Research article

Hydrochemical and Isotopic Characteristics of Irrigation Channel Water in Oil Palm Plantations, Kuala Selangor, Malaysia

MAYU OGIYA*
Faculty of Science, Shinshu University, Matsumoto, Japan
Faculty of Forestry and Environment, University Putra Malaysia, Serdang, Malaysia
Email: mayuogiya@gmail.com

CHEN ZHUO
Faculty of Forestry and Environment, University Putra Malaysia, Serdang, Malaysia

SITI NURHIDAYU
Faculty of Forestry and Environment, University Putra Malaysia, Serdang, Malaysia

YUSRA SHABIR
Faculty of Forestry and Environment, University Putra Malaysia, Serdang, Malaysia

TAKASHI NAKAMURA
Interdisciplinary Center for River Basin Environment, University of Yamanashi, Kofu, Japan

RORY WALSH
Department of Geography, Swansea University, Swansea, United Kingdom

KOICHI SAKAKIBARA
Faculty of Science, Shinshu University, Matsumoto, Japan

Received 20 May 2024 Accepted 8 May 2025 (*Corresponding Author)

Abstract The rapid expansion of oil palm plantation areas in Southeast Asia has brought economic benefits but has also led to substantial environmental challenges due to deforestation and excessive fertilizer use. This study examined the hydro-chemical and isotopic characteristics of water in irrigation channels in oil palm plantations in Kuala Selangor, Malaysia. Water samples demonstrated oxidative environments with pH ranging from 2.67–6.59, EC ranging from 7.27–138 mS/m and DO ranging from 0.46–4.83 mg/L. Channel waters in peatland areas were highly acidic (pH 3.25–3.67), probably because of the presence of humic acids. Isotopic analysis indicated that meteoric water was the primary source of water in the irrigation channels, with isotope fractionation due to water evaporation observed at specific points. The $\delta^{15}N$ and $\delta^{18}O$ values of NO_3^- suggest that the sources of nitrate were primarily ammonia fertilizers and atmospheric deposition. Overall, these findings imply that after precipitation enters the plantation irrigation water, subsequent evaporation and human activities modify water quality. These results highlight the need for sustainable oil palm management practices to safeguard water resources and mitigate the environmental impacts on surrounding ecosystems.

Keywords oil palm plantation, isotope tracer, water quality, irrigation channel, peatland

INTRODUCTION

Oil palm plantation areas are rapidly expanding in Southeast Asia because of their high productivity, commercial profitability at large scales among oil-producing plants, and rising palm oil demand (Sheil et al., 2009). However, intensive fertilizer use and land conversion have led to environmental concerns, such as eutrophication and water quality deterioration.

Several studies have reported higher electrical conductivity (EC), sulfate ion, and dissolved organic carbon (DOC) concentrations in river and drainage water in oil palm areas than in forest areas, attributing these differences to the use of fertilizers and herbicides (Itoh et al., 2023). High nitrate (NO_3^-) and ammonium (NH_4^+) concentrations have been detected in groundwater, river water, and irrigation channels (Muneoka et al., 2014), while several studies have recorded low NO_3^- concentrations, potentially due to denitrification or plant absorption (Fadhullah et al., 2020). These studies suggest that the water quality in oil palm plantation areas differs from that in forest areas. However, the factors contributing to these results are unclear. Nitrate-nitrogen and -oxygen isotope ratios ($\delta^{15}N$ and $\delta^{18}O$ of NO_3^-) can reveal the existence of denitrification and the source of NO_3^- in oil palm plantation areas (Nishina et al., 2023). Water isotope ratios (δ^2H and $\delta^{18}O$ of H_2O) provide information for understanding the hydrological cycle, such as identifying water sources and tracing phase changes (Itoh et al., 2023). Therefore, combining isotopic analyses ($\delta^{18}O$, δ^2H, $\delta^{15}N$) with chemical tracers is a robust approach for understanding the hydrological cycle and its characteristics. Irrigation of oil palm areas can be a direct source of environmental pollution; however, studies on the characteristics and dynamics of irrigation water remain limited.

