

DISTILLERY EFFLUENT IRRIGATION, BIOCHAR, AND SOIL NUTRIENT BALANCE

IRRIGATION À BASE D'EFFLUENTS DE DISTILLERIE, BIOCHAR ET ÉQUILIBRE NUTRITIONNEL DU SOL

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ABSTRACT

Climate change has intensified hydrological variability and destabilized water supply and demand, increasing competition for freshwater among agricultural, domestic, and industrial sectors. Consequently, non-traditional water resources have become an important irrigation option. Reclaimed effluent has considerable reuse potential, but its high nutrient and sodium contents may also increase the risk of soil salinization.

This study was conducted in Kinmen County, a region with chronic water scarcity. Distillery effluent was mixed with Houlong Creek water at 0, 20, 40, 60, and 80% proportions to produce five irrigation treatments, each with and without biochar application (0.625 t/ha), resulting in ten sorghum field treatments. Water quality, sorghum uptake, soil properties, and nutrient accumulation were analyzed. A soil nutrient balance equation was established by integrating water quality, water losses, and crop uptake to estimate and validate soil nutrient contents.

Results showed that irrigation water pH, EC, and nutrient contents increased with effluent proportion. Soil pH and EC also increased after irrigation. Compared with non-biochar treatments, biochar further increased soil pH and mitigated EC increase. Nutrient balance analysis indicated that Na accumulated in nearly all treatments, whereas P and K decreased in most treatments. Only some treatments achieved mass balance closure, indicating that the equation still requires refinement. Overall, reclaimed effluent has potential as a non-traditional irrigation water source, but routine monitoring of EC, SAR, ESP, and major crop nutrients, together with leaching and drainage management, remains necessary to enhance irrigation resilience under water-supply uncertainty.

Keywords : Distillery Effluent Irrigation, Biochar, Soil salinization and Nutrient Balance.

RÉSUMÉ

Le changement climatique a accentué la variabilité hydrologique et déstabilisé l'offre et la demande en eau, ce qui a accru la concurrence pour l'eau douce entre les secteurs agricole, domestique et industriel. Par conséquent, les ressources en eau non traditionnelles sont devenues une option d'irrigation importante. Les effluents traités présentent un potentiel de réutilisation considérable, mais leur teneur élevée en nutriments et en sodium peut également accroître le risque de salinisation des sols.

Cette étude a été menée dans le comté de Kinmen, une région souffrant d'une pénurie chronique d'eau. Les effluents de distillerie ont été mélangés à l'eau du ruisseau Houlong dans des proportions de 0, 20, 40, 60 et 80 % afin de créer cinq traitements d'irrigation, chacun avec et sans application de biochar (0,625 t/ha), ce qui a donné lieu à dix traitements sur des champs de sorgho. La qualité de l'eau, l'absorption par le sorgho, les propriétés du sol et l'accumulation de nutriments ont été analysées. Une

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équation de bilan nutritif du sol a été établie en intégrant la qualité de l'eau, les pertes en eau et l'absorption par les cultures afin d'estimer et de valider les teneurs en nutriments du sol.

Les résultats ont montré que le pH, la conductivité électrique (CE) et les teneurs en nutriments de l'eau d'irrigation augmentaient avec la proportion d'effluents. Le pH et la CE du sol ont également augmenté après l'irrigation. Par rapport aux traitements sans biochar, le biochar a encore augmenté le pH du sol et atténué l'augmentation de la CE. L'analyse du bilan nutritif a indiqué que le Na s'est accumulé dans presque tous les traitements, tandis que le P et le K ont diminué dans la plupart d'entre eux. Seuls certains traitements ont permis d'atteindre l'équilibre massique, ce qui indique que l'équation doit encore être affinée. Dans l'ensemble, les effluents réutilisés ont un potentiel comme source d'eau d'irrigation non traditionnelle, mais le suivi régulier de la CE, de la SAR, de l'ESP et des principaux nutriments des cultures, ainsi que la lixiviation et la gestion du drainage, reste nécessaire pour renforcer la résilience à l'irrigation face à l'incertitude de l'approvisionnement en eau.

