

Application of Calcium-rich Clay Mineral Under Nonwoven Fabric Mats and Sand Armor as Cap Layer for Interrupting N and P Release from River Sediments

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Research Article

Keywords: In-situ capping, Sediment, Calcium, Clay mineral, Phosphate, Nitrogen

Posted Date: January 3rd, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1126422/v1>

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Version of Record: A version of this preprint was published at Environmental Science and Pollution Research on April 6th, 2022. See the published version at <https://doi.org/10.1007/s11356-022-19998-y>.

Abstract

This work investigates the applicability of thermally treated calcium-rich clay minerals (CRCMs), such as sepiolite (SPL), attapulgite (ATT), and dolomite (DLM) to hinder the nitrogen (N) and phosphorus (P) release from river sediments. A non-woven fabric mat (NWFM) or a sand layer were also capped as armor layers, i.e., placed over CRCMs to investigate the capping impact on the N/P release. The capping efficiency was evaluated in a cylindrical reactor, consisting of CRCMs, armor layers, sediments, and sampled water. We monitored N/P concentrations, dissolved oxygen (DO), oxidation reduction potential, pH, and electric conductivity in overlying water over 70 days. The DO concentrations in the uncapped and capped conditions were preserved for 30 days and 70 days (until the end of experiment duration), respectively. ATT showed higher efficiency for $\text{NH}_4\text{-N}$ and T-N than the other two materials, and the capping efficiency of $\text{NH}_4\text{-N}$ was measured as 96.4%, 93.7%, and 61.6% when capped with 2 cm sand layer, 1 cm sand layer, and NWFM layer, respectively. DLM showed a superior rejection capability of $\text{PO}_4\text{-P}$ to ATT and SPL, reported as 97.2% when capped with 2 cm sand armor. The content of weakly adsorbed-P was lower in the uncapped condition than in the capping condition. It can be concluded that ATT and DLM can be used as capping agents to deactivate N and P, respectively, to reduce water contamination from sediments of the eutrophic river.

1. Introduction

Phosphorus (P) and nitrogen (N), i. e., vital nutrients to living organisms in aquatic environments, often trigger eutrophication (Correll 1999; Zhu et al. 2019). Excessive P concentrations initiate eutrophication in freshwater resources such as lakes, reservoirs, streams, and the headwaters of estuarines, and eutrophication by excessive N is often observed in ocean environments (Correll 1999). These eutrophication phenomena degrade organic matter on sediment surfaces, deplete dissolved oxygens near the bottom of the water column, and accelerate the nutrient flux from sediments to the overlying water column (Holmboe et al. 2001). Once started, eutrophication can continue for several decades due to the internal nutrient loading from sediments (Yin et al. 2016; Zhan et al. 2019).

In situ capping is an effective method for mitigating potential water-body eutrophication by impeding the nutrient migration from polluted sediments to the water above them (Jiao et al. 2020). Compared to monitored natural recovery and dredging, this treatment method is less costly, less disruptive, and less time-consuming (Ghosh et al. 2011). In capping technology, a layer of material is placed on top of contaminated sediment as a physical barrier to prevent the contaminant release into the overlying layer and to sequester contaminants in sediments (Gu et al. 2017; Perelo 2010). The choice of suitable capping material is, therefore, of particular importance to mitigate the contaminant release and other environmental impacts (Zhu et al. 2019). Capping materials used in laboratories and field studies include activated carbon (Gu et al. 2017), phoslock (Wang et al. 2017), and natural/modified zeolites (Hong et al. 2019; Jacobs and Waite 2004; Xiong et al. 2018; Zhan et al. 2019). Other materials newly studied include apatite (Knox et al. 2014), attapulgite (ATT) (Yin et al. 2016), biochar (Wang et al. 2018; Zhu et al. 2019),

calcium peroxide (Zhou et al. 2020), illite (Gu et al. 2019), layered double hydroxide (Wu et al. 2020), lanthanum-modified bentonite (Kong et al. 2020), and zero-valent iron (Todaro et al. in press).

In recent years, calcium-based materials have received close attention because of their high potential to inhibit the P release from sediment, in addition to their straightforward implementation, cost-effectiveness, and environmental-friendliness (Zhou et al. 2020). Necessary conditions of capping materials include high adsorption efficiency of target contaminants, cost-effectiveness, and mass-production potential to cover large areas of contaminated sediments. In previous studies, calcium-rich clay minerals (CRCMs), such as sepiolite (SPL) (Hong et al. 2020), ATT (Kim et al. 2018a), and dolomite (DLM) (Kim et al. 2018b) were considered adequate for adsorbing phosphorus in aqueous solution, showing extra-potential of improved adsorption capacity by thermal treatment. In comparison to synthetic materials, the above-mentioned natural adsorbates are much more environmentally friendly as being used as effective capping materials for sediment remediation (Jacobs and Förstner 1999; Jacobs and Waite 2004).

A total of 16 large weirs along the four major rivers in South Korea, including the Han, Geum, Yeongsan, and Nakdong Rivers, were constructed between December 2008 and April 2012 as part of the Four Major Rivers Restoration Project (Jun and Kim 2011). The construction of artificial impoundments, such as dams or weirs, has altered carbon and nutrient fluxes from sediments and the deposition of sediments due to changes in hydrological flow (Chen et al. 2017). Although river-side weirs were constructed to secure water resources and mitigate seasonal floods, accumulated sediments due to the altered flow patterns seem to deteriorate the overlying water quality (Lee et al. 2018). The increase in hydraulic retention time by the impoundment may influence sedimentation of inorganic/organic nutrients and also the gradual change of stratification patterns (Fantin-Cruz et al. 2016).

In this work, we applied the new CRCMs to investigate their remediation potential for contaminated sediments formed by artificial impoundments and compared their capping efficiencies to interrupt the N and P release from sediments to the overlying water. We compared the performance of sand and non-woven fabric mat (NWFM) as armors of capping layers and monitored T-N, NH₄-N, NO₃-N, T-P, and PO₄-P concentrations in overlying water, and calculated nutrient fluxes from the sediment layer to the overlying water. Other environmental parameters were also observed, such as pH, oxidation reduction potential (ORP), electrical conductivity (EC), and dissolved oxygen (DO), to investigate any possible impacts or correlations to the capping-enhanced sediment remediation.