OBJECTIVES

The main objectives of this study were to assess and understand the hydro-chemical and isotopic characteristics of water in the irrigation channels within oil palm plantation areas in Kuala Selangor, Malaysia, and thereby help in assessing the environmental impact of oil palm plantations.

METHODOLOGY

Study Area

The study area is located between Kuala Selangor and Batang Berjuntai in the lowland section of the Selangor River Basin in Malaysia (Fig. 1). The major land uses along the river include oil palm and coconut plantations, orchards, villages, and peat swamp forests. Forest conversion to oil palm plantations has increased oil palm cover in the northern Selangor area from 249.3 km^2 in 1989 to 700.7 km^2 in 2016, whereas rainforest cover has decreased from 1455.7 km^2 to 880 km^2 (Charters et al., 2019).

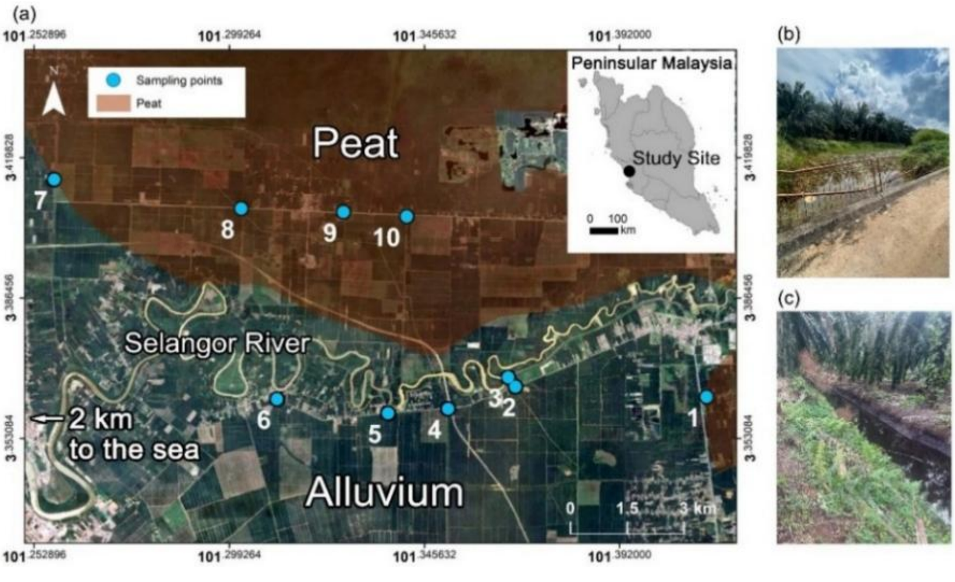

Fig. 1 Map of study area

(a) Sampling locations and soil types in Kuala Selangor, Malaysia (Satellite imagery sourced from Google Earth), (b) Photograph of P5, and (c) Photograph of P8

Soil types in the study area are peat to the north of the river, Selangor-Kangkong (Alluvial Sediments), and Kranji (Acid Sulfate Soil) to the south of the river (Department of Agriculture Malaysia, 2023). The area is influenced by two monsoon seasons: the northeast (NE) monsoon from November to March and the southwest (SW) monsoon from April to October. The mean annual precipitation is 1572 mm (Department of Irrigation and Discharge Malaysia, 2002-2024).

