

# Effects of alkalinity-controlling chemicals on biofilter performance and sludge properties in freshwater recirculating aquaculture systems

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## ABSTRACT

This study aims to enrich potassium (K) content in sludge from recirculating aquaculture systems (RAS) by replacing sodium (Na)-based alkalinity-controlling chemicals with K-based derivatives. Nine identical pilot-scale RAS rearing rainbow trout (*Oncorhynchus mykiss*) were operated for 10 weeks in triplicate treatments with  $K_2CO_3$ ,  $NaHCO_3$ , and NaOH as alkalinity-controlling chemicals. Water and sludge samples were collected weekly from the RAS for water quality and sludge property measurements. Results showed that  $K_2CO_3$  significantly increased K concentrations, reaching average values of 190 mg/L in water samples and 180 mg/kg in sludge samples. These levels were 17–20 times and 14 times higher than those observed in  $NaHCO_3$  and NaOH treatments, respectively. All treatments achieved satisfactory biofilter performance ( $TAN < 1$  mg/L and  $NO_2-N < 0.2$  mg/L), and good fish production performance ( $FCR=0.96-1.17$ , survival  $> 95\%$ ). Significant accumulation of Na in rearing water from  $NaHCO_3$  and NaOH treatments was observed with  $133 \pm 7$  mg/L and  $136 \pm 2$  mg/L at the end of experiment, respectively, which are far above phytotoxic Na threshold of 50 mg/L. In contrast,  $K_2CO_3$  treatment maintained low and stable Na levels over sampling period, ranging from  $4.0 \pm 1.3$  mg/L to  $6.3 \pm 0.6$  mg/L. No difference observed among treatments on other sludge (TN, TP, DM, TSS and  $SVI_{30}$ ) and water (TN, TP, Ca, Mg, S, and Si) parameters. This study confirms that  $K_2CO_3$  as an alkalinity-controlling chemical in RAS is a feasible and synergistic solution in unifying alkalinity adjustment and producing a K-rich fertilizer from RAS sludge, which enhances the sustainability and circularity of aquaculture production.

## 1. Introduction

Recirculating aquaculture systems (RAS) play an important role in aquatic food supply to meet the demands from the rapidly growing global population (Ahmed and Turchini, 2021). RAS enable high-intensity fish production in an environmental controlled condition with high-degree water reuse during the production, improve biosecurity, and allow for all-year-round production with reduced environmental impacts (Brown et al., 2025). However, a significant amount of sludge from fish faeces and uneaten feed is continuously generated during RAS operation, which poses environmental and economic burdens. According to Rødvei et al. (2025), 1 kg of feed can yield approximately 130 g of dry sludge (5% water content) during Atlantic salmon smolt production. RAS sludge is rich in nutrients, containing organic matter, nitrogen (N) and phosphorus (P), but with variably high moisture content (An-Stepec et al., 2025; van Rijn, 2013). If discharged untreated, it can lead to eutrophication and cause harm to the function of

aquatic ecosystems (Chary et al., 2024; Letelier-Gordo and Fernandes, 2021). Currently, sludge is transported offsite, e.g., incineration or biogas plants for treatment, incurring transportation and disposal costs for farmers (Howard et al., 2023; Mann, 2023). On the other hand, the nutrient-rich sludge represents a valuable resource suitable for recovery processes. One such valorization pathway is the use of RAS sludge as a fertilizer (Brod et al., 2023; Brod and Øgaard, 2021).

Sludge intended for reuse as fertilizer comes primarily from freshwater RAS, as the high salt content in sludge from saline system poses significant challenges in its reuse (Howard et al., 2023). Sludge contained sufficient content of macronutrients, i.e., essential nutrients required by the plant in large amounts, including N, P, and sulfur (S). The RAS sludge has been used as a fertilizer in both soil-based and soilless plant production systems. In soil-based agriculture, common application methods include direct land application of sludge, sludge composting, and anaerobic digestion of sludge as liquid fertilizer (Brod et al., 2023; Brod and Øgaard, 2021; Howard et al., 2023; Lenz et al.,

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2021; Wheaton et al., 2025). In soilless system, such as hydroponics or aquaponics, the common methods for fertilizer use are the application of the remaining effluent from the sludge dewatering process and the utilization of products from anaerobic digestion of sludge (Harabiš et al., 2025; Howard et al., 2023; Madady et al., 2025; Tetreault et al., 2021). However, the nutrient profile of RAS sludge didn't provide a complete complement of nutrients for optimal plant growth. RAS sludge was deficient in certain nutrients, particularly potassium (K), an essential macronutrient for the physiological functions in plants, such as stomatal regulation, photosynthesis, enzyme activation, water uptake, stress response, sugar production and transportation, and fruit ripening (Johnson et al., 2022; Lunda et al., 2019; Sardans and Peñuelas, 2021). In practice, discharged sludge needed to be supplemented with inorganic fertilizers to achieve a desired nutrient profile, such as the Hoagland's solution used in hydroponics (Roy et al., 2025). However, this practice contradicted the circular economy principle, as it relied on mining the finite reserves of inorganic fertilizer salts on Earth, which was both economically and environmentally costly. Therefore, increasing the intrinsic K content of the sludge is essential for sludge valorization as a fertilizer. Recent efforts have successfully increased K levels in RAS sludge using tailored fish feed that includes K as a dietary supplement (Roy et al., 2025; Siqwepu et al., 2020). Previous studies have proposed that K content in RAS sludge can be improved by modifying the choice of alkalinity-controlling chemical used, e.g., potassium hydroxide (KOH), potassium bicarbonate (KHCO<sub>3</sub>), and potassium carbonate (K<sub>2</sub>CO<sub>3</sub>) (Lunda et al., 2019; Rao, 2020). Wenzel et al. (2021) reported that the application of KOH as alkalinity-controlling chemical in RAS can improve the nutritional profile of the RAS water for aquaponics plant production. However, the method of using K-based alkalinity-controlling chemical to improve RAS sludge nutrient profiles has not yet been experimentally validated.

Alkalinity, the capacity of water to resist pH changes, is a critical water quality parameter in daily RAS operation. Insufficient alkalinity levels could lead to unstable pH, exacerbating the toxicity of fish metabolites, such as ammonia and CO<sub>2</sub>, thereby compromising fish health (Skov, 2019; Summerfelt et al., 2015). Alkalinity can also impact biofilter performance and the efficiency of CO<sub>2</sub> stripping in degassing units (Jafari et al., 2024; Summerfelt et al., 2015). The interdependence of alkalinity, pH, CO<sub>2</sub>, and nitrification kinetics underscores the necessity of maintaining optimal alkalinity levels in RAS to ensure system stability. Jafari et al. (2024) suggested that alkalinity levels range between 50 and 200 mg/L as calcium carbonate (CaCO<sub>3</sub>) for effective total ammonia-nitrogen (TAN) removal in freshwater RAS. Alkalinity is required and consumed during nitrification process. As a rule of thumb, 7.14 g of alkalinity as CaCO<sub>3</sub> are consumed in nitrification process for the conversion of 1 g TAN into nitrate-nitrogen (Timmons et al., 2018). In addition to the stoichiometric requirement, residual alkalinity also neutralizes the acid generated by the nitrification process to maintain suitable pH range for nitrifying bacteria (Biesterfeld et al., 2003). Furthermore, the cellular synthesis and growth of nitrifying bacteria require the inorganic carbon source, which can be supplemented by carbonate alkalinity (Biesterfeld et al., 2003; Timmons et al., 2018). Alkalinity adjustment in RAS is normally done by the addition of a base (e.g., hydroxide, bicarbonate, and carbonate), and sodium bicarbonate (NaHCO<sub>3</sub>) is commonly used buffer due to its safeness, high solubility, easy access, and low cost (Jafari et al., 2024; Timmons et al., 2018). From the perspective of valorizing RAS sludge into fertilizer, the use of NaHCO<sub>3</sub> as alkalinity-controlling chemical may not be an ideal candidate because it can result in excessive sodium (Na) content in sludge that exceeds phytotoxic concentrations (Lunda et al., 2019; Rakocy, 2012), which made sludge not suitable for direct fertilizer use. One option to decrease the high Na concentrations in RAS sludge and make sludge more suitable for fertilizer use is to replace the Na-based alkalinity-controlling chemicals with K-based alternatives. However, the effect of alkalinity type on sludge nutrient profiles, biofilter performance, and fish production performance in RAS has not been systematically

evaluated.