2. Materials And Methods

2.1 Sampling for water and sediment

We selected a sampling site at a location (36° 28' 56", 127° 17' 15"), i.e., about 6 km upstream of the Sejong weir (constructed in 2009), where Geum River is curved, resulting in sediment deposition. The sediments were collected using a Van Veen grab sampler and mechanically mixed to be uniform before

use. We also sampled 40 L of river water using a polyvinyl chloride airtight container and subsequently filtered it using a GF/C filter (1.2 μm pore size, Whatman, UK) to remove large debris and suspended particulates.

2.2. Capping materials

All the calcium-rich clay minerals, ATT and DLM (Rexem Co., Pohang, Korea) and SPL (Sigma-Aldrich), were sieved with a standard sieve No. 200 (75 μm) to use upper-sized particles only. Thermal treatment under anoxic conditions was performed to improve the adsorption capacity of these materials using a tube furnace (CRFT 830S, Dongseo Science Co., Ltd., Korea), using optimal temperatures of ATT, DLM, and SPL, for the highest phosphate removal at 700°C, 900°C, 950°C, respectively, (Kim et al. 2018a; Kim et al. 2018b; Hong et al. 2020). Their physicochemical properties and phosphate adsorption capacity can be found elsewhere (Hong et al. 2020; Kim et al. 2018a; Kim et al. 2018b), as summarized in Table 1. The NWFM samples (E&H company, Pochon, Korea) have an average pore diameter of 15.64 μm and a thickness of 300 μm , which were synthesized from polypropylene via the melt-blown method (E&H Company). The clean sand (> 90% of SiO_2 , Jumunjin silica sand Co., Korea) was washed with deionized water before use as amour for the cap layer.

Table 1

Physical properties, elemental composition, and adsorption capacity of calcium-rich clay minerals including sepiolite, attapulgite, and dolomite. Summarized from previous studies (Hong et al. 2020; Kim et al. 2018a; Kim et al. 2018b).

		Sepiolite	Attapulgite	Dolomite
		950°C	700°C	900°C
Surface area (m ² /g)		7.66	69.8	8.41
Pore volume (cm ³ /g)		0.08	0.24	0.05
Pore size (nm)		28.37	0.12	25.63
Bulk density		0.86	0.72	0.63
pH		12.88	10.40	11.39
Elemental composition (%) obtained by XRF	MgO	27.0	7.1	29.2
	Al ₂ O ₃	1.8	20.7	2.6
	SiO ₂	35.3	53.7	19.8
	K ₂ O	0.3	2.9	0.0
	CaO	34.1	6.1	43.3
	Fe ₂ O ₃	0.0	5.8	2.2
Adsorption capacity (mg/g)	NH ₄ -N	0.52	0.6	11.74
	NO ₃ -N	0	0	0
	PO ₄ -P	172.34	54.4	385.51

2.3 Lab-scale sediment incubation experiments

Nine incubation experiments (three different capping adsorbents × three different armors) and two controls (uncapped condition) were performed to evaluate the efficiencies of ATT, DLM, and SPL to block the N and P release, as shown in Fig. 1. Four armoring conditions were applied to investigate the efficiency of capping materials: (1) no capping; (2) 1 cm capping of adsorbent under NWFM; (3) 1 cm capping of adsorbent under 1 cm sand armor; and (4) 1 cm capping of adsorbent under 2 cm sand armor. In the absence of capping materials or sand armor layers, sand was positioned below the sediments to make a total thickness of 9 cm and provide the same interval between the bottom of the water column and the sampling hole. Sediment incubation experiments were performed using a cylindrical tank with an inner radius of 7.5 cm and a depth of 25 cm, and the sampling hole was positioned 10 cm above the base side. Through the sampling port, 30 mL of overlying water were obtained using a disposable syringe to analyze the concentrations of N and P. A DO meter (HI9146, Hanna Instruments, Romania) was

implanted in the middle of the caps and sealed using silicone resin paste. The sampled river water of 3 L was injected into the cylindrical tank using a peristaltic pump (Model 7527-15, Cole-Parmer, USA) at a mild flow rate of 20 mL/min to minimize any potential erosions of sediments and capping materials. The cylindrical tanks containing sediments, capping materials, and mixed water were maintained in an incubator (IB3-15, JEIO Tech Co., Korea) at a constant temperature of 25°C without lights for 70 days. Water was sampled at 1, 2, 3, 7, 14, 21, 28, 42, 54, and 70 days after the initiation of the incubation to analyze environmental parameters (pH, EC, DO, and ORP) and different N and P species concentrations (NH₄-N, NO₃-N, T-N, PO₄-P, and T-P). The procedures for analyzing the nutrient concentration in sediments and overlying water were provided in Supplementary Information (Section 2.4.). The flux of nutrients per unit area during a day was calculated using Eq. S1. After the end of experiments, the four types of P-fraction (Adsorbed-P, Non-apatite inorganic P, Apatite-P, and Residual-P) under capping materials were analyzed using methods reported by Hieljst and Lijklema (1980). The detailed procedure for analyzing each P-fraction was described in Supplementary Information (Section 2.5.).

3. Results And Discussion

3.1 Properties of river water and sediments

The properties and concentrations of the river water and sediments obtained from the sampling sites described in Section 2.1. are presented in Table S1. DO and T-P concentrations were 8.71 and 0.13 mg/L, qualified to be Level 1 and Level 3 standard, respectively, by the Korean water quality standards (Level 1–6) for rivers. Both SS and TN concentrations were found to be highly contaminated as they are classified at Level 6. The COD concentration in water is at Level 5, and COD in sediments was within the moderate pollution range (40,000–80,000 mg/kg) by the United States Environmental Protection Agency (US EPA) sediment criteria. In the sediments, T-N and T-P contents were 2478 and 839 mg/kg, respectively, which are below the sediment quality guidelines (T-N: <5600 mg/kg and T-P: <1600 mg/kg, respectively) of the Korean Ministry of Environment, which is less strict than those of US EPA guidelines (T-N: > 2000 mg/kg and T-P: > 650 mg/g, respectively). The organic matter content of the sampled sediments was measured as 9.98%, which was higher than the 8%, to be classified as seriously polluted sediment by US EPA guidelines. The high contents of organic matter, N, and P in the sediments indicate that the nutrients in the sediments may be high enough to lead to eutrophication.