Sampling and Analysis

An intensive field survey was conducted during the SW monsoon on July 7th and 8th, 2024. Water samples were collected from ten locations (P1–P10). Nine were landed in irrigation channels between the oil palm plantations and an access road, but P3 was taken from a drainage channel within plantation land a few meters before entering the Selangor River. At each sampling site, two water samples were filtered through a 0.45 µm Polyethersulfone (PES) filter and collected in 50 ml and 20 ml polypropylene (PP) bottles. Water temperature, pH, EC, oxidation-reduction potential (ORP), and dissolved oxygen (DO) were measured *in situ* using a digital thermometer (Testo104, testo), portable pH and conductivity meter (D-210PC-S, HORIBA), and portable DO and ORP meter (D-210PD-S, HORIBA). Water samples for ion concentration and water isotope analyses were refrigerated at 4°C, while those for $\delta^{51}N$ and $\delta^{18}O$ of NO_3^- were frozen at -18°C until analysis. The dissolved ion concentrations for F^-, Cl^-, NO_3^-, SO_4^{2-}, Na^+, NH_4^+, K^+, Mg^{2+}, and Ca^{2+} were analyzed using ion chromatography (ICS-1500, ICS-2100, DIONEX). Bicarbonate concentration (HCO_3^-) was measured by titration to pH 4.8 using a 0.005 mol/L sulfuric acid solution. The δ^2H and $\delta^{18}O$ of H_2O were analyzed using wavelength-scanning cavity ring-down spectroscopy (L2130-i, PICARRO). The $\delta^{15}N$ and $\delta^{18}O$ of NO_3^- were analyzed using isotope ratio mass spectrometry (Hydra 20-20, SerCon) after NO_3^- was converted to nitrous oxide (N_2O) using the denitrifier method (Sigman et al., 2001). The stable isotope ratios of N, H, and O are defined by the following equation Eq. 1.

$$\delta_{Sample}\ (‰) = \{R_{Sample} / R_{Standard} - 1\} \times 1000 \tag{1}$$

Where R is the ^{15}N / ^{14}N or ^{18}O / ^{16}O ratio in NO_3^- and ^2H / ^1H or ^{18}O / ^{16}O ratios in the water of a sample or standard. The isotope values were calibrated using international standard materials (IAEA-N3, USGS34, USGS35, and V-SMOW: Vienna Standard Mean Ocean Water). The measurement accuracy (σ1) was ±0.025‰ for $\delta^{18}O$ of H_2O, ±0.1‰ for δ^2H of H_2O (Sanyo Trading), ±0.2‰ for $\delta^{15}N$ of NO_3^-, and 0.3‰ for $\delta^{18}O$ of NO_3^-.

RESULTS AND DISCUSSION

Hydro Chemical Characteristics

Results of the selected water quality and isotopic analyses are summarized in Table 1. The pH ranged from 2.67 to 6.59, and the EC ranged from 7.27 to 138 mS/m. DO range from 0.46 to 4.83 mg/L and ORP from 125 to 520 mV, indicating an oxidative environment. At P4 and P6, the pH was particularly low (less than 3), with high EC and ORP. Irrigation channels in peatland areas (P7–P10), pH (3.25–3.67), and EC (7.23 –25.5 mS/m) showed low variability between samples. These findings might be due to the presence of natural organic matter, such as humic and fulvic acids in peatlands, which decrease pH (Qadafi et al., 2023). Peatlands are usually reductive environments, but the ORP of irrigation channel waters in peatlands indicates an oxidative environment. This suggests that oil palm

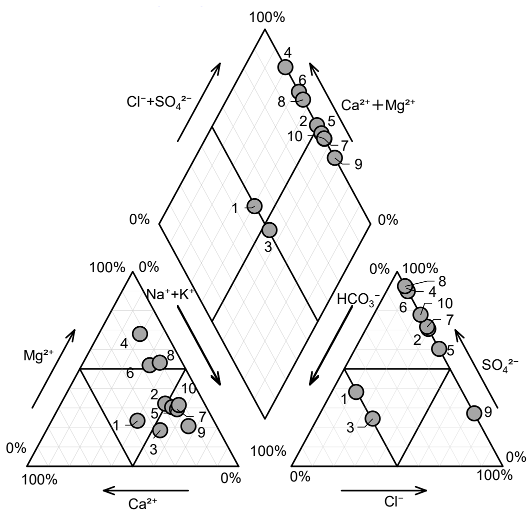

Fig. 2 Hydro-chemical composition of irrigation water

plantation activities expose peat to the atmosphere, leading to an oxidative environment. In contrast, P1 and P3 showed near-neutral pH, low EC, and low ORP values.