Mots-clés : Irrigation par effluents de distillerie; Biochar; Salinisation du sol et bilan nutritif.

1. INTRODUCTION

Climate change has intensified drought frequency and hydrological variability, worsening the imbalance between water supply and demand and increasing competition for water among agriculture, domestic use, and industry. Since agriculture accounts for approximately 70–80% of global freshwater withdrawals (Liu et al., 2022), the development of non-traditional water resources has become an important adaptation strategy in water-scarce regions. Reclaimed effluent has gradually been used in agricultural irrigation because of its relatively stable supply, lower cost, and nutrient contents that are directly available to crops and may enhance soil nutrient accumulation (Guo et al., 2023). However, long-term use may also cause soil salinization, heavy metal accumulation, salt buildup, and toxic hazards, thereby limiting its agricultural reuse potential (Mugwanya et al., 2022).

Although various effluent pre-treatment technologies are available, their application in resource-limited regions remains difficult because of technical complexity and high cost (Gallego-Valero et al., 2021). Therefore, combining reclaimed effluent with low-cost soil amendments may provide a practical risk mitigation strategy. Previous studies have shown that biochar can improve soil structure, enhance nutrient retention, and alleviate the stress imposed by effluent irrigation on soil and crops; in some cases, the combined use of effluent irrigation and biochar has also improved crop growth and agricultural productivity (Kaetzel et al., 2020).

However, few field-scale studies have simultaneously evaluated soil property changes and elemental nutrient balances under high-salinity effluent irrigation combined with biochar application. The nutrient budget quantifies nutrient inputs, outputs, accumulation, and depletion, and is therefore useful for evaluating nutrient management efficiency and environmental risk in agricultural systems (Zhang et al., 2020). Therefore, this study focused on soil properties and the nutrient balances of Na, P, and K under high-salinity effluent irrigation, and further examined whether biochar application could mitigate salinization risk and improve nutrient management efficiency in water-scarce regions.

2. MATERIALS AND METHODS

The field experiment was conducted at the Kinmen Agricultural Research Institute in Kinmen County, Fujian Province, during 2024/08/28–2025/02/11. Irrigation water was prepared by mixing Kinmen Kaoliang Liquor (KKL) effluent with Houlong Creek water at five effluent proportions (0, 20, 40, 60, and 80% KKL) and stored in 2-ton field tanks. Each treatment included a control plot and experimental (with biochar) plot, giving 10 plots in total (8 m × 4 m each). Biochar was applied at 0.625 t/ha, and one runoff collector and one infiltration collector were installed in each plot. Sorghum cultivar Taichung No. 5 (*Sorghum bicolor* L. Moench) was used. Heiwangte No. 1 organic compound fertilizer (N–P₂O₅–K₂O–CaO–S–O.M.: 20–5–10–6.5–4.5–3) was applied at 4 kg/plot (1.25 t/ha). The following sections describe sample analyses and nutrient balance calculations.

2.1 Water Sampling and Analysis

Irrigation was conducted three times, on 2024/12/09, 2024/12/24, and 2025/01/15. Irrigation water was prepared by mixing Houlong Creek water with distillery effluent according to the designed proportions. Before irrigation, two 500 mL samples were collected from each treatment, one unacidified and one acidified with nitric acid for elemental analysis. Water pH and EC were measured using a portable meter, and Na, K, and P contents were determined by inductively coupled plasma optical emission spectrometry (ICP-OES).