3.2 Change of water environment parameters under different capping conditions

Figure S1 shows variations of DO, pH, EC, and ORP under the capping of CRCMs and armoring materials along with those in the uncapped condition for 70 days. The DO concentrations of uncapped sediment decreased continuously below 0.5 mg/L within 16 days and reached zero on day 30, but those under capped conditions approached finite plateau values. The average concentrations of DO in the overlying water were in decreasing order (unit: mg/L): S1/SPL (4.8±0.9) > S1/DLM (4.7±0.9) > S2/DLM (4.5±1.1) > S2/SPL (4.4±1.2) > NWFM/SPL (4.1±1.0) > S2/ATT (4.0±1.6) > S1/ATT (3.6±1.5) > NWFM/DLM (2.3±1.7)

> NWFM/ATT (1.6 ± 2.0) > UN-CAP (0.9 ± 1.8). Higher DO concentrations were observed in the overlying water above sand armor than NWFM because the thicker sand cap-layer retarded the DO depletion by interrupting organic matter release from sediments. The higher DO concentrations under capping conditions observed here indicate the valuable potential of capping materials for the remediation of eutrophic lake sediments. Our findings are supported by Yin and Kong (2015)'s work that managing higher DO concentrations in overlying water helps prevent the liberation of P from sediments, protect benthic animals, and restore submerged vegetation. Although the pH of UN-CAP was maintained at pH 7.7, the pHs of overlying-water under CRCMs capping conditions were observed higher than that of UN-CAP. The pH increase under the capping condition was due to the alkaline nature of the capping materials: the dissolution of Ca^{2+} from CRCMs increases the pH of the overlying water as Ca is a base cation (Alvarado et al. 2020; McBride 1994). The decrease in pH under capping conditions from day 28 to day 70 indicates that the potential toxic effect associated with pH decreases over time. When the incubation experiments were finished, the pH under capping with SPL and DLM was measured about pH 11, much higher than that under ATT capping. The impact of ATT on the pH was not as significant as that of the other two materials. The EC under all experimental conditions increased slightly until day 14, and that of UN-CAP was greater than that of the other capping conditions measured at the end of the experiment. The ORP (Eh) reduced during the first 28 days and subsequently rebounded with gradual increases. The ORP under SPL and DLM capping showed distinct behavior from that with ATT; the pH results also showed a similar feature.

3.3 Release of nitrogen and phosphorus from uncapped/capped sediments to the overlying water

Figure 2 shows concentrations of T-N, $\text{NH}_4\text{-N}$, and $\text{NO}_3\text{-N}$ in the overlying water released from sediments during the experiment period. In Figure 2(a), the T-N concentration of UN-CAP continuously increased up to 22.7 mg/L; such an increase in T-N was also observed under the capping experiments except for S1/ATT and S2/ATT. In Figure 2(b), an increase in the $\text{NH}_4\text{-N}$ concentration was also observed under uncapped conditions. The ratio of $\text{NH}_4\text{-N}$ /T-N under uncapped conditions ranged from 16.2–94.3%, and it was less than 50% at the beginning of incubation but higher than 75% after day 7. A high fraction of $\text{NH}_4\text{-N}$ in the N of overlying water was also observed in other studies (Gu et al. 2017), who reported that the portion of $\text{NH}_4\text{-N}$ increased from 64.0 to 91.8% as the incubation time increased. The release of N from sediments, mainly as $\text{NH}_4\text{-N}$, may be attributed to the anaerobic condition after the depletion of DO ceased the nitrification of NH_4 to NO_3 (Beutel 2006; Lin et al. 2011). The higher amount of $\text{NH}_4\text{-N}$ released from uncapped sediments is consistent with the gradual decrease of $\text{NO}_3\text{-N}$ concentration that disappeared on Day 21. The nitrification process is considered halted under anaerobic conditions, leading to the buildup of NH_4 in the pore water occupied in the sediment layer and ensuing discharge of NH_4 into the overlying water (Beutel 2006). In the capping conditions with DO remained, NO_3 release from capped sediments was retarded during the incubation experiments.

The T-P and PO₄-P concentrations in the overlying water during the incubation experiments are shown in Fig. 3. For the uncapped sediments, both T-P and PO₄-P increased continuously throughout the incubation experiments. The T-P concentration under uncapped conditions increased up to 0.727 mg/g, which can cause eutrophication and severe problems in water bodies. In most lakes, streams, reservoirs, and estuaries, 0.1 mg/L of T-P concentration is unacceptably high, and 0.02 mg/L of T-P often causes problems such as eutrophication (Correll 1998). Increases in T-P and PO₄-P concentrations over time were also observed in the capped conditions, but these were lower than those of UN-CAP. The ratio of PO₄-P and T-P in the uncapped condition ranged from 54.2–69.5%, with an average of 69.5%. The effect of the capping treatment for blocking the release of T-P and PO₄-P is described in Section 3.4.

3.4 Flux of nitrogen and phosphorus under different capping conditions

The fluxes of T-N, NH₄-N, and NO₃-N under different capping conditions were calculated, and the results are illustrated in Fig. 4. The flux of T-N in decreasing order are as follows: NWFM/SPL > NWFM/DLM > UN-CAP > S1/DLM > S1/SPL > S2/DLM > S2/SPL > NWFM/ATT > S1/ATT > S2/ATT. The T-N flux of NWFM/SPL and NWFM/DLM was higher than that of UN-CAP, indicating that the capping treatment using NWFM/SPL and NWFM/DLM was ineffective for blocking the release of T-N. In the case of ATT, a higher flux of T-N capped with NWFM when compared to the two different sand armor depths was also observed, similar to SPL and DLM. These results indicate that the sand armor shows better performance for blocking the release of T-N than NWFM, an observation that has also been noted by other researchers (Jiao et al. 2020; Lampert et al. 2011). The thicker the capping layer, the greater the diffusion distance between sediments and overlying water, and more time is required for nutrients to travel from sediments to overlying water (Jiao et al. 2020). A lower T-N flux for the 2 cm sand armor compared to the 1 cm sand armor was observed under all three different capping materials, and their difference corresponded to 4.4–9.0% of the T-N flux of UN-CAP. The effect of capping treatment on NH₄-N flux was similar to that of T-N flux, and the flux of NH₄-N in decreasing order is: UN-CAP > NWFM/SPL > NWFM/DLM > S2/DLM > S1/DLM > S1/SPL > S2/SPL > NWFM/ATT > S1/ATT > S2/ATT. This result can be expected because the T-N released from sediment to overlying water was mainly composed of NH₄-N, as described above. The NH₄-N flux of Ca-rich clay minerals under NWFM was also higher than that under sand armor, but the difference in NH₄-N flux between sand armor depths of 1 cm and 2 cm was not significant.