The dissolved ion results are shown in a Piper diagram (Fig. 2). Only P1 and P3 plots in the middle of the key diagram, indicating the dominance of Ca-HCO_3 compared to other samples. These samples showed near-neutral pH, low EC, and low ORP values. P3 is located near its inflow point to the river; therefore, there may have been some mixing with river water. Ca-HCO_3 can act as a buffer to achieve a neutral pH, which may explain the near-neutral pH of P1 and P5. The extremely low pH (2.7–3.3) noted at P4, P6, and P8 plots in the upper right of the key diagram are dominated by Mg^{2+}, SO_4^{2-}, and Cl^-. Other points (P2, P5, P7, P9, and P10) were dominated by Na^+, Mg^{2+}, SO_4^{2-}, and Cl^-. There was a high positive correlation between NO_3^- and SO_4^{2-} ($r = 0.84$, $p < 0.01$), except for P3. Possible sources of SO_4^{2-} are fertilizers (such as kieserite and ammonium sulfate) and geological sources. However, the sources of NO_3^- include fertilizers, organic nitrogen in soil, and nitrification reactions. Since the primary common source for these two ions is fertilizer, the strong positive correlation observed between nitrate and sulfate indicates that both ions may have increased in the water due to fertilizer-runoff. Na^+ and Cl^- could be derived from aerosols evaporated from seawater and transported by precipitation, which is characteristic of coastal regions.

Table 1 Water quality and isotope analysis

ID	Water Temp	pH	EC	DO	ORP	Cl^-	NO_3^-	SO_4^{2-}	HCO_3^-	Na^+	NH_4^+	K^+	Mg^{2+}	Ca^{2+}	$\delta^{18}O$ -H_2O	δ^2H -H_2O	$\delta^{15}N$ -NO_3^-	$\delta^{18}O$ -NO_3^-
	°C		mS/m	mg/L	mV	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	‰	‰	‰	‰
P1	32.3	6.6	11.3	2.4	134	4.1	0.1	18.2	30.5	3.2	0.3	4.6	1.8	12.7	-5.1	-34.4	-2.4	7.4
P2	31.0	4.4	28.9	0.5	255	26.1	0.1	84.2	0.0	15.8	3.5	6.4	6.7	9.3	-5.9	-37.6	-7.4	29.4
P3	31.6	6.4	13.3	3.4	125	10.5	4.4	13.3	34.2	5.3	0.5	3.3	1.3	15.7	-6.3	-40.6	5.5	-1.6
P4	31.9	2.7	138.0	1.3	520	39.8	0.7	570.3	0.0	15.1	1.5	12.7	41.5	13.8	-6.3	-39.2	-1.4	25.6
P5	33.5	3.8	32.5	4.0	431	35.7	0.1	73.3	0.0	20.3	2.6	6.3	7.2	10.2	-6.0	-37.9	-10.2	3.8
P6	32.0	2.8	88.5	4.8	505	22.5	0.8	268	0.0	16.7	2.0	9.7	19.1	10.1	-5.8	-37.1	6.9	9.8
P7	28.6	3.7	15.0	2.1	369	4.2	0.2	14.3	0.0	4.7	0.1	1.2	1.5	1.2	-6.0	-37.3	-4.1	18.7
P8	28.8	3.3	25.5	3.4	435	3.1	0.2	51.7	0.0	3.8	0.1	1.1	3.4	2.6	-6.3	-38.1	0.6	26.3
P9	30.2	3.7	7.3	3.4	372	0.8	0.2	0.4	0.0	1.1	0.2	0.2	0.2	0.8	-6.7	-41.5	-1.9	8.4
P10	30.6	3.6	8.7	3.5	335	0.9	0.2	4.1	0.0	1.2	0.2	0.3	0.4	0.9	-6.7	-41.1	-0.4	3.7

Irrigation Water Dynamics

The δ-diagram of δ^2H and $\delta^{18}O$ of H_2O (Fig. 3a) shows that for irrigation channel water, δ^2H ranged from -6.7‰ to -5.1‰, and $\delta^{18}O$ from -41.5‰ to -34.4‰. Marryanna et al. (2017) found that the Local Meteoric Water Line (LMWL) in Peninsular Malaysia was δ^2H (‰) = 7.9 $\delta^{18}O$ (‰) + 11.6 (r^2 = 0.98) during the SW monsoon and δ^2H = 7.8 $\delta^{18}O$ (‰) + 9.3 (r^2 = 0.99) during the NE monsoon. Water samples for this study were collected in July 2024 during the SW monsoon season. Water collected in the peatland areas at P8, P9, and P10 were plotted on the SW LMWL, with results indicating that the source of peatland irrigation water was SW monsoon meteoric water. Water retained in peatland soil may comprise recent precipitation that has displaced old water from the NE monsoon.