Therefore, the main aim of this study was to increase K content in RAS sludge by the application of K-based alkalinity-controlling chemicals. Specific objectives were to investigate the effects of potassium carbonate (K<sub>2</sub>CO<sub>3</sub>) as alkalinity-controlling chemical on 1) biofilter performance; 2) sludge properties; and 3) fish production performance compared to Na-based derivatives.

## 2. Materials and methods

### 2.1. Experimental design

The experiment was conducted in nine identical pilot-scale freshwater RAS at the Natural Resources Institute Finland (Luke) research infrastructure in Laukaa, Finland. The details of the experimental RAS facility are described in more depth previously (Pulkkinen et al., 2018). In brief, each individual RAS unit consists of a 500 L bottom-drained rearing tank, a feed collector, a swirl separator, a drum filter with the micro-screen mesh size of 60 μm, a 147-L moving-bed biofilm reactor (MBBR) filled with 60 L RK bioelements (Dania Plast A/S, Skive, Denmark), a trickling filter with height of 0.8 m filled with Bio-Blok®200 filter media (EXPO-NET Danmark A/S, Hjørring, Denmark), and a 70-L pump sump. Before the start of experiment, MBBR was acclimated for three months to get full maturity, specifically one month in the absence of fish with feeding ammonium chloride and adding K<sub>2</sub>CO<sub>3</sub> for pH buffering, and two months in the presence of fish with commercial feed and addition of K<sub>2</sub>CO<sub>3</sub> for pH adjustment.

The nine RAS units were randomly divided into three treatment groups in triplicate: 1) RAS with NaHCO<sub>3</sub> alkalinity supplementation (NaHCO<sub>3</sub>); 2) RAS with K<sub>2</sub>CO<sub>3</sub> alkalinity supplementation (K<sub>2</sub>CO<sub>3</sub>); and 3) RAS with sodium hydroxide (NaOH) alkalinity supplementation (NaOH) (Fig. 1). Each rearing tank was stocked with rainbow trout (*Oncorhynchus mykiss*) with a similar total biomass of around 13.7 kg at the start of experiment. The fish were reared in freshwater and fed in the experimental tanks for two months before changing alkalinity-controlling chemicals into the system. After fish transfer, the three treatment groups were acclimated for one month by feeding 4.5 mm feed pellets (Efico Environ 923 Advance, BioMar, Denmark) and the specific alkalinity chemicals before sampling. Alkalinity chemicals were added daily in both acclimation and sampling phase to maintain water alkalinity levels around 100 mg CaCO<sub>3</sub>/L. On average, approximate 48 g/d of NaHCO<sub>3</sub>, 41 g/d of K<sub>2</sub>CO<sub>3</sub>, and 98 mL/d of 50% NaOH solution were added to each replicate treatment tanks throughout the experiment. During sampling phase, water and sludge samples in each RAS unit were collected weekly for measurements.

All RAS units were operated under constant conditions at a temperature around 15 °C, dissolved oxygen saturation about 100% saturation, and photoperiod of 24 h light. The water renewal rate was set at 700 L/kg feed, and the make-up water was taken from the oligotrophic Lake Peurunkajärvi (62°26'56''N, 25°51'7''E). Fish was fed with a commercial diet (4.5 mm, Efico Environ 923 Advance, BioMar, Denmark) using a commercial feeding system (T Drum 2000; Arvo-Tec, Joroinen, Finland) with feeding rate of 150 g/d.

### 2.2. Water sampling and characterization

All water samples were collected in the morning before any daily routines. A 1 L of water sample was collected weekly from the outlet of each rearing tank during sampling phase and split into homogenous subsamples for water quality measurements. pH and alkalinity levels were analysed with a titrator (TitraLab AT 1000, HACH, Loveland, USA). Turbidity was measured with a portable turbidimeter (2100Q, HACH, Loveland, USA). The water samples were filtered through a 0.45-μm syringe filter (J.T. Baker®, VWR International Oy, Finland) before total TAN, nitrite (NO<sub>2</sub>-N), and nitrate (NO<sub>3</sub>-N) analysis. TAN, NO<sub>2</sub>-N, NO<sub>3</sub>-N, total nitrogen (TN), and total phosphorous (TP) were analysed in

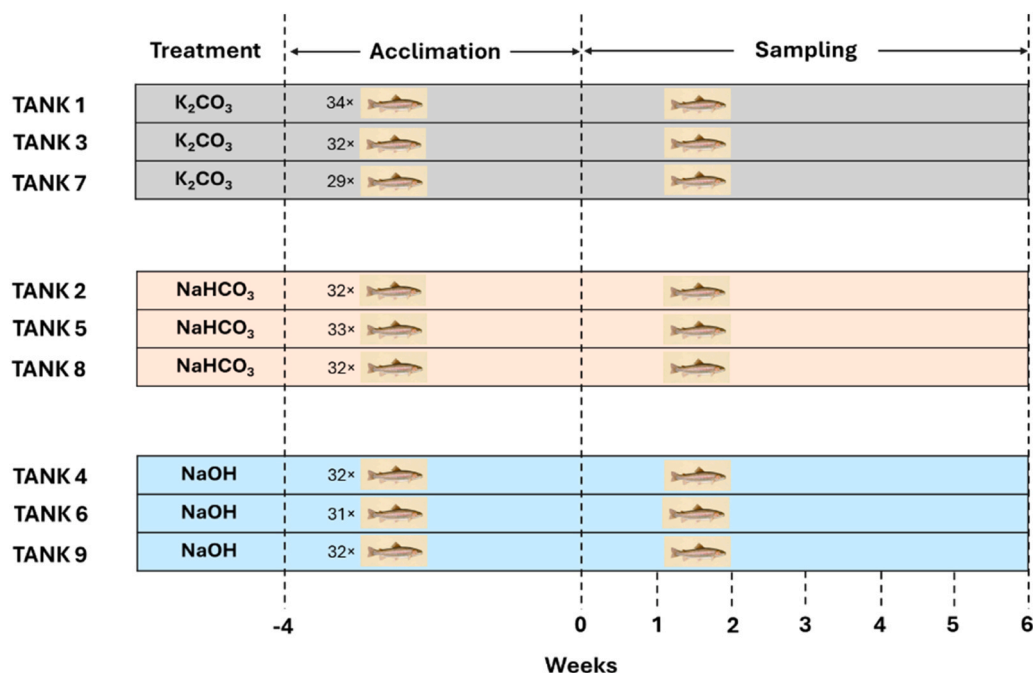


Fig. 1. Schematic representation of the experimental design.

a spectrophotometer (DR 3900, HACH LANGE, USA) with Hach Lange test kits of Nessler agent sets, LCK341, LCK340, LCK338, and LCK349, respectively. Some selected “plant-essential” elements in water samples were also quantified, including the primary macronutrient K, secondary macronutrients calcium (Ca), magnesium (Mg), and S, and micro-nutrients iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), Boron (B), and nickel (Ni). In addition, non-essential but potentially plant-beneficial elements such as Na, Aluminum (Al), and silicon (Si) (Nunes da Silva et al., 2022), as well as toxic heavy metals lead (Pb), cadmium (Cd) and chromium (Cr) in water samples were analysed. Acid soluble concentrations of K, Ca, Mg, S, Fe, Zn, Cu, Mn, B, Ni, Na, Al, Si, Pb, Cd, and Cr were quantified with inductively coupled plasma optical emission spectrometry (ICP-OES) after  $HNO_3$  digestion in accordance with SFS-EN ISO 11885:2007 standard at Luke Viikki Laboratory (FINAS accredited laboratory T024).

### 2.3. Sludge sampling and characterization

The sludge samples were collected weekly over a 6-hour period (approximately 8 a.m.–2 p.m.) from the backwashing of the drum filter. The sludge was mixed homogeneously before measurements. The dry matter (DM) content, total suspended solids (TSS) content and settleability (sludge volume index at 30 min,  $SVI_{30}$ ) of sludge were determined according to standard methods 2540B, 2540D, and 2710D, respectively (APHA, 2017). The TN content in sludge was analyzed with Hach Lange test kit LCK 338. Sludge samples were digested with aqua regia under pressure in microwave digester CEM Mars 6 (model 240/50. CEM, Matthews, NC, USA) before TP and TK measurements. The TP and TK content were then measured from the solution with plasma emission spectrometry (ICP-OES, Perkin Elmer Optima 8300, USA).