A lower flux of NH₄-N was observed under all capping treatments than UN-CAP, and the NH₄-N fluxes of ATT were lower than those of the other two capping materials. This result can be explained by higher adsorption capacity (11.74 mg/g) of ATT for NH₄-N than the other two materials (SPL: 0.60 mg/L; DLM: 0.52 mg/L). Ammonium can be removed from water by ATT through electrostatic adsorption and ion exchange (Sun et al. 2017).

The fluxes of T-P and PO₄-P under uncapped and capped with different Ca-rich clay minerals and armors are presented in Fig. 5. The lower T-P flux under capping conditions than UN-CAP indicates that all capping materials used in this study were useful for interrupting T-P release from sediments. Similar to T-P, the effect of capping was also observed in the reduction of the PO₄-P flux. This result was expected because the T-P in the overlying water accounted for approximately 70% of T-P, as described in Section 3.3. For all capping materials, sand armor with a depth of 2 cm was more effective than 1 cm. In contrast to NH₄-N and T-N fluxes, the T-P and PO₄-P fluxes between the sand armor and NWFM did not show significant differences, and the PO₄-P and T-P fluxes of SPL with 1 cm of sand were higher than those of SPL with NWFM. The negatively charged surface of the sand was not adequate for adsorbing the anion PO₄³⁻, but the sand layer blocked the release of PO₄-P only by acting as a physical barrier interrupting PO₄-P diffusion. Compared to the flux of T-N and NH₄-N, the fluxes of T-P and PO₄-P showed a significant difference of capping material. ATT was the most effective capping material for interrupting the release of T-N and NH₄-N; however, it was less effective for T-P and PO₄-P than SPL and DLM. This result is also consistent with the order of the PO₄-P adsorption capacity of Ca-rich clay minerals, as shown in Table 1. The adsorption capacity for PO₄-P follows in decreasing order: DLM (385.5 mg/g) > SPL (172.3 mg/g) > ATT (54.5 mg/g), and this order is inverse proportional to the order of PO₄-P flux and proportionate to the blocking efficiency of PO₄-P. Ca²⁺ eluted from SPL and DLM can enhance the removal of PO₄³⁻ in the overlying water by forming calcium-bound P (Ca-P) precipitation (Hong et al. 2020; Kim et al. 2018b; Yin et al. 2013).

3.5 Effect of capping treatment on the P fractions in sediments

The P fractions, including Adsorbed-P, NAI-P, Apatite-P, and Residual-P of sediment under different capping treatments, are presented in Fig. 6(a). Under all experimental conditions, most of the P in the sediment was present in the form of NAI-P and Residual-P, and the Adsorbed-P, a weakly adsorbed state, accounts for less than 1% of the total amount of P in sediments. The content of Adsorbed-P in UN-CAP was 5.5 mg/kg (Fig. 6(b)), which is equal to 0.5% of the T-P. The lower fraction of Adsorbed-P in UN-CAP compared to other conditions can be explained by a more incredible amount of P released from sediments into the overlying water, as shown in Fig. 3. A lower Adsorbed-P fraction was also observed under ATT capping than under SPL and DLM capping. This result is also consistent with the higher release of P to the overlying water under ATT capping than the other two Ca-rich clay minerals. Under all capping conditions, the fraction of NAI-P was bound to Al/Fe and released from sediments under anaerobic conditions (Hong et al. 2020; Kaiserli et al. 2002). The Residual-P fraction, the most stable form of P and not readily released to overlying water, increased up to > 80% under all capping conditions, indicating that the less stable P was converted to Residual-P through the Ca-rich capping treatment. The P fraction showed a distinct difference according to the Ca-rich clay mineral used, but not the armor used. The 2 cm of sand armor showed the highest Residual-P fraction for SPL and DLM, but the lowest Residual-P fraction was observed under ATT.

4. Conclusions

The results suggest that the application of Ca-rich clay minerals can remediate sediments deposited by the construction of artificial impoundments. The effectiveness of the sand layer and NWFM were also evaluated as armor materials. While DO was depleted under the uncapped condition on Day 30, the DO under all capping conditions was preserved during the 70 days of the incubation experiment. The pH under the use of SPL and DLM significantly increased, and the pH of ATT was slightly higher than that of UN-CAP. The ATT effectively blocked the liberation of T-N and $\text{NH}_4\text{-N}$ from sediments by adsorbing ammonia via ion exchange. Less $\text{PO}_4\text{-P}$ and T-P from sediments were released from sediment capped with DLM than the other materials, which is attributed to the higher adsorption capacity of DLM for PO_4^{3-} . A thicker sand layer retarded the release of N and P from sediments by increasing the diffusion distance between the sediments and the overlying water. Higher Residual-P and lower Adsorbed-P fractions were obtained using Ca-rich clay mineral capping than under uncapped conditions, indicating that P sequestration by capping was feasible. ATT is a useful capping material for interrupting N release whilst not having a significant influence on the pH. Owing to its low blocking efficiency of the P release, however, ATT should be mixed with a material such as DLM, which has excellent P adsorption capacity.

Declarations

Conflicts of interest: The authors declare that they have no competing interests

Authors' contributions

Seung-Hee Hong: Conceptualization, Experiment, Data analysis; **Chang-Gu Lee:** Writing-review and editing; **Seong-Jik Park:** Conceptualization, Writing-original draft; Writing-review & editing, Supervision, Funding acquisition

Funding

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. 2020R1C1C1008982).

Ethics approval and consent to participate: Not applicable

Consent for publication: Not applicable

Consent for participation: Not applicable

Availability of data and materials

All data generated or analysed during this study are included in this published article.