2.2 Plant, Soil, and Biochar Sampling and Analysis

The experiment was harvested on 2025/02/11. At harvest, three sorghum plants were collected from each of the 10 plots as triplicate samples, yielding 30 plant samples for laboratory analysis. Roots were washed with clean water, and the plants were oven-dried at 65°C for 48 h, then separated into roots, stems, leaves, and panicles, weighed, ground, and sealed for storage; soil samples (0–15 cm) were collected by composite sampling and oven-dried at 30°C for 72 h before analysis. Seven soil sampling events were conducted during the experiment. Soil pH and EC were measured at soil-to-water ratios of 1:1 and 1:5 (w/v), respectively. For Na, K, and P analysis, 0.5 g of each sample was digested with aqua regia by microwave digestion. The digest was diluted to 50 mL, and Na, K, and P concentrations were measured by ICP-OES. Biochar were digested with nitric and hydrofluoric acids, and Na, K, and P were analyzed by ICP-OES.

2.3 Soil Nutrient Balance Calculation and Validation

The soil nutrient balance equation developed in this study is shown in Eqn (1), together with the validation method used to compare estimated and measured soil nutrient concentrations. The equation was calculated in grams. Estimated soil concentrations were derived using a cultivated area of 32 m², a topsoil depth of 15 cm, and a bulk density of 1.44 g/cm³, and were compared with measured concentrations from soil samples collected at harvest. Soil concentration change was calculated using Eqn (2), and soil nutrient concentration at harvest was estimated by Eqn (3). Because field experiments show high spatial variability, uncertainty was addressed following Roy et al. (2003). Reported errors for different components range from 5% to 200%, with most between 10% and 30%. Therefore, an estimated error of ±20% was applied to each nutrient input and output term to account for field variability and validate the nutrient balance results.

$$\text{Soil accumulation potential(g)} = \text{Input } [I_{\text{fert}} + I_{\text{irr}} + I_{\text{rain}} + I_{\text{biochar}}] - \text{Output } [O_{\text{surf+inf}} + O_{\text{plant}}] \quad (\text{Eqn 1})$$

I_{fert} : Fertilizer, 4 kg per plot; I_{irr} : irrigation water, 3000 L/plot; I_{rain} : Rainfall, rainfall was low and no analysis was conducted; I_{biochar} : Biochar, in experiment plots; $O_{\text{surf+inf}}$: Runoff and Infiltration losses; O_{plant} : Crop uptake.

$$\text{Estimated soil concentration change} = \frac{\text{potential soil elemental accumulation}}{\text{cultivated area} \times \text{soil depth} \times \text{bulk density}} \quad (\text{Eqn 2})$$

$$\text{Estimated soil concentration} = \text{initial soil concentration} + \text{estimated soil concentration change} \quad (\text{Eqn 3})$$

3. RESULTS AND DISCUSSION

3.1 Irrigation Water Quality

The irrigation water quality results are presented in Table 1. Irrigation water pH ranged from 6.7 to 8.2, and all values met the regulatory standards. Electrical conductivity ranged from 805 to 3300 $\mu\text{S/cm}$, and all values exceeded the irrigation water quality standard. Elemental analysis further showed that sodium, potassium, and phosphorus concentrations increased with increasing proportions of distillery effluent.

Table 1. Irrigation Water quality analysis

	pH	EC(μ S/cm)	Na (mg/L)	K (mg/L)	P (mg/L)
0% KKL	7.1 $\pm$ 0.4	805.1 $\pm$ 50.6	77 $\pm$ 6.9	32.3 $\pm$ 8.2	2.9 $\pm$ 2.5
20% KKL	7.6 $\pm$ 0	1275.7 $\pm$ 113.2	174.4 $\pm$ 14.9	61.8 $\pm$ 9.3	20 $\pm$ 7.2
40% KKL	7.9 $\pm$ 0.2	1954.7 $\pm$ 93.4	297.1 $\pm$ 22.6	106.4 $\pm$ 8.4	41.9 $\pm$ 9.1
60% KKL	8.1 $\pm$ 0.1	2665.7 $\pm$ 53.2	417.6 $\pm$ 22.8	154.8 $\pm$ 12.5	64.9 $\pm$ 15
80% KKL	8.2 $\pm$ 0.1	2875.3 $\pm$ 403	462.1 $\pm$ 51	175.5 $\pm$ 40.4	75.2 $\pm$ 27.6