### 2.4. Data and statistical analysis

#### 2.4.1. Fish growth parameters calculation

$$\text{Weight gain (kg)} = W_2 \text{ (kg)} - W_1 \text{ (kg)} \quad (1)$$

$$\text{Survival rate (\%)} = 100 \times Q_2 / Q_1 \quad (2)$$

Feed conversion ratio (FCR) = Total input of feed (as is basis, kg) / Weight gain (kg) (3)

Where  $W_1$  and  $W_2$  were the initial and final fish weight (kg),  $Q_1$  and  $Q_2$  were the number of fish at the start and the end of experiment, respectively.

#### 2.4.2. Statistical analysis

During the seventh week of the trial (third week for sampling), one replicate tank in NaOH treatment experienced an acute suffering event caused by an incorrect NaOH addition with high concentrations. As this incident severely affected water quality and fish performance and welfare, the data from this tank was omitted from the data analyses. In other words, the experiment consisted of three replicates for treatments  $K_2CO_3$  and  $NaHCO_3$ , but only two replicates for NaOH treatment.

Given this unbalanced design and the repeated measures structure of the data, the effect of treatment on response parameters (e.g., N, P, K, etc.) was analysed using a linear mixed-effects model (LMM), with treatment and time included as fixed effects, along with their interaction term to assess whether treatment effects varied over time. To account for the non-independence of repeated measurements within the same rearing tank, the tank ID was included as a random effect. The model was specified as follows:

$$\text{Response parameter} \sim \text{Treatment} \times \text{Week} + (1 | \text{tank ID})$$

Model assumptions were evaluated to ensure validity of LMM. Residuals were checked for normality using Q-Q plots and supported with Shapiro-Wilk test. Homoscedasticity was examined by plotting standardized residuals against fitted values, with residual spread quantified as the ratio of standard deviations between the highest and lowest thirds of fitted values. If significant deviations from normality or homoscedasticity were detected, the data were transformed using either a logarithmic or Yeo-Johnson power transformation prior to refitting the LMM. In cases where the treatment effect was significant, *post-hoc* pairwise comparisons were conducted using the *emmeans* package in R with Tukey’s HSD adjustment to identify differences between treatment groups. All statistical analyses were performed in RStudio (version 2025.05.0), and significance was determined at  $p = 0.05$ .

### 3. Results

#### 3.1. System water parameters

##### 3.1.1. System water quality

LMM analysis showed that no significant differences were found for the concentrations of TAN, NO<sub>2</sub>-N, or NO<sub>3</sub>-N among treatments, but significant differences over sampling week were observed for TAN and NO<sub>3</sub>-N concentrations (Table 1).

The TAN concentrations ranged from 0.63 ± 0.04 mg/L to 0.97 ± 0.02 mg/L among three treatments throughout sampling period (Fig. 2a). By the end of experiment, the TAN concentrations were significantly elevated to 0.93 ± 0.04 mg/L, 0.97 ± 0.02 mg/L, and 0.94 ± 0.11 mg/L for the K<sub>2</sub>CO<sub>3</sub>, NaHCO<sub>3</sub>, and NaOH treatments, respectively (Fig. 2a). The NO<sub>2</sub>-N concentrations varied slightly over sampling period for three treatments, ranging from 0.08 ± 0.02 mg/L to 0.13 ± 0.04 mg/L (Fig. 2b). The NO<sub>3</sub>-N concentrations increased significantly over the sampling period, with increases of 13.7%, 11.3%, and 15.2% from the initial (Week 0) values by the end of the experiment (Week 6) in the K<sub>2</sub>CO<sub>3</sub>, NaHCO<sub>3</sub>, and NaOH treatments, respectively

Table 1

Type III analysis of variance (ANOVA) for the effects of treatment, week and their interaction on measured water parameters.

Parameter	Predictor	F-value (F <sub>df1, df2</sub> )	p-value
TAN	Treatment	F <sub>2,5</sub> = 0.9727	0.43973
	Week	F <sub>6,30</sub> = 17.1360	< 0.001***
	Treatment*Week	F <sub>12,30</sub> = 2.0396	0.05604
NO <sub>2</sub> -N	Treatment	F <sub>2,5</sub> = 0.0819	0.9226
	Week	F <sub>6,30</sub> = 1.7774	0.1377
	Treatment*Week	F <sub>12,30</sub> = 1.6922	0.1189
NO <sub>3</sub> -N	Treatment	F <sub>2,5</sub> = 0.0058	0.9942
	Week	F <sub>6,30</sub> = 10.8807	< 0.001***
	Treatment*Week	F <sub>12,30</sub> = 0.2959	0.9853
Turbidity	Treatment	F <sub>2,5</sub> = 0.9289	0.4539
	Week	F <sub>6,30</sub> = 0.5070	0.7981
	Treatment*Week	F <sub>12,30</sub> = 0.8025	0.6453
pH	Treatment	F <sub>2,5</sub> = 0.3737	0.705885
	Week	F <sub>6,30</sub> = 24.7081	< 0.001***
	Treatment*Week	F <sub>12,30</sub> = 2.8910	< 0.01**
Alkalinity	Treatment	F <sub>2,5</sub> = 0.3472	0.72247
	Week	F <sub>6,30</sub> = 11.0531	< 0.001***
	Treatment*Week	F <sub>12,30</sub> = 1.9943	0.06184
TN	Treatment	F <sub>2,5</sub> = 0.0078	0.9922
	Week	F <sub>6,30</sub> = 13.6587	< 0.001***
	Treatment*Week	F <sub>12,30</sub> = 0.6903	0.7475
TP <sup>a</sup>	Treatment	F <sub>2,5</sub> = 0.0561	0.9460230
	Week	F <sub>6,30</sub> = 5.9699	< 0.001***
	Treatment*Week	F <sub>12,30</sub> = 0.7099	0.7299891
TK <sup>b</sup>	Treatment	F <sub>2,5</sub> = 1354.7263	< 0.001***
	Week	F <sub>6,30</sub> = 18.7009	< 0.001***
	Treatment*Week	F <sub>12,30</sub> = 6.6828	< 0.001***
Ca <sup>a</sup>	Treatment	F <sub>2,5</sub> = 0.5762	0.5954
	Week	F <sub>6,30</sub> = 16.1084	< 0.001***
	Treatment*Week	F <sub>12,30</sub> = 2.5160	0.0200*
Mg <sup>a</sup>	Treatment	F <sub>2,5</sub> = 0.3241	0.73730
	Week	F <sub>6,30</sub> = 20.2060	< 0.001***
	Treatment*Week	F <sub>12,30</sub> = 2.0678	0.05271
S <sup>a</sup>	Treatment	F <sub>2,5</sub> = 0.0485	0.95309
	Week	F <sub>6,30</sub> = 15.7163	< 0.001***
	Treatment*Week	F <sub>12,30</sub> = 2.1279	0.04625*
Na <sup>b</sup>	Treatment	F <sub>2,35</sub> = 2871.4813	< 0.001***
	Week	F <sub>6,35</sub> = 12.5782	< 0.001***
	Treatment*Week	F <sub>12,35</sub> = 1.0082	0.4622
Si <sup>a</sup>	Treatment	F <sub>2,5</sub> = 1.1498	0.3883
	Week	F <sub>6,30</sub> = 41.1246	< 0.001***
	Treatment*Week	F <sub>12,30</sub> = 0.9477	0.5159

Note: ANOVA was conducted using Satterthwaite's method within the linear mixed-effects model framework. Asterisks indicate statistically significant differences: \*P < 0.05, \*\*P < 0.01, \*\*\*P < 0.001. Abbreviations: df1, numerator degrees of freedom; df2, denominator degrees of freedom. <sup>a</sup> Yeo-Johnson transformed data; <sup>b</sup> log-transformed data.