The δ^2H and $\delta^{18}O$ of H_2O at P1, P2, P3, and P6 showed large deviations from the SW LMWL. The regression line slope for these four points was 3.95, which is much lower than the typical LMWL slope. This deviation suggests that the irrigation water was influenced by evaporation, which led to isotope fractionation. The regression line slopes of the δ-diagram are usually smaller when evaporation enrichment occurs because the lighter isotopes evaporate preferentially, whereas the heavier isotopes remain in the liquid phase. The slow flow in the irrigation channels of the study area may have caused water to stagnate for a long period, which in turn may have accelerated evaporation, resulting in isotopic enrichment of irrigation channel waters. If fertilizer input increases in the future, evaporation may lead to higher nitrate concentrations. However, in peatland areas, the groundwater table is high (Evans et al., 1999), and even small amounts of precipitation can saturate the peat, resulting in rapid surface water flushing. The effect of evaporation is considered to be small because the water in the irrigation channels is easily flushed and does not tend to remain stagnant. It is also possible that isotopic ratios may have been diluted in the peatland areas due to the supply of groundwater to surface water.

Nitrate Sources of Irrigation Water

The $\delta^{15}N$ and $\delta^{18}O$ of NO_3^- vary depending on the source of nitrate in the environment and microbial activity (Kendall et al., 2007). Figure 3b illustrates the δ-diagram of the $\delta^{15}N$ and $\delta^{18}O$ of NO_3^- in the irrigation water in this study.

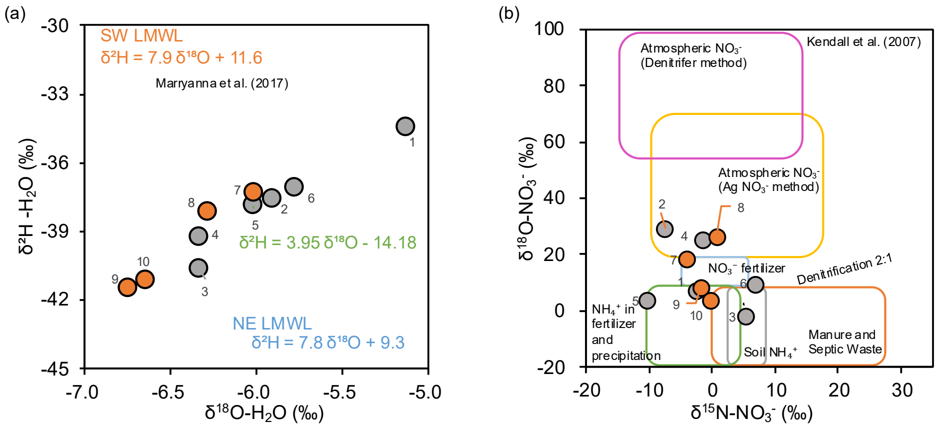

Fig. 3 The δ-diagram of irrigation water

orange dots: samples in peatland, gray dots: samples in alluvium (a) water isotopes, (b) nitrate nitrogen and oxygen isotopes