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

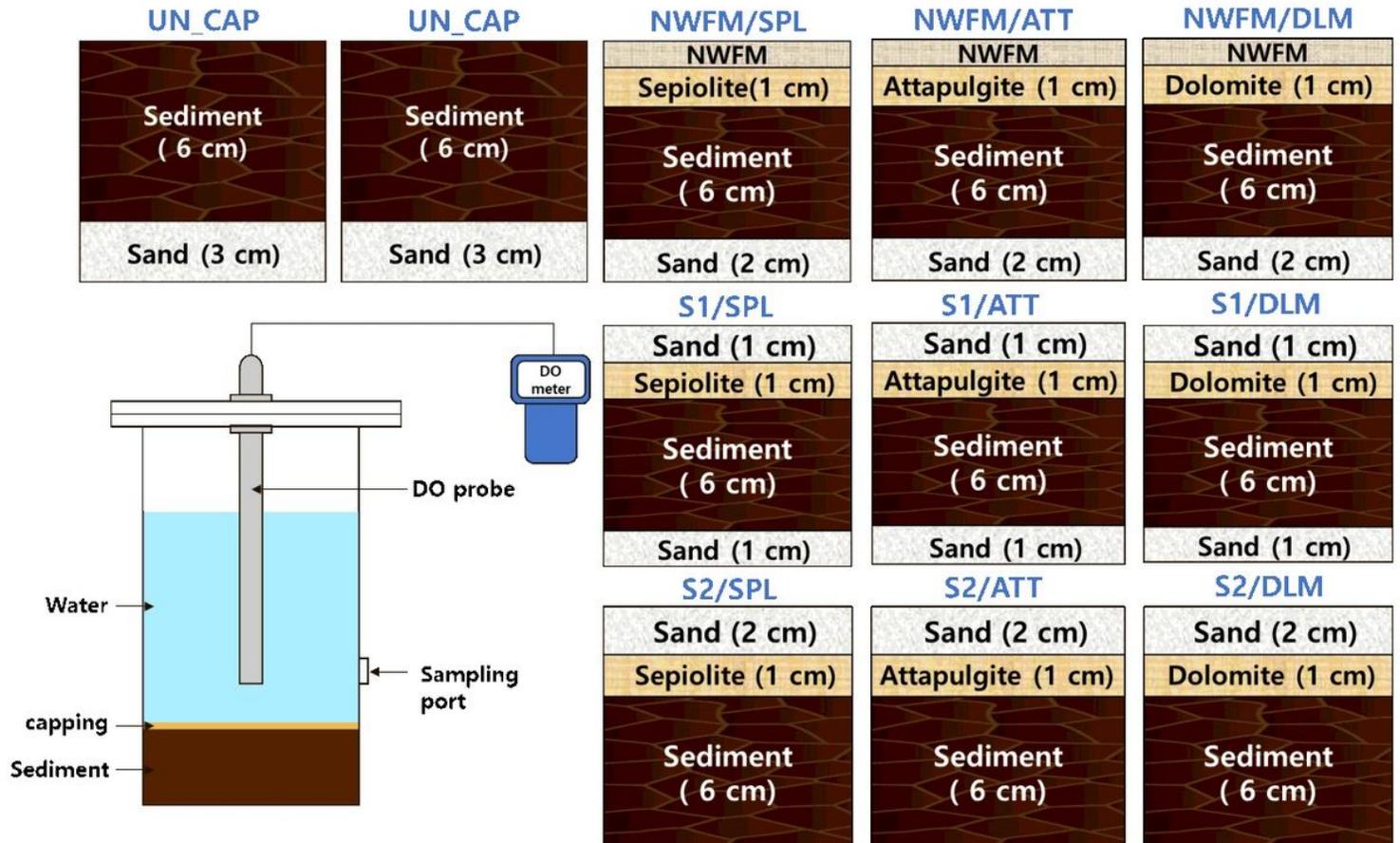


Figure 1

Schematic diagram of the experimental setup

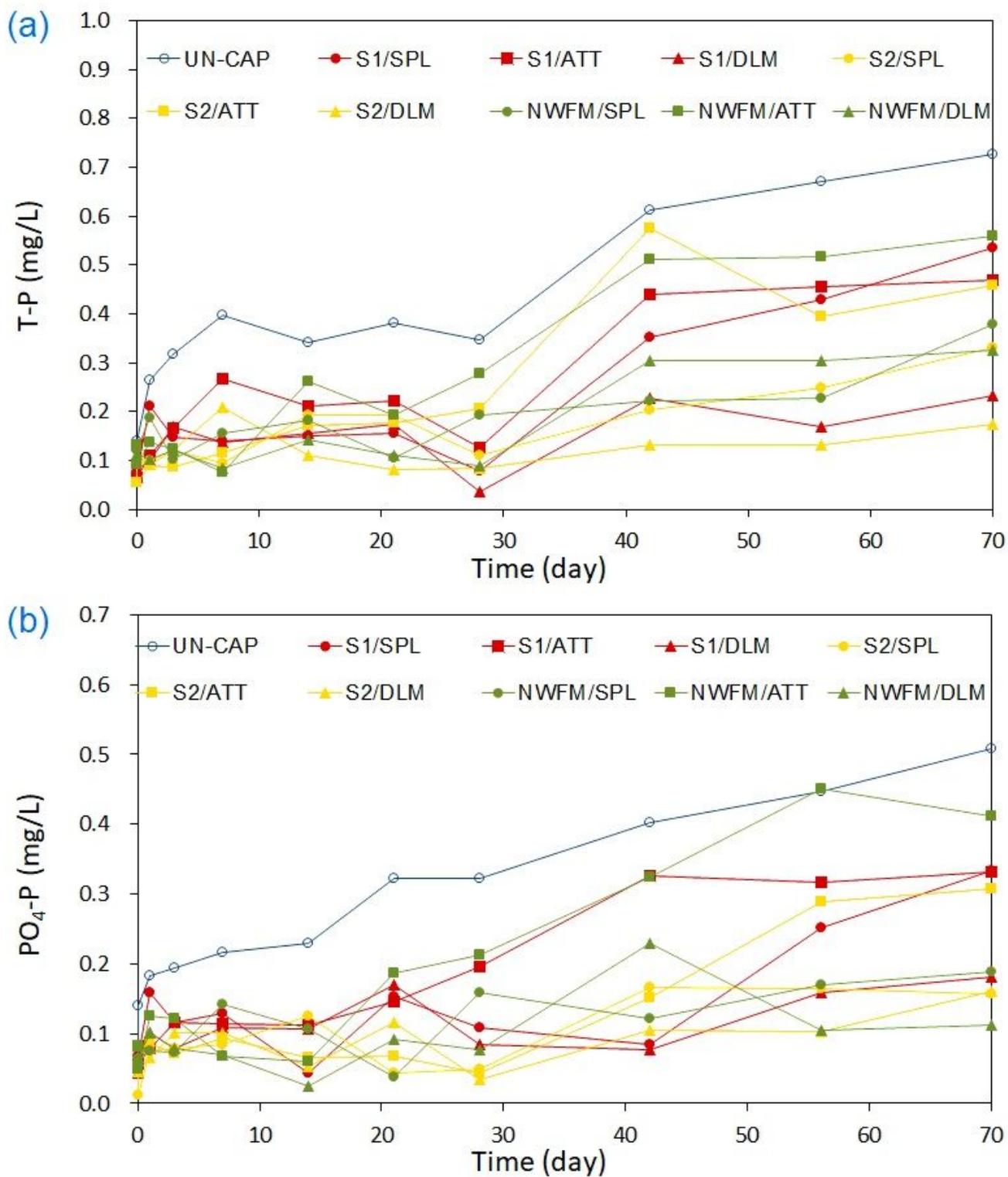


Figure 2

Changes in (a) T-N (mg/L), (b) NH₄-N (mg/L), and (c) NO₃-N (mg/L) concentration in the water overlying sediment (UN-CAP), different Ca-rich clay minerals (SPL, ATT, and