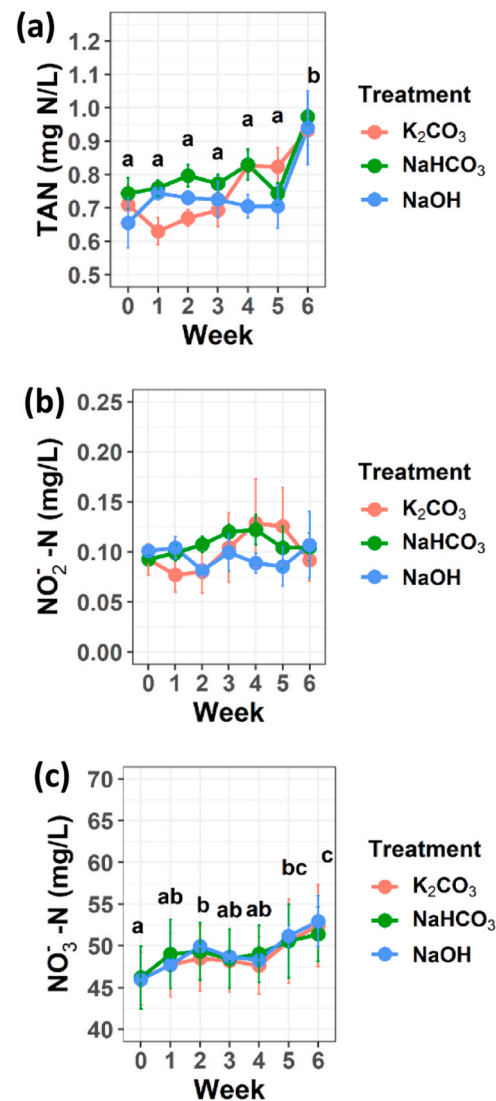


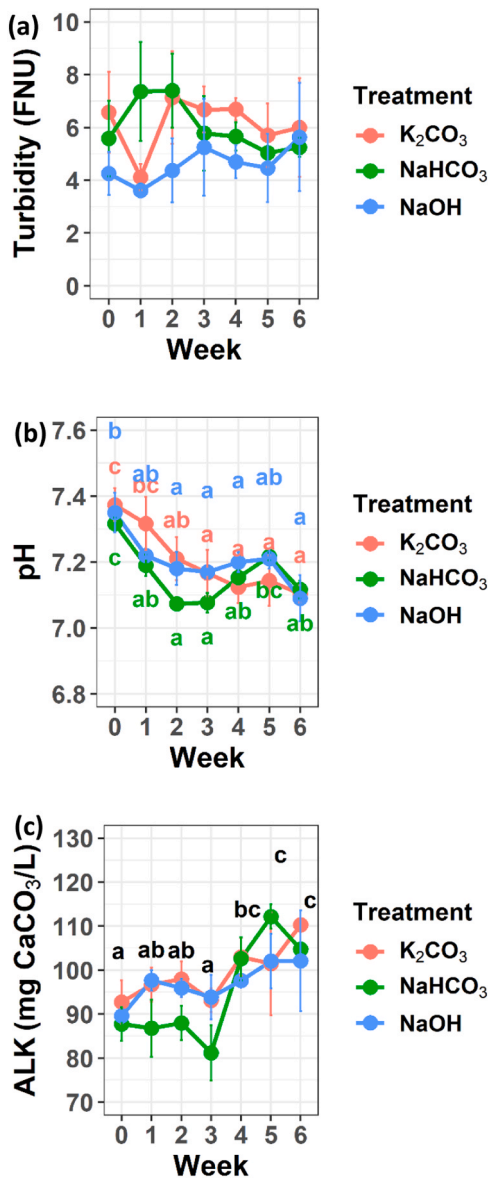
Fig. 2. The concentrations of TAN (a), NO<sub>2</sub>-N (b), and NO<sub>3</sub>-N (c) in water samples collected from three treatment groups throughout sampling period. Data are presented as mean±SE. Different lowercase letters above the data points indicate significant difference among sampling weeks (Tukey's HSD test, p < 0.05). The comparison was performed on the overall model estimates.

(Fig. 2c).

No significant main effects of treatment were found for water turbidity, pH or alkalinity. However, for pH and alkalinity, significant effects of sampling week were observed. Moreover, water pH was also significantly influenced by the interaction between treatment and sampling week (Table 1). The water turbidity level ranged from 3.6 ± 0.3 FNU to 7.4 ± 1.4 FNU among three treatments over sampling period (Fig. 3a). The water pH decreased significantly over the sampling period for each treatment, with a pH value reduction of 0.27, 0.20, and 0.26 from the initial (Week 0) values by the end of the experiment (Week 6) in the K<sub>2</sub>CO<sub>3</sub>, NaHCO<sub>3</sub>, and NaOH treatments, respectively (Fig. 3b). The water alkalinity levels increased significantly over the sampling period, with an alkalinity increase of 17.6 mg CaCO<sub>3</sub>/L, 17.1 mg CaCO<sub>3</sub>/L, and 12.5 mg CaCO<sub>3</sub>/L from the initial values by the end of the experiment in the K<sub>2</sub>CO<sub>3</sub>, NaHCO<sub>3</sub>, and NaOH treatments, respectively (Fig. 3c).

##### 3.1.2. Nutrients in system water

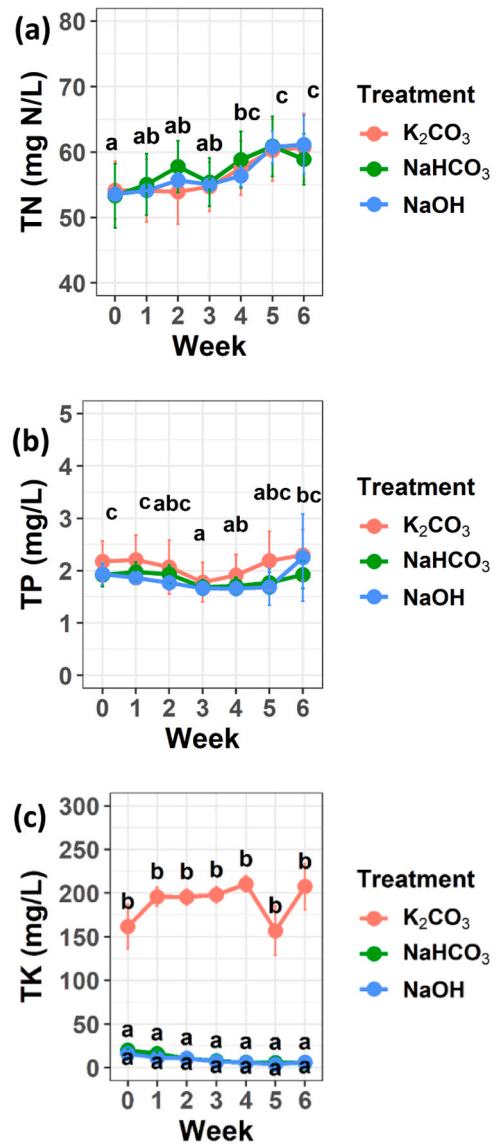
Regarding primary macronutrients, no significant main effects of treatment were found for TN or TP in water samples, but significant



**Fig. 3.** Turbidity (a), pH (b), and alkalinity (c) levels in water samples collected from three treatment groups throughout sampling period. Data are presented as mean±SE. Different lowercase letters in Fig. 3b indicate significant difference over sampling week within each treatment, and different lowercase letters in Fig. 3c indicate significant difference among sampling weeks based on overall model estimates (Tukey's HSD test,  $p < 0.05$ ).

main effects of sampling week were observed for TN and TP. The TK concentration in water samples was significantly influenced by the main effects of treatment, sampling week, and their interaction (Table 1).

