscript reports valuable field data regarding nutrient dynamics in a paddy field. The results of differences between two depths and two seasons are interesting and worth to be published. However, there are several parts that are poorly explained or lack clearness. I commented directly on the manuscript. These comments should be properly amended.

The annotated manuscript can be found at the following link: https://f1000researchdata.s3.amazonaws.com/linked/419959.Koki_Toyota_review_ngan_nguyen-vo-chau.pdf

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and is the work technically sound?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 21 Nov 2022
Ngan Nguyen-Vo-Chau

Response to reviewer:
Thank you very much for giving us constructive comments that helped us improve this paper immensely. All your comments have been carefully read and revised to elucidate underlying aspects. Our responses to your comments are as follows:

- **Abstract:**

  1.1 **Comment 1 & comment 2:** please describe the contents. I guess the following expression is preferable. "Surface water, subsurface water, and topsoil samples were collected eight times during the ***"; during the rice-growing seasons to estimate/clarify
Answer: Thank you so much for your commendation. The recommendation has been adopted. We revised it as follows “Surface water, subsurface water (30–45 cm), and topsoil (0–20 cm) were collected eight times during the rice-growing seasons to clarify its nutrient dynamic”.

1.2 Comment 2: describe the P-value in case of P>0.05.
Answer: We rephrased the sentence as follows: “no significant difference was disclosed (P>0.05)” to make it clearer to readers. Detailed interpretation of the p-value was cleared in the methodology section “A P-value less than 0.05 was statistically significant, while a P-value greater than 0.05 indicated no effect. Significantly different comparison was considered at ***P < 0.001, **P < 0.01, *P < 0.05 and †P > 0.05.”

1.3 Comment 3: “total P losses mainly occur through runoff rather than leaching” à better to describe the results supporting this conclusion.
Answer: We added the result to support the conclusion. It is as follows “Under conventional rice cultivation, the low concentration of N-NH$_4$+ , P-PO$_4$3- and total P in the subsurface water indicated that nutrient losses mainly occur through runoff rather than leaching”.

1.4 comment 4: “While N-NO$_3$- loss is similar in surface water and subsurface water” à not clear. How do the authors define “loss”?
Answer: We agree with the reviewer that the conclusion is not clear and did not strongly support the conclusion. It is, therefore, eliminated.

1.5 Comment 5: “dynamic simulation” à not clear
Answer: We revised the sentences as follows: “Future work should consider the nutrient balance and nutrient dynamic simulation in surface and subsurface of the lowland paddy soil in the Vietnamese Mekong Delta”.

Introduction:

2.1 Comment 1: “common practice” à common practice in the MD or VN
Answer: It has been corrected in the context of the mentioned paper. The revision is as follows: “Common practices in the MD typically use fertilizers, water, and seeds well exceeding recommended rates”.

2.2 Comment 2: “recommend rate” by ??
Answer: We added more information to make it clear to readers. The supplementary information is as follows: “Common practices in the MD typically use fertilizers, water, and seeds well exceeding recommended rates sustainable rice farming practices combined in the national program “One Must Do, Five Reductions” (1M5R)”.

2.3 Comment 3: “Nutrient migration was lost” à not clear
Answer: We revised this sentence to make it clearer to readers which is as follows: Several previous studies reported that nutrient losses primarily occurred via surface water (SW) and sub-surface water (SbW).

Methods:

3.1 Comment 1 “sand, 1.9%, and clay, 66.4%” à silt ??%.
Answer: We supplemented the percentage of silt as follows: “soil texture (sand, 1.9%, silt, 31.7%, and clay, 66.4%)”.

3.2 Comment 2 “soil organic matter (SOM), 35.4 mg kg$^{-1}$” à too low value
Answer: Thank you so much for recognizing the low value. This was our miswriting when it came to filling the unit. It has been adopted and revised as follows: “soil organic matter (SOM), 35.4 g kg$^{-1}$”

Results:

4.1 Comment 1: “P > 0.05” à describe the P value
Answer: Please see our response in “comment 1.2”

4.2 Comment 2: N-NH$_4^+$ (18.41–29.6 mg kg$^{-1}$) à 18.4
Answer: It has been adopted. Revision is as follows: “N-NH$_4^+$ (18.4–29.6 mg kg$^{-1}$)”

Discussion:

4.1 Comment 1: “This means that nutrient loss mainly occurred through the SW” à This is a bit radical interpretation. Please explain more logically why the authors describe “mainly”. In addition to this hypothesis, uptake of the nutrients by rice plants must also occur.
Answer: Thank you so much for providing a hypothesis related to rice plant absorption. Actually, our hypothesis was impressing the loss of nutrients via the SW pathway rather than SbW percolation. In the rice ecosystems, the loss could be attributed to runoff, evaporation (nitrogen gases), and rice plant absorption. We seriously adopted your mentioned hypothesis to amend the explanation. The modification is as follows “This means that nutrient losses could occur through the SW runoff, evaporation (nitrogen gases) and rice plant absorption rather than leaching to SbW”

4.2 Comment 2: “N concentration loss” à ??
Answer: We removed “concentration” has been eliminated. It is as follows “N loss”

4.3 Comment 3: “It is well-known that N-NH$_4^+$ in the rhizosphere area generally lowers the N-NO$_3^-$ as rice prefers N-NH$_4^+$, up taking N-NH$_4^+$ faster than N-NO$_3^-$” à not clear
Answer: We rephrased the sentence in cohesion with the first sentence which is as follows: “Our study found that N-NO$_3^-$ concentrations showed no significant difference between the SW and SbW, while N-NH$_4^+$ in the SbW was consistently lower than in the SW (Ngan et al., 2021). This could be partly explained by rice plants preferring uptake of N-NH$_4^+$ rather than N-NO$_3^-$, resulting in higher N-NO$_3^-$ concentration disclosed in the SbW”.

4.4 Comment 4: “a higher concentration of N-NO$_3^-$ found below the soil surface (mostly in the rhizosphere) resulted in it being quickly transported to the soil surface” à correct? to the subsoil?
Answer: Thank you for correcting the expression. It has been adopted. Revision is as follows “a higher concentration of N-NO$_3^-$ found below the soil surface (mostly in the rhizosphere) resulted in it being quickly transported to the subsoil”.

4.5 Comment 5: This implied that the regression of organic matter mineralization/decomposition could occur slowly à not clear
Answer: We agree with the reviewer that the expression did not clear. Thus, we simplified
this sentence as follows: This implied that the regression of organic matter mineralization/decomposition could occur slowly “SOM plays an inevitable role in promoting nutrient availability and improving soil fertility. Our study found that SOM change was minor during rice growth. This could be partly explained by no organic matter sources being incorporated into the soil.”

We look forward to hearing from you.
Best regards,
Authors.

**Competing Interests:** No competing interests were disclosed