DLM), and armor materials (S1, S2, and NWFM) during 70 days of laboratory incubations.

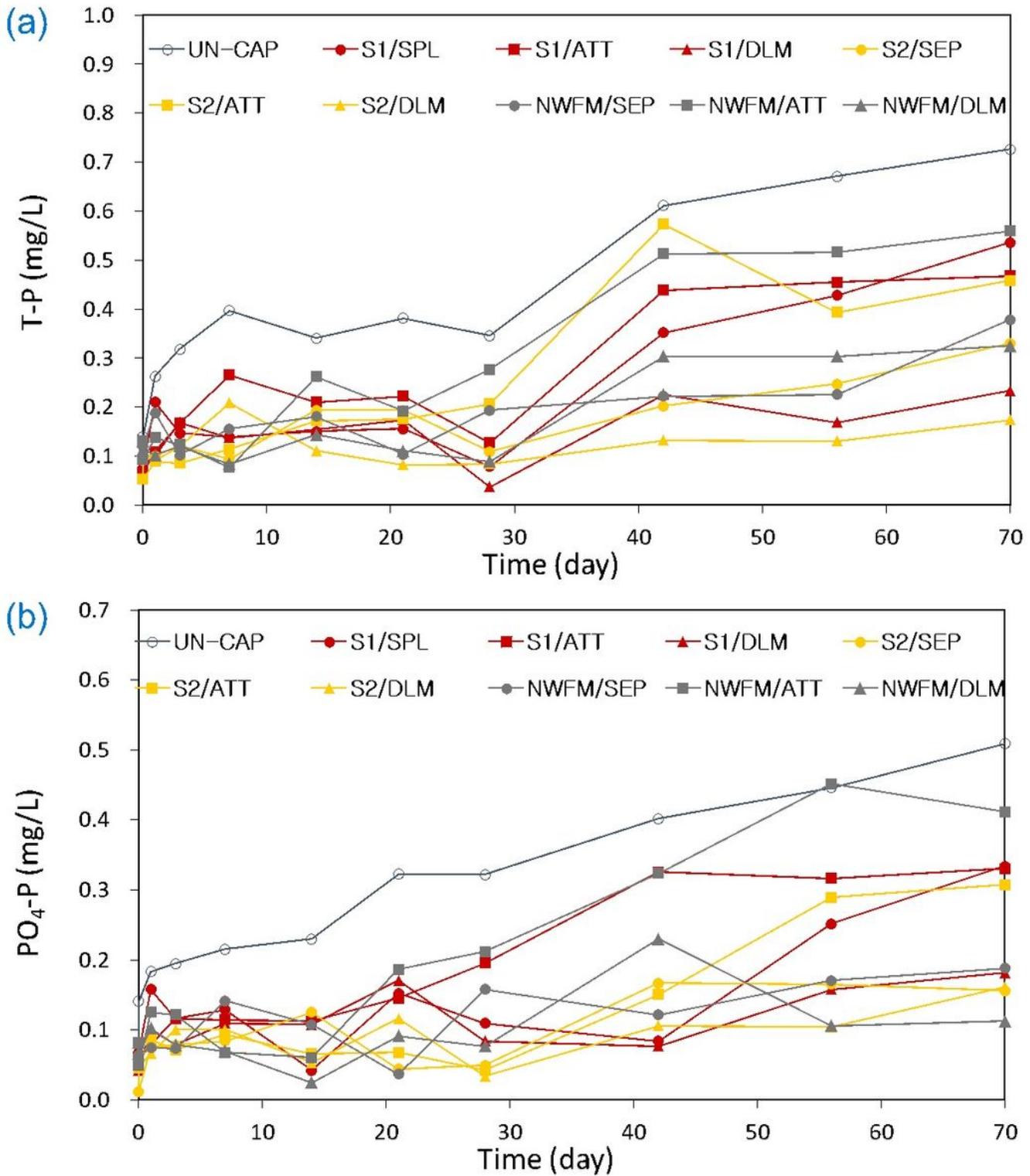


Figure 3

Changes in (a) T-P (mg/L) and (b) PO₄-P (mg/L) concentration in the water overlying sediment (UN-CAP), different Ca-rich clay minerals (SPL, ATT, and DLM), and armor materials (S1, S2, and NWFM) during 70 days of laboratory incubations.