TN showed a clear increasing trend over sampling weeks in all treatments, ranging from  $54.2 \pm 4.4$  mg/L to  $60.7 \pm 5.1$  mg/L for the  $K_2CO_3$  treatment, from  $53.3 \pm 4.9$  mg/L to  $58.9 \pm 3.9$  mg/L for the  $NaHCO_3$  treatment, and from  $53.6 \pm 1.1$  mg/L to  $61.2 \pm 4.5$  mg/L for the NaOH treatment (Fig. 4a). TP concentration varied significantly along with sampling week, exhibiting a pattern of an initial decline to the lowest value by Week 3 followed by a subsequent recovery. The TP concentrations ranged from  $1.78 \pm 0.38$  mg/L to  $2.30 \pm 0.48$  mg/L for the  $K_2CO_3$  treatment, from  $1.68 \pm 0.14$  mg/L to  $1.97 \pm 0.19$  mg/L for the  $NaHCO_3$  treatment, and from  $1.66 \pm 0.13$  mg/L to  $2.25 \pm 0.83$  mg/L for the NaOH treatment (Fig. 4b). TK concentration was significantly higher in  $K_2CO_3$  treatment than that in  $NaHCO_3$  and NaOH treatments across all sampling weeks. In contrast, there were no significant



**Fig. 4.** Total N (a), P (b) and K (c) contents in water samples collected from three treatment groups throughout sampling period. Data are presented as mean±SE. Different lowercase letters in Fig. 4a and Fig. 4b indicate significant difference among sampling weeks based on overall model estimates, and different lowercase letters in Fig. 4c indicate significant difference among treatments within each sampling week (Tukey's HSD test,  $p < 0.05$ ).

differences in TK concentration between  $NaHCO_3$  and NaOH treatments at each sampling week. On average, the TK concentration in  $K_2CO_3$  treatment was approximately 17 times higher than that in  $NaHCO_3$  and 20 times higher than that in NaOH treatments across all sampling weeks (Fig. 4c).

As for secondary macronutrients, no significant main effects of treatment were found for Ca, Mg or S in water samples, but significant main effects of sampling week were observed for Ca, Mg and S. In addition, both Ca and S were also significantly influenced by the main effects of interaction between treatment and sampling week (Table 1). The Ca concentrations ranged from  $2.69 \pm 0.19$  mg/L to  $5.62 \pm 2.30$  mg/L for the  $K_2CO_3$  treatment, from  $2.51 \pm 0.05$  mg/L to  $4.77 \pm 0.47$  mg/L for the  $NaHCO_3$  treatment, and from  $2.33 \pm 0.09$  mg/L to  $5.00 \pm 1.12$  mg/L for the NaOH treatment. Specifically, the  $K_2CO_3$  treatment yielded a significantly higher Ca concentration that was 29% higher than NaOH treatment in Week 1 and 110% higher than  $NaHCO_3$  treatment in Week 5 (Fig. 5a). The Mg concentration exhibited a

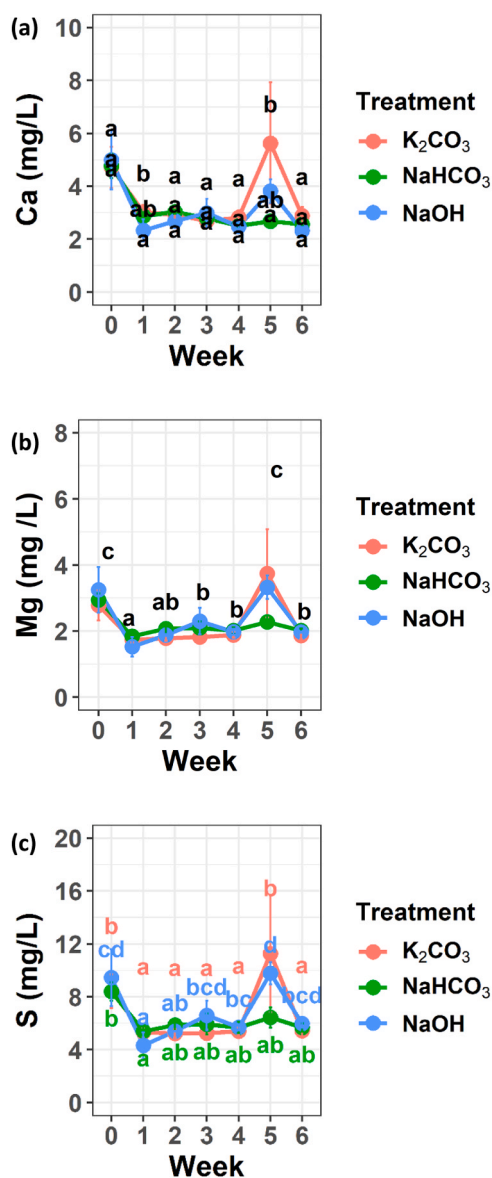


Fig. 5. Concentrations of secondary macronutrients Ca (a), Mg (b), and S (c) in water samples collected from three treatment groups throughout sampling period. Data are presented as mean $\pm$ SE. Different lowercase letters in Fig. 5a indicate significant difference among treatments within each sampling week, different letters in Fig. 5b indicate significant difference among sampling weeks based on overall model estimates, and different letters in Fig. 5c indicate significant difference over sampling week within each treatment (Tukey's HSD test,  $p < 0.05$ ).

significant non-linear trajectory, with an initial decrease to the minimum in Week 1, followed by an increase to a peak in Week 5, and a subsequent decline at the end of experiment. The Mg concentrations ranged from  $1.53 \pm 0.30$  mg/L to  $3.74 \pm 1.33$  mg/L among three treatments across sampling period (Fig. 5b). The S concentrations varied significantly with sampling week for each treatment. Specifically, S concentration in NaHCO<sub>3</sub> treatment showed an initial significant reduction after Week 1, dropping from  $8.40 \pm 0.69$  mg/L to  $5.40 \pm 0.35$  mg/L, followed by a stable phase for the subsequent sampling weeks. The S concentration in K<sub>2</sub>CO<sub>3</sub> and NaOH treatments both displayed a significant non-linear trajectory, with an initial decrease in Week 1, followed by an increase to a peak in Week 5, and a subsequent decline at the end of experiment. The S concentrations ranged from  $5.22 \pm 0.33$  mg/L to  $11.26 \pm 4.42$  mg/L for the K<sub>2</sub>CO<sub>3</sub> treatment and from

$4.61 \pm 0.78$  mg/L to  $9.78 \pm 0.83$  mg/L for the NaOH treatment (Fig. 5c). Overall, the order of secondary macronutrient output in RAS water was  $S > Ca > Mg$ .

As for micronutrients, the concentrations of Fe, Zn, Cu, Mn, B and Ni were  $< 0.11$  mg/L,  $< 0.04$  mg/L,  $< 0.05$  mg/L,  $< 2$   $\mu$ g/L,  $< 0.02$  mg/L, and  $< 2$   $\mu$ g/L in all samples from the three treatments throughout the sampling period, respectively (Table S1).

Regarding non-essential but potentially plant-beneficial elements, the concentrations of Al were  $< 0.02$  mg/L in all samples from the three treatments throughout the sampling period, respectively (Table S1). The Na concentration in water samples was significantly affected by the main effects of treatment and sampling week, and Si concentration was significantly affected by the main effects of sampling week (Table 1). The K<sub>2</sub>CO<sub>3</sub> treatment yielded significantly lower Na concentrations than both NaHCO<sub>3</sub> and NaOH treatments across all sampling weeks (Fig. 6a). The accumulated Na concentrations reach to  $133 \pm 7$  mg/L for NaHCO<sub>3</sub> treatment and  $136 \pm 2$  mg/L for NaOH treatment at the end of experiment. In contrast, Na concentration in NaHCO<sub>3</sub> and NaOH treatments were similar at each sampling week except for Week 5, when NaHCO<sub>3</sub> treatment resulted in Na concentration about 33% higher than that of NaOH treatment. On average, the Na concentrations in the NaHCO<sub>3</sub> and NaOH treatments were higher than in the K<sub>2</sub>CO<sub>3</sub> treatment by factors of approximately 20 and 19, respectively (Fig. 6a). The Si concentration exhibited a decrease pattern over sampling weeks except in Week 5, where a sudden increase was observed (Fig. 6b). The Si concentrations ranged from  $0.68 \pm 0.02$  mg/L to  $2.75 \pm 0.50$  mg/L for the K<sub>2</sub>CO<sub>3</sub> treatment, from  $0.70 \pm 0.06$  mg/L to  $2.46 \pm 0.14$  mg/L for the NaHCO<sub>3</sub> treatment, and from  $0.55 \pm 0.19$  mg/L to  $2.47 \pm 0.22$  mg/L for the NaOH treatment (Fig. 6b).