The typical ranges of $\delta^{15}N$ and $\delta^{18}O$ of NO_3^- for each source of nitrate were referenced from Kendall et al. (2007). The $\delta^{15}N$ of NO_3^- ranged from -6.7‰ to -5.1‰ and $\delta^{18}O$ of NO_3^- in irrigation water ranged from -41.5‰ to -34.4‰. These results indicate that the source of nitrate was dominated by ammonia nitrogen fertilizer and atmospheric deposition. Common fertilizers in Malaysia include urea, ammonium sulfate, ammonium nitrate, ammonium phosphate, and NPK compound fertilizer (FAO, 2004); however, nitrate fertilizer is not used in Malaysia. Thus, although some study sites were plotted in the nitrate fertilizer range, their source was not nitrate fertilizer. Fadhullah et al. (2020) reported that reservoir water in Malaysia has higher values of the $\delta^{18}O$ of NO_3^- than those derived from areas of nitrification and lower values than those from the atmosphere, and a similar pattern was observed in this study. This suggests that the mixing process of atmospheric nitrate with high values of $\delta^{18}O$ of NO_3^- and nitrate from other sources with low values of $\delta^{18}O$ of NO_3^-, such as fertilizer or soil. As mentioned earlier, this finding is consistent with water isotope evidence, which indicates that one source of nitrate is atmospheric precipitation. Thus, although the nitrate transported during the SW monsoon is considered to be derived primarily from fertilizers, some also derives from the mixing of marine aerosols and atmospheric pollutants.

NO_3^- concentrations were low (range: 0.09-0.84 mg/L) at all points except P3 (4.41 mg/L). Denitrification usually occurs in a reductive environment, such as below a DO of 2 mg/L. As several sampling points showed DO values greater than 3 mg/L, this reasoning cannot explain all the low NO_3^- values. Alternatively, when isotope data show a linear relationship with a $\delta^{18}O$-NO_3^-: $\delta^{15}N$-NO_3^- ratio of approximately 1:2, it can be assumed that denitrification is occurring (Kendall et al., 2007). Although the ORP indicated an oxidative environment, nitrification was inhibited at pH values below 5.5 (Gieseke et al., 2015). Therefore, it is likely that nitrification did not occur at this location, which is consistent with the observed low NO_3^- concentrations.

CONCLUSION

This study investigated the water quality and isotopic characteristics of irrigation channels in an oil palm plantation area in Kuala Selangor. The results revealed that the hydrological cycle and geological conditions influence the water in irrigation channels in oil palm plantations. In the peatland area, the pH was lowered, likely due to the presence of humic and fulvic acids, and the main source of irrigation water was meteoric water. The δ^2H and δ^{18}O of H_2O results indicated that the main source of irrigation water was meteoric water, with isotopic fractionation due to evaporation observed at certain sites. The δ^{15}N and δ^{18}O of NO_3^- data showed that the main nitrate source in the water of the irrigation channel was nitrate from ammonia fertilizers and the atmosphere.

Overall, these results suggest that after precipitation enters the plantation area, factors such as evaporation, geological factors, and fertilization influence water quality. The natural nitrogen removal functions of peatlands and geology have thus far prevented serious pollution. However, if fertilizer application increases in the future, fertilizer runoff and evaporation in irrigation channels will lead to elevated nitrate concentrations; therefore, proper fertilizer application management is important. These findings highlight the importance of sustainable oil palm plantation management and water quality.

ACKNOWLEDGEMENTS

This research was supported by a grant for overseas joint research for researchers at Shinshu University, Japan.

REFERENCES

Charters, L.J., Aplin, P., Marston, C.G., Padfield, R., Rengasamy, N., Bin Dahalan, M.P. and Evers, S. 2019. Peat swamp forest conservation withstands pervasive land conversion to oil palm plantations in North Selangor, Malaysia. International Journal of Remote Sensing, 40 (19), 7409-7438, Retrieved from DOI https://doi.org/10.1080/01431161.2019.1574996

Department of Irrigation and Drainage Malaysia. 2024. Meteorological dataset (2002-2024). Unpublished data, obtained directly from the Department of Irrigation and Drainage Malaysia office on 3 December 2024.