3.2.1 Soil Properties Analysis Results

The soil property results are shown in Figure 1. After irrigation, soil pH, EC, and Na all increased, and the magnitude of change generally became greater with increasing effluent proportion, indicating that high-salinity effluent was a major source of salinization risk. Compared with non-biochar treatments, biochar-treated soils showed a greater increase in pH but smaller increases in EC and Na accumulation, suggesting that biochar improved the soil chemical environment and mitigated salt and sodium buildup. This effect is likely related to the strong adsorption capacity of biochar through electrostatic interactions, ion exchange, and binding with surface functional groups (Ahsan et al., 2025).

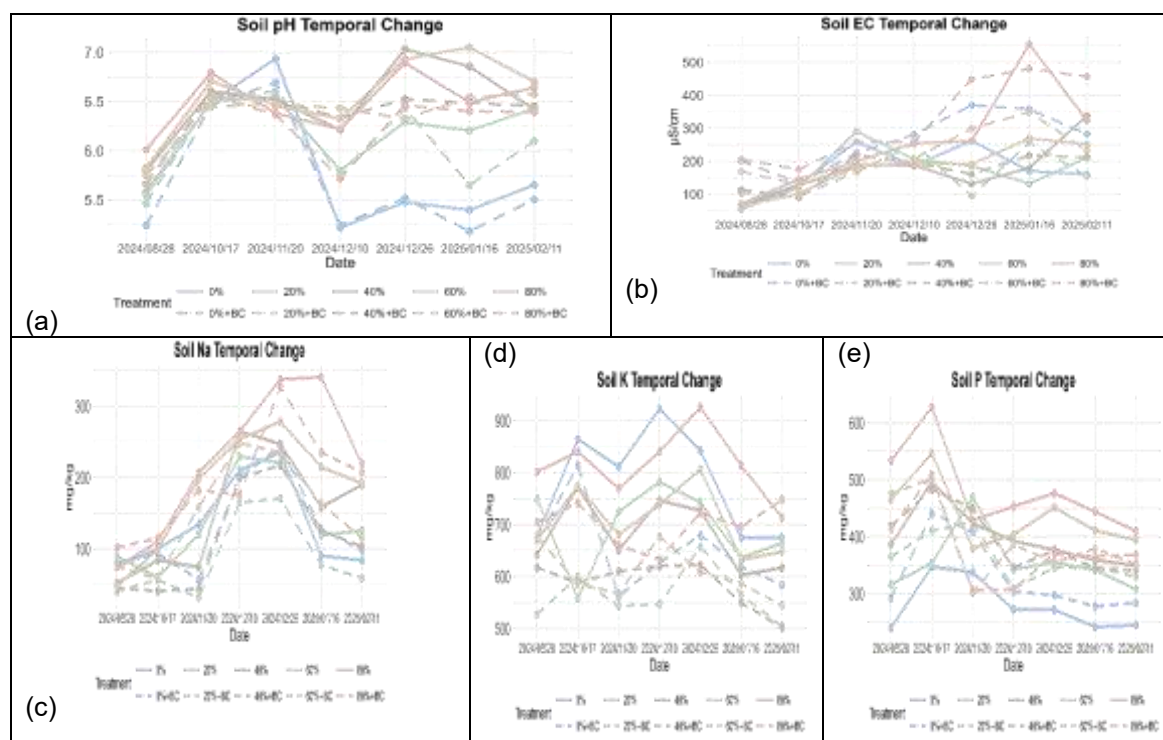


Figure 1. Temporal variations in soil (a) pH, (b) EC, (c) sodium, (d) potassium, and (e) phosphorus. Plots with biochar application are indicated by “+BC”.