As for toxic heavy metals, Pb, Cd, and Cr were below the detection limits in all samples from the three treatments throughout the sampling period, with concentrations  $< 5$   $\mu$ g/L for Pb,  $< 0.7$   $\mu$ g/L for Cd, and  $< 1$   $\mu$ g/L for Cr, respectively (Table S1).

### 3.2. Sludge properties

#### 3.2.1. Sludge physicochemical parameters

As for sludge physicochemical parameters of DM, TSS, SVI<sub>30</sub> and sludge volume, no significant main effects of treatment were found for them, but significant main effects of sampling week were observed for DM and TSS. In addition, TSS was also significantly influenced by the main effects of interaction between treatment and sampling week (Table 2).

The DM content exhibited a significant non-linear trajectory, with an initial decrease to the minimum in Week 3, followed by an increase to a peak in Week 4, and followed by a stable phase for the subsequent sampling weeks. The DM content ranged from  $0.09\% \pm 0.003\%$  to  $0.13\% \pm 0.010\%$  among three treatments over sampling weeks (Fig. 7a). The TSS content ranged from  $0.24 \pm 0.05$  g/L to  $0.37 \pm 0.06$  g/L for the K<sub>2</sub>CO<sub>3</sub> treatment, from  $0.29 \pm 0.05$  g/L to  $0.35 \pm 0.04$  g/L for the NaHCO<sub>3</sub> treatment, and from  $0.23 \pm 0.03$  g/L to  $0.60$  g/L for the NaOH treatment. Specifically, the NaOH treatment yielded a significant higher TSS content that was approximately 107% higher than K<sub>2</sub>CO<sub>3</sub> treatment and 82% higher than NaHCO<sub>3</sub> treatment at the end of experiment (Fig. 7b). The SVI<sub>30</sub> ranged from  $61.4 \pm 14.5$  mL/g to  $88.1 \pm 15.7$  mL/g for the K<sub>2</sub>CO<sub>3</sub> treatment, from  $38.7$  mL/g  $\pm 12.2$  to  $97.5 \pm 17.4$  mL/g for the NaHCO<sub>3</sub> treatment, and from  $66.7 \pm 0.4$  mL/g to  $78.4 \pm 8.4$  mL/g for the NaOH treatment (Fig. 7c). The sludge volume collected ranged from  $1.44 \pm 0.30$  L/h to  $1.72 \pm 0.49$  L/h for the K<sub>2</sub>CO<sub>3</sub> treatment, from  $1.27 \pm 0.07$  L/h to  $1.42 \pm 0.16$  L/h for the NaHCO<sub>3</sub> treatment, and from  $0.82 \pm 0.20$  L/h to  $1.56 \pm 0.29$  L/h for the NaOH treatment (Fig. 7d).

#### 3.2.2. Nutrients in sludge

No significant main effects of treatment were found for TN or TP concentrations in sludge samples, but significant main effects of

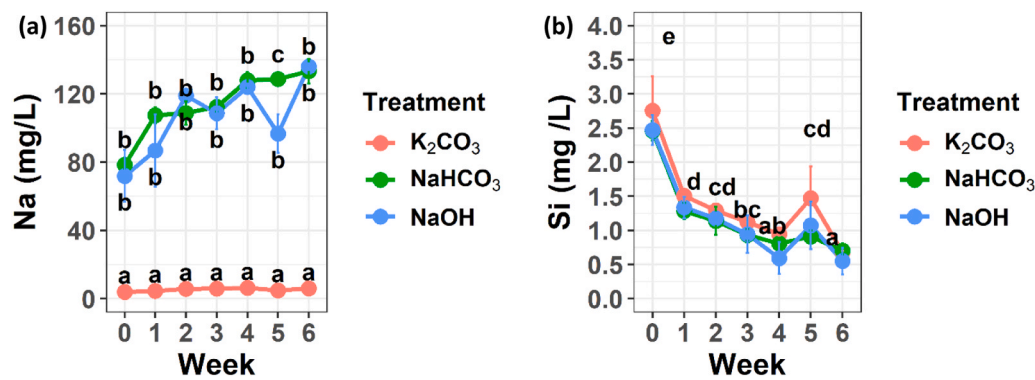


Fig. 6. Concentrations of Na (a) and Si (b) in water samples collected from three treatment groups throughout sampling period. Data are presented as mean $\pm$ SE. Different lowercase letters in Fig. 6a indicate significant difference among treatments within each sampling week, and different letters in Fig. 6b indicate significant difference among sampling weeks based on overall model estimates (Tukey's HSD test,  $p < 0.05$ ).

Table 2

Type III analysis of variance (ANOVA) for the effects of treatment, week and their interaction on measured sludge parameters.

Parameter	Predictor	F-value ( $F_{df1, df2}$ )	p-value
DM	Treatment	$F_{2,5} = 1.8353$	0.2525212
	Week	$F_{6,30} = 6.2816$	< 0.001***
	Treatment*Week	$F_{12,30} = 0.9286$	0.5323175
TSS	Treatment	$F_{2,5} = 2.6815$	0.1616986
	Week	$F_{6,30} = 5.6852$	< 0.001***
	Treatment*Week	$F_{12,30} = 2.4560$	0.0227450*
SVI <sub>30</sub>	Treatment	$F_{2,5} = 0.1314$	0.8798
	Week	$F_{6,30} = 0.9263$	0.4904
	Treatment*Week	$F_{12,30} = 0.4481$	0.9290
Sludge volume	Treatment	$F_{2,5} = 1.0053$	0.4296
	Week	$F_{6,30} = 1.0194$	0.4318
	Treatment*Week	$F_{12,30} = 0.9450$	0.5182
TN	Treatment	$F_{2,5} = 0.6438$	0.56392
	Week	$F_{6,30} = 9.7169$	< 0.001***
	Treatment*Week	$F_{12,30} = 2.6249$	0.01585*
TP	Treatment	$F_{2,5} = 3.3434$	0.119727
	Week	$F_{6,30} = 4.2226$	< 0.01**
	Treatment*Week	$F_{12,30} = 1.3356$	0.250701
TK <sup>a</sup>	Treatment	$F_{2,5} = 561.549$	< 0.001***
	Week	$F_{6,30} = 182.521$	< 0.001***
	Treatment*Week	$F_{12,30} = 55.435$	< 0.001***

Note: ANOVA was conducted using Satterthwaite's method within the linear mixed-effects model framework. Asterisks indicate statistically significant differences: \* $P < 0.05$ , \*\* $P < 0.01$ , \*\*\* $P < 0.001$ . Abbreviations: df1, numerator degrees of freedom; df2, denominator degrees of freedom. <sup>a</sup> log-transformed data.

sampling week were observed for TN and TP. Moreover, TN concentrations were also significantly affected by the main effects of interaction between treatment and sampling week. The TK concentration in sludge samples was significantly influenced by the main effects of treatment, sampling week, and their interaction (Table 2). TN concentrations in both  $K_2CO_3$  and  $NaHCO_3$  treatments varied slightly over sampling period, ranging from  $62.3 \pm 5.2$  mg/L to  $74.4 \pm 8.0$  mg/L for the  $K_2CO_3$  treatment and from  $64.1 \pm 1.0$  mg/L to  $76.0 \pm 5.6$  mg/L for the  $NaHCO_3$  treatment. In contrast, TN concentration varied significantly with sampling week for NaOH treatment with an initial significant increase after Week 2, elevating from  $62.5 \pm 2.6$  mg/L to  $84.1 \pm 4.4$  mg/L, followed by a stable phase for the subsequent sampling weeks ranging from  $76.2 \pm 0.8$  mg/L to  $91.8 \pm 4.0$  mg/L (Fig. 8a). TP concentration varied significantly with sampling week, exhibiting an increasing pattern over sampling weeks, although the pattern was not strictly monotonic. The TP concentration ranged from  $9.8 \pm 0.8$  mg/kg to  $15.3 \pm 3.1$  mg/kg for the  $K_2CO_3$  treatment, from  $10.7 \pm 1.2$  mg/kg to  $16.8 \pm 3.0$  mg/kg for the  $NaHCO_3$  treatment, and from  $14.7 \pm 0.5$  mg/kg to  $28.9 \pm 7.9$  mg/kg for the NaOH treatment (Fig. 8b). TK concentration

was significantly higher in  $K_2CO_3$  treatment than that in  $NaHCO_3$  and NaOH treatments across all sampling weeks. In contrast, there were no significant differences in TK concentration between  $NaHCO_3$  and NaOH treatments at each sampling week, with an exception at the end of experiment, when NaOH treatment resulted in TK concentration being about 43% higher than that in  $NaHCO_3$  treatment. On average, the TK concentration in  $K_2CO_3$  treatment was approximately 14 times higher than that in both  $NaHCO_3$  and NaOH treatments across all sampling weeks (Fig. 8c).