Department of Agriculture Malaysia. 2023. Agricultural statistics overview, Retrieved from URL https://www.doa.gov.my

Evans, M.G., Burt, T.P., Holden, J. and Adamson, J.K. 1999. Runoff generation and water table fluctuations in blanket peat: Evidence from UK data spanning the dry summer of 1995. Journal of Hydrology, 221 (3-4), 141-160, Retrieved from DOI https://doi.org/10.1016/S0022-1694(99)00085-2

Fadhullah, W., Yaccob, N.S., Syakir, M.I., Muhammad, S.A., Yue, F.J. and Li, S.L. 2020. Nitrate sources and processes in the surface water of a tropical reservoir by stable isotopes and mixing model. Science of the Total Environment, 700, 134517, Retrieved from DOI https://doi.org/10.1016/j.scitotenv.2019.134517

FAO. 2004. Fertilizer use by crop in Malaysia. Land and Plant Nutrition Management Service Land and Water Development Division, First ed. Food and Agriculture Organization of the United Nations. Rome, Italy. Retrieved from URL https://www.fao.org/4/y5797e/y5797e00.htm

Gieseke, A., Tarre, S., Green, M. and Beer, D. 2006. Nitrification in a biofilm at low pH values: role of in situ microenvironments and acid tolerance. Applied and environmental microbiology, 72 (6), 4283-4292, Retrieved from DOI https://doi.org/10.1128/AEM.00241-06

Itoh, M., Osaka, K., Iizuka, K., Kosugi, Y., Lion, M. and Shiodera, S. 2023. Assessing the changes in river water quality across a land-use change (forest to oil palm plantation) in peninsular Malaysia using the stable isotopes of water and nitrate. Science of The Total Environment, 859, 160319, Retrieved from DOI http://dx.doi.org/10.1016/j.scitotenv.2022.160319

Kendall, C., Elliott, E.M. and Wankel, S.D. 2007. Tracing anthropogenic inputs of nitrogen to ecosystems. In Michener, R., and Lajtha, K. (Eds.), Stable Isotopes in Ecology and Environmental Science, 2nd ed. Blackwell Publishing, 375-449, Retrieved from DOI https://doi.org/10.1002/9780470691854.ch12

Marryanna, L., Kosugi, Y., Itoh, M., Noguchi, S., Takanashi, S., Katsuyama, M., Tani, M. and Siti-Aisah, S. 2017. Temporal variation in the stable isotopes in precipitation related to the rainfall pattern in a tropical rainforest in Peninsular Malaysia. Journal of Tropical Forest Science, 29 (3), 349-362, Retrieved from DOI https://doi.org/10.26525/jtfs2017.29.3.349362

Muneoka, T., Yamazaki, Y., Wakou, S., Kimura, M. and Tsuji, O. 2014. Evaluation of nitrate pollution in river water at agricultural watershed. International Journal of Environmental and Rural Development, 5 (2), 51-

56, Retrieved from DOI https://doi.org/10.32115/ijerd.5.2_51
Nishina, K., Melling, L., Toyoda, S., Itoh, M., Terajima, K., Waili, J.W., Wong, G.X., Kiew, F., Aeries, E.B., Hirata, R., Takahashi, Y. and Onodera, T. 2023. Dissolved N_2O concentrations in oil palm plantation drainage in a peat swamp of Malaysia. Science of The Total Environment, 872, 162062, Retrieved from DOI https://doi.org/10.1016/j.scitotenv.2023.162062
Qadafi, M., Wulan, D.R., Notodarmojo, S. and Zevi, Y. 2023. Characteristics and treatment methods for peat water as clean water sources: A mini review. Water Cycle, 4, 60-69, Retrieved from DOI https://doi.org/10.1016/j.watcyc.2023.02.005
Sigman, D.M., Casciotti, K.L., Andreani, M., Barford, C., Galanter, M. and Böhlke, J.K. 2001. A bacterial method for the nitrogen isotopic analysis of nitrate in seawater and freshwater. Analytical Chemistry, 73 (17), 4145-4153, Retrieved from DOI https://doi.org/10.1021/ac010088e
Sheil, D., Casson, A., Meijaard, E., van Noordwijk, M., Gaskell, J., Sunderland-Groves, J., Wertz, K. and Kanninen, M. 2009. The impacts and opportunities of oil palm in Southeast Asia: What do we know and what do we need to know? Center for International Forestry Research, 51, Retrieved from DOI https://doi.org/10.17528/cifor/002792