In contrast, soil K and P contents decreased after irrigation, indicating that sorghum uptake exceeded nutrient supply and compensation for losses. In addition to crop uptake, biochar may also reduce nutrient accumulation through adsorption of soluble nutrients (Sadowska et al., 2020). Potassium is relatively mobile in soil, and competition between Na and K for exchange sites and root uptake may promote K depletion through displacement, leaching, and crop absorption (Han et al., 2023). The decline in phosphorus was more pronounced under higher effluent proportions and may be related to precipitation under saline conditions, runoff loss of particulate phosphorus, or downward movement below the sampled depth (Mahmoud et al., 2020). In addition, the short-term adsorption effect of biochar may further reduce soil K and P contents. Overall, although effluent irrigation can supply nutrients, high effluent proportions were still associated with salt accumulation and nutrient imbalance; therefore, routine monitoring of soil salinity and major nutrients remains necessary.

3.2.2 Soil Nutrient Balance Results and Validation

Figure 2 shows the validation results of the soil nutrient balance model. Only sodium showed relatively close agreement between measured and estimated values in a few treatments, whereas potassium and phosphorus were generally overestimated, indicating that the equation tended to overestimate soil nutrient retention. Several factors may explain this discrepancy. First, crop uptake showed high individual variability, and only one runoff collector and one infiltration collector were installed in each plot, limiting the ability to capture nutrient losses accurately. Second, the equation did not include several unquantified output terms, such as nutrient uptake by weeds, nutrient consumption by soil biota, and nutrient loss due to wind erosion (Blanco-Canqui et al., 2009). Third, the model did not account for biochar adsorption or nutrient release dynamics, which may have contributed to overestimation of short-term soil nutrient concentrations (Joseph et al., 2021). In addition, the estimation method considered only the upper 15 cm of topsoil and did not account for possible nutrient movement into deeper layers. Overall, the equation can serve as a preliminary tool for estimating nutrient accumulation and depletion trends under effluent irrigation; however, future improvements should incorporate biochar adsorption–release dynamics, deep percolation, and other unquantified loss pathways.

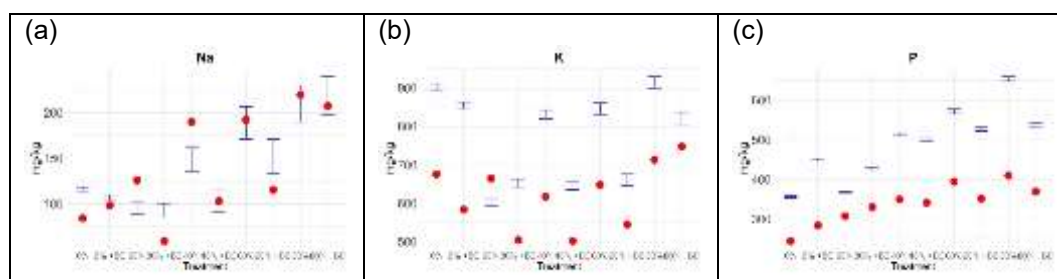


Figure 2. Estimated and validated nutrient balances of (a) sodium, (b) potassium, and (c) phosphorus. Plots with biochar application are indicated by “+BC”.

4. CONCLUSION

The results showed that the irrigation water contained high nutrient levels, with particularly high EC and sodium, indicating its potential as an alternative water source but also its associated salinization risk. After effluent irrigation, soil pH, EC, and Na all increased with irrigation water quality. In contrast, biochar application increased soil pH and reduced salt and Na accumulation, indicating its potential as a buffering amendment under high-salinity irrigation conditions. Soil nutrient balance analysis further showed that Na generally had a positive balance, whereas K and P had negative balances, suggesting that long-term use may lead to nutrient imbalance. The equation also tended to overestimate soil nutrient retention; future improvements should therefore incorporate deep percolation, other unquantified loss pathways, and the adsorption–release dynamics of biochar. Overall, reclaimed effluent has potential as a non-traditional irrigation water source; however, its practical use should be accompanied by routine monitoring of EC, SAR, ESP, and major crop nutrient requirements, together with leaching, drainage, and appropriate fertility management, to enhance irrigation resilience in water-scarce regions.

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