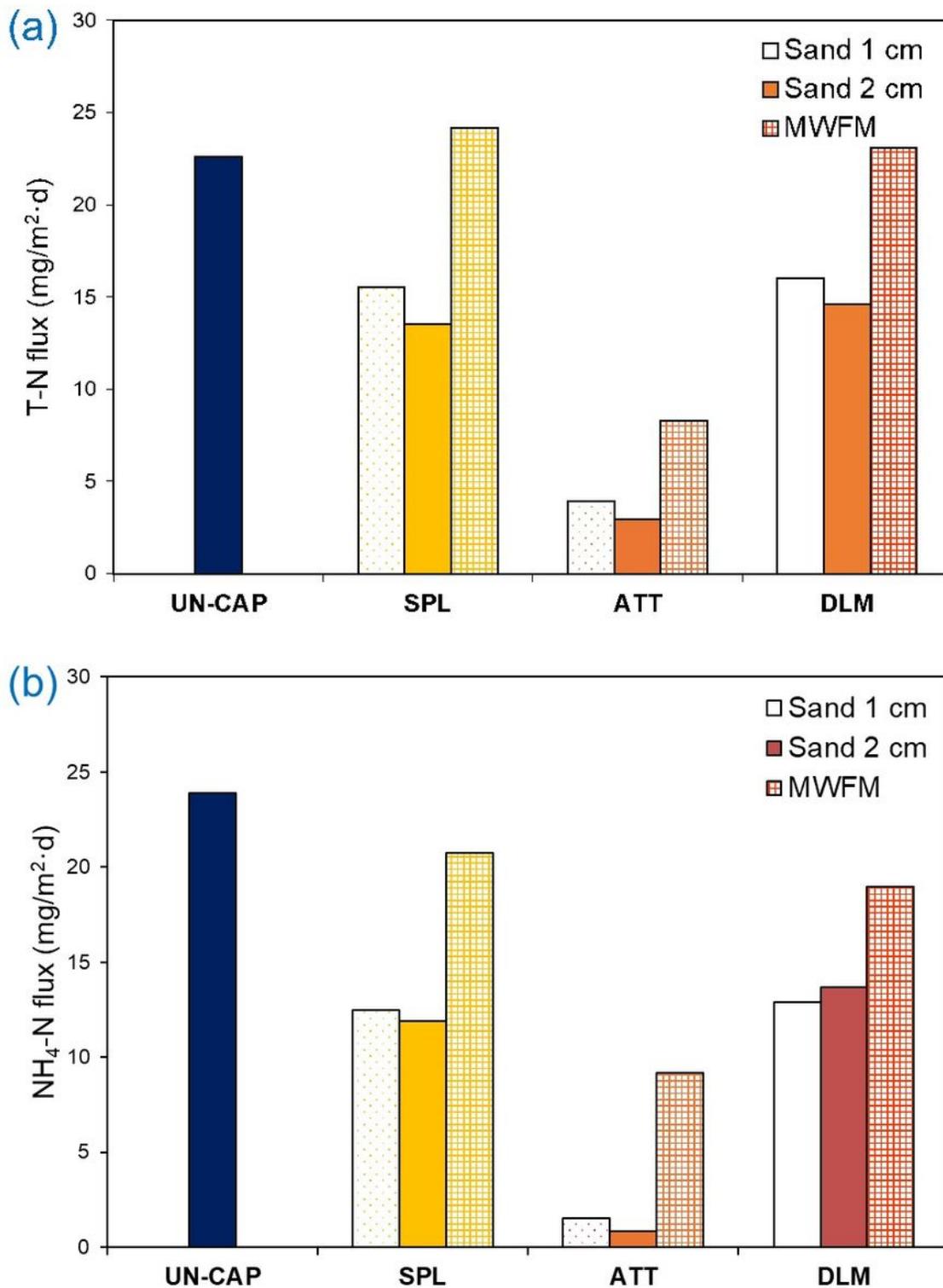


Figure 4

Flux ($\text{mg}/\text{m}^2\cdot\text{d}$) of (a) T-N and (b) $\text{NH}_4\text{-N}$ from sediments to overlying water under the uncapped condition and capped conditions with different Ca-rich clay minerals (SPL, ATT, and DLM) and armor materials (S1, S2, and NWFM) during 70 days of laboratory incubations.