### 3.3. Fish production performance

During the experiment, a total of 5, 1 and 5 mortalities were recorded in  $K_2CO_3$ ,  $NaHCO_3$ , and NaOH treatments, respectively. The fish production performance is summarized in Table 3. Neither the FCR nor the survival rate was significantly affected by the treatments with alkalinity-controlling chemicals.

## 4. Discussion

The use of  $K_2CO_3$ ,  $NaHCO_3$ , and NaOH as alkalinity-controlling chemicals to reach alkalinity levels around 100 mg  $CaCO_3$ /L in this study was found to achieve similarly satisfactory biofilter nitrification performance. This finding is in line with previous studies reporting that the form of alkalinity within the carbonate system, such as  $NaHCO_3$ ,  $CaCO_3$ , calcium hydroxide ( $Ca(OH)_2$ ), sodium carbonate ( $Na_2CO_3$ ), did not affect nitrification performance in biofloc systems (Furtado et al., 2011; Martins et al., 2017). The observed TAN accumulation at the end of sampling period is more likely explained by the increasing TAN excretion associated with fish growth and the resulting gradual rise in FCR. Under fixed feeding and water exchange rate, the amount of TAN excretion increased as the fish grew, while biofilter capacity remained constant. This led to TAN production exceeding the system's nitrification and dilution capacity, resulting in elevated TAN levels. It should be noted that this study adopted long acclimation period to ensure stable nitrification performance in each treatment before comparing the treatment effects. As a result, the potential differences in biofilter startup dynamics between Na- and K-based alkalinity-controlling chemicals were not assessed in this study, meaning that some important aspects of early biofilm development in biofilter may have been overlooked. Future research focusing on biofilter startup dynamics under different alkalinity-control regimes would be valuable.

The study showed increasing alkalinity concurrently with a gradual pH decrease in rearing water over the sampling period. This is primarily explained by the accumulation of  $CO_2$  from fish and microbial respiration, which forms carbonic acid and is the dominant driver of pH reductions in freshwater RAS (Qi et al., 2022; Skov, 2019; Timmons et al., 2018). Additionally, nitrification also generates acidity to reduce pH

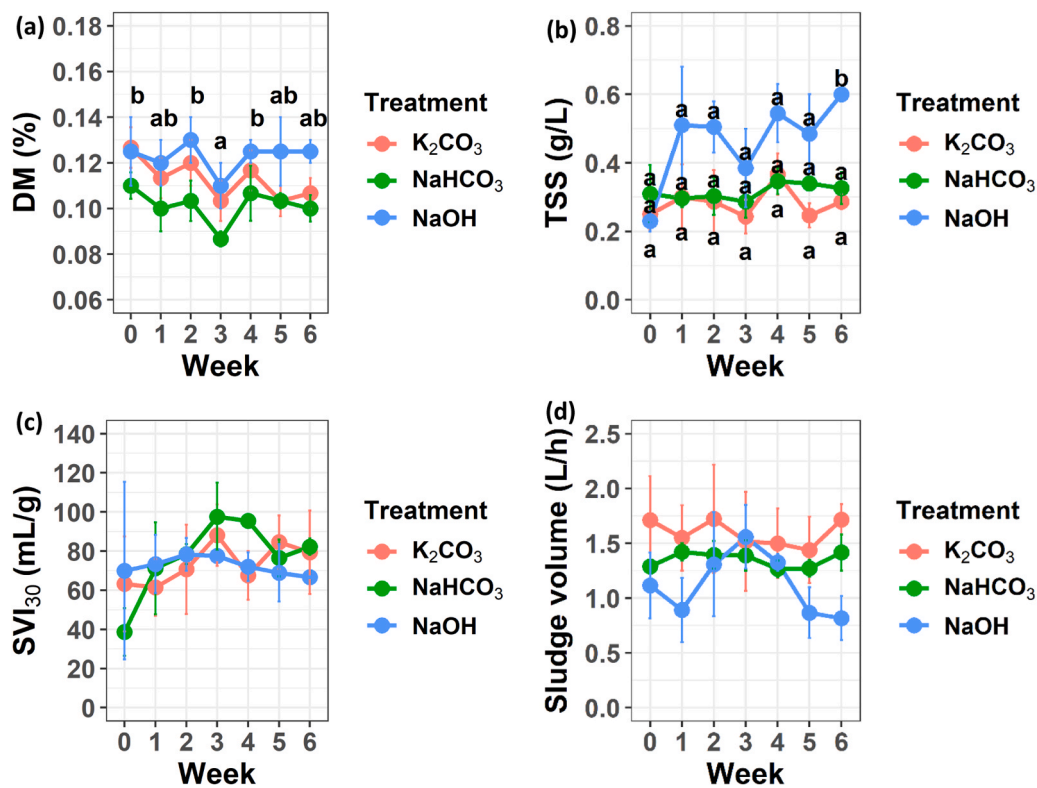


Fig. 7. Dry matter (DM) content (a), total suspended solids content (b),  $SVI_{30}$  value (c), and collected volume (d) in sludge samples collected from three treatment groups throughout sampling period. The sludge samples were collected weekly over a 6-hour period (approximately from 8 AM to 2 PM) from the backwashing of the drum filter. Data are presented as mean  $\pm$  SE. Different lowercase letters in Fig. 7a indicate significant difference among sampling weeks based on overall model estimates, and different letters in Fig. 7d indicate significant difference among treatments within each sampling week (Tukey's HSD test,  $p < 0.05$ ).

(Timmons et al., 2018). The combined acidifying effects of  $CO_2$  and nitrification exceeded the system's buffering capacity, resulting in a net decrease in pH. Nevertheless, both pH (from 7.07 to 7.37) and alkalinity (from 81 to 112 mg  $CaCO_3/L$ ) levels remained within favourable ranges for both rainbow trout growth and nitrifying bacteria activity throughout the experiment (FAO, 2009; Timmons et al., 2018; Woyanovich et al., 2011).

The nutrient inputs into RAS include the intake water, fish feed, make-up water, and water treatment chemicals (e.g., alkalinity-controlling chemicals, and disinfectants). With all operating conditions identical except for the alkalinity-controlling chemicals added, the choice of  $K_2CO_3$ ,  $NaHCO_3$ , and  $NaOH$  as alkalinity-controlling chemicals didn't affect TN, TP, Ca, Mg, S, or Si concentrations in rearing water. As expected, TK concentration in rearing water was significantly higher in  $K_2CO_3$  treatment compared to  $NaHCO_3$  and  $NaOH$  treatments. Previous studies also reported that the use of K-based buffering salts (i.e., KOH) increased K concentrations in RAS water (Lunda et al., 2019; Wenzel et al., 2021).

Similarly, Na concentrations were significantly higher in  $NaHCO_3$  and  $NaOH$  treatments than that of  $K_2CO_3$  treatment. This finding is in line with previous study reporting that common-used buffer agent  $NaHCO_3$  elevated Na concentration in RAS water (Rao, 2020). It should be pointed out that Na concentrations ( $> 130$  mg/L) from  $NaHCO_3$  and  $NaOH$  treatments at the end of experiment exceeded concentrations considered to be phytotoxic (50 mg Na/L) (Lunda et al., 2019; Rakocy, 2012). Elevated Na concentration could disrupt K homeostasis at both cellular and whole-plant levels, thereby impairing the critical physiological processes such as photosynthesis, transpiration, and reactive oxygen species production, and ultimately reducing plant growth and yield (Kronzucker et al., 2013). Yep et al. (2020) reported Na concentration  $> 115$  mg/L in hydroponic solution may decrease yield and potency of drug-type *Cannabis sativa L.* Instead, Na concentration in RAS

water from  $K_2CO_3$  treatment was below 6.3 mg/L throughout the experiment, which was far below the phytotoxic threshold. From this point, RAS water from  $K_2CO_3$  treatment was more suitable for direct fertilizer use.

For sludge properties, the use of  $K_2CO_3$ ,  $NaHCO_3$ , and  $NaOH$  as alkalinity-controlling chemicals did not affect DM, TSS,  $SVI_{30}$ , collected sludge volume, TN, and TP. The DM content of the sludge ( $< 0.13\%$ ) was considerably lower than the 1.97% reported by Netshivhumbe et al. (2024) for the sludge under similar sampling protocol. The discrepancy likely stemmed from differences in backwashing frequency and backwash water between the two studies. In spite of that, the sludge DM content observed was still within the range of solid content in RAS effluents ( $< 2\%$ ) summarized by van Rijn (2013). The TSS content of sludge was also remarkably lower than the 0.96 g/L reported for marine RAS sludge (Letelier-Gordo and Fernandes, 2021) and 8 g/L for freshwater RAS sludge (Madady et al., 2025). This larger difference was likely attributed to very low dry matter content of sludge in this study and the RAS setup varieties (e.g., production scale, species, sludge sampling protocol, etc.) among the studies. The  $SVI_{30}$  was below 100 mL/g, indicating good sludge settling characteristics and aligning with typical sludge volume index values reported for RAS sludge in previous studies (Mirzoyan et al., 2008). The volume of the generated sludge was estimated to be 33 L/d on average, which resulted in a sludge generation rate of 220 L sludge per kg feed in this study. Given the high moisture content ( $> 99\%$ ) of the sludge, the density of sludge can be reasonably assumed to approximate that of water (i.e., 1 g/cm<sup>3</sup>). Under this assumption, 1 kg feed can approximately yield 220 kg raw (wet) sludge (water content of 99.9%), equivalent to 220 g of dry sludge in a freshwater RAS rearing rainbow trout. This value (220 g dry sludge/kg feed) falls within the range reported in previous studies, including 400 g dry sludge/kg feed by Gómez et al. (2019) and 130 g dry sludge/kg feed by Rødvei et al. (2025). As expected, the use of  $K_2CO_3$  significantly

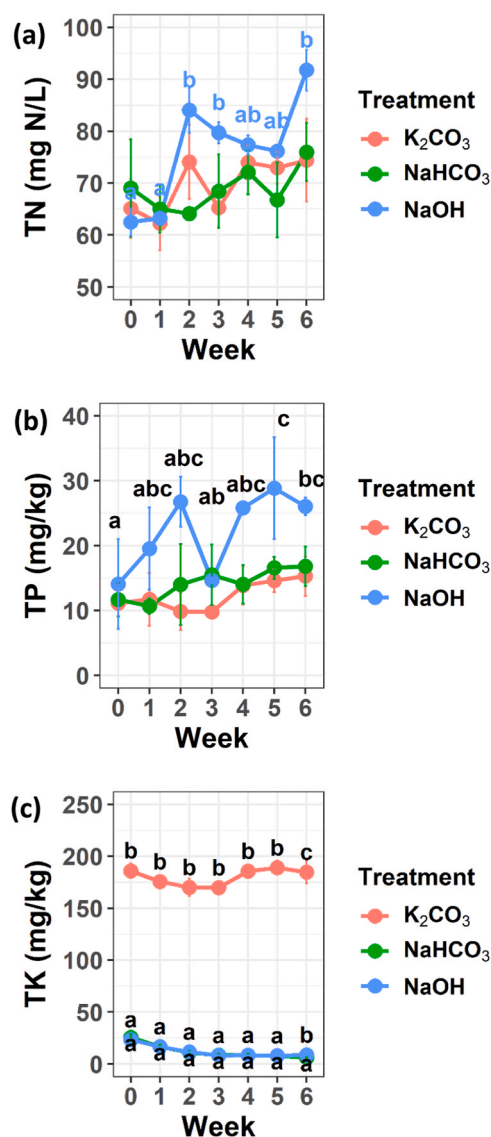


Fig. 8. Total N (a), P (b) and K (c) contents in sludge samples collected from three treatment groups throughout sampling period. Data are presented as mean $\pm$ SE. Different lowercase letters in Fig. 8a indicate significant difference among sampling weeks within NaOH treatment, different letters in Fig. 8b indicate significant difference among sampling weeks based on overall model estimates, and different lowercase letters in Fig. 8c indicate significant difference among treatments within each sampling week (Tukey's HSD test,  $p < 0.05$ ).

Table 3

Fish production performance at different alkalinity-controlling chemical treatments.

Treatment	Feeding rate (g/d)	FCR	Survival (%)
K <sub>2</sub> CO <sub>3</sub>	150	1.12 $\pm$ 0.08 <sup>a</sup>	95 $\pm$ 6.2 <sup>a</sup>
NaHCO <sub>3</sub>	150	0.96 $\pm$ 0.04 <sup>a</sup>	99 $\pm$ 1.7 <sup>a</sup>
NaOH	150	1.17 $\pm$ 0.32 <sup>a</sup>	95 $\pm$ 7.1 <sup>a</sup>

enhanced the K concentrations in sludge. It should be noted that the concentrations of these parameters may be influenced by the backwashing processes of the drum filters. Although each treatment RAS was equipped with identical drum filter, the operational conditions, such as water-level-triggered backwash timing and variation in intake water (i. e., from pump sump) during backwashing, can introduce some observed variabilities in these parameters.

The use of water treatment chemicals in RAS should avoid the risks of causing harm to the fish and the microbes responsible for nitrification process within biofilters (Qi et al., 2025). This study proved that the use of K<sub>2</sub>CO<sub>3</sub> didn't cause harm to nitrification process within biofilters and rainbow trout production performance in RAS. However, excessively high K concentrations can be toxic to fish, disrupting osmoregulatory function, acid-base balance, nerve function, protein solubilization, and muscle-contraction (Rao, 2020; Tkatcheva et al., 2007; Wenzel et al., 2021). For example, Davidson et al. (2011) observed unusual swimming behaviours and deformities in rainbow trout reared in low-exchange RAS, where K accumulated to approximately 110–130 mg/L alongside other factors. Moreover, recent studies found low acute toxicity of K<sub>2</sub>CO<sub>3</sub> to rainbow trout with median lethal concentration (LC50) of 3470 mg/L after 24-hour exposure (Rao, 2020). The corresponding K concentration at this LC50 was far above the levels measured in K<sub>2</sub>CO<sub>3</sub> treatment of this study. Studies on other species, such as African catfish, have shown improved welfare status at 200–400 mg/L K in aquaponic system (Wenzel et al., 2021), which illustrated that potassium tolerance varies across species and production systems. Therefore, the effects of K-based alkalinity controlling chemicals on fish physiology, health and welfare need further investigation before their safe and effective application in RAS.

## 5. Conclusions

The study systematically compared the effects of K<sub>2</sub>CO<sub>3</sub>, NaHCO<sub>3</sub>, and NaOH as alkalinity-controlling chemicals in RAS on sludge nutrient profiles, biofilter performance, and fish production performance. The use of K<sub>2</sub>CO<sub>3</sub> significantly increased K content in sludge to an average value of 180.1 mg/kg while maintaining a low and stable Na concentration ( $\leq 6.3$  mg/L) in the system water. In contrast, both NaHCO<sub>3</sub> and NaOH resulted in a low sludge K content ( $\leq 25.5$  mg/kg) and caused significant accumulations of Na concentrations that exceed phytotoxic levels ( $> 50$  mg/L) in the rearing water. All three chemicals achieved similarly satisfactory biofilter and fish production performance. The study confirms the feasibility of replacing Na-based alkalinity-controlling chemicals with K-based derivatives to enhance RAS sludge nutrient profiles suitable for fertilizer use without compromising system performance.

## CRediT authorship contribution statement

**Jouni Vielma:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Wanhe Qi:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.aquaeng.2026.102726](https://doi.org/10.1016/j.aquaeng.2026.102726).

## Data availability

Data will be made available on request.

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