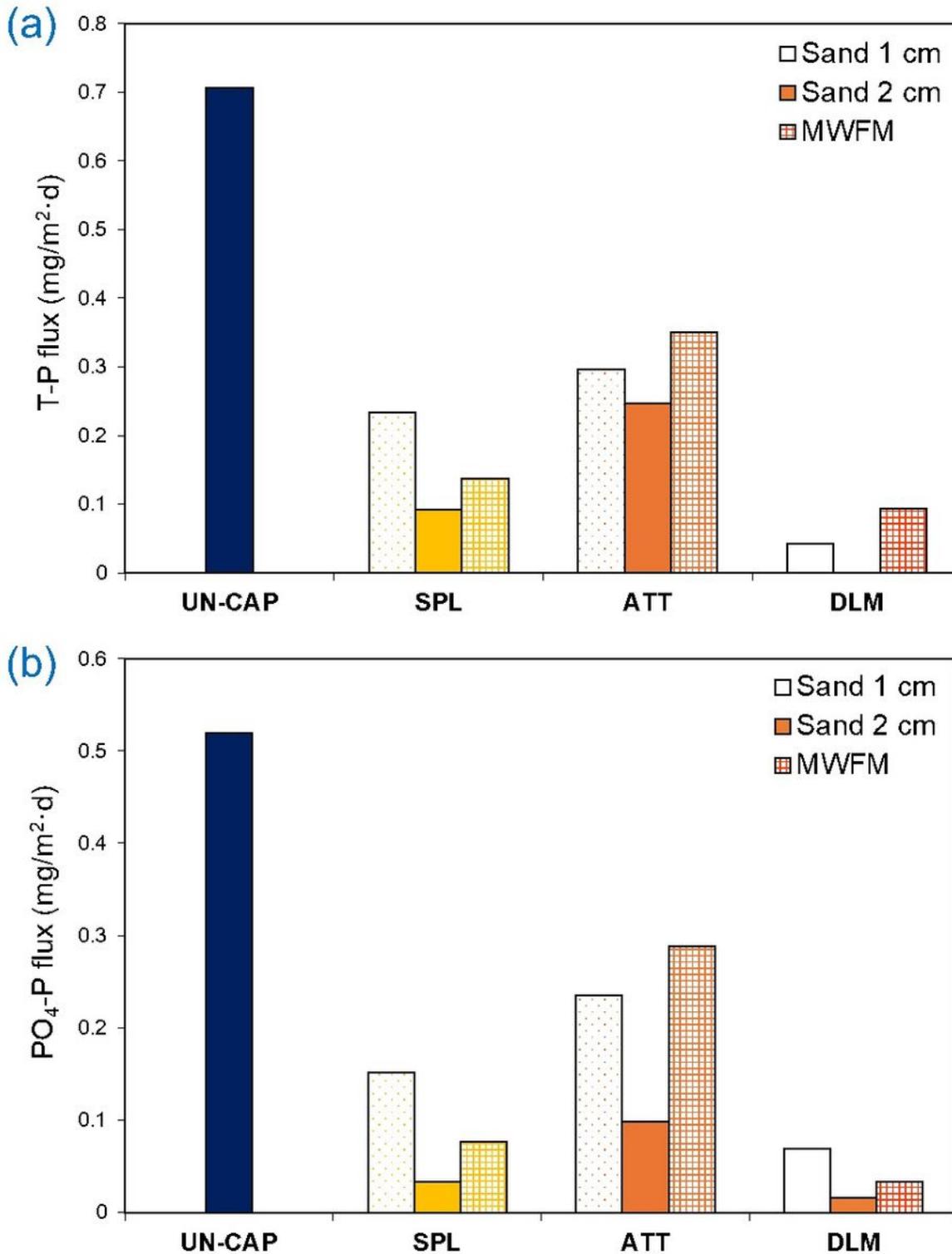


Figure 5

Flux ($\text{mg}/\text{m}^2\cdot\text{d}$) of (a) T-P and (b) $\text{PO}_4\text{-P}$ from sediments to overlying water under the uncapped condition and capped conditions with different Ca-rich clay minerals (SPL, ATT, and DLM) and armor materials (S1, S2, and NWFM) during 70 days of laboratory incubations.

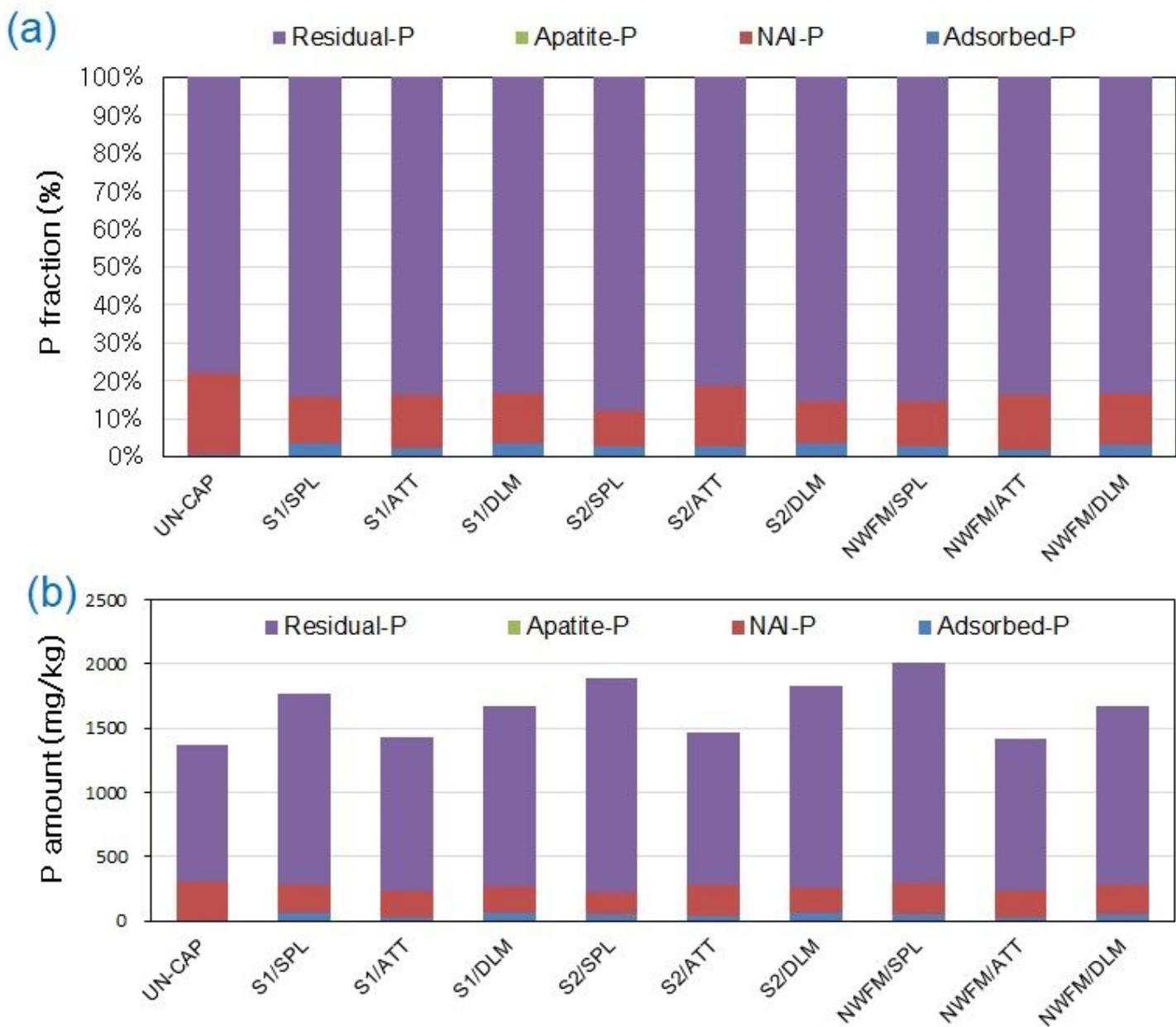


Figure 6

(a) P Fraction (%) and (b) P amount (mg/g) of Adsorbed-P, NAI-P, Apatite-P, and Residual-P in uncapped sediments and 1 cm of sediments adjacent to Ca-rich clay minerals (SPL, ATT, and DLM).

Supplementary Files

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