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Agricultural Reuse Suitability of Treated Faecal Sludge Effluent from an Integrated Waste Stabilization Pond and Constructed Wetland System at Busoka Sludge Treatment Plant, Kahama, Tanzania

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ABSTRACT:
Safe reuse of treated faecal sludge effluent is becoming an important option for sustainable sanitation and irrigation in many African towns where fresh water is limited. This study assessed the agricultural reuse suitability of the treated effluent from an integrated waste stabilization pond and constructed wetland system at Busoka Sludge Treatment Plant in Kahama, Tanzania. A quantitative field design was adopted, and composite samples were collected at five sequential treatment stages over four months. Physicochemical, nutrient, microbiological and heavy metal parameters, together with the sodium adsorption ratio, the soluble sodium percentage, the magnesium adsorption ratio and the salinity classification, were determined using various standard methods and were compared with the recommended irrigation guidelines. Electrical conductivity fell from 2482.75 to 249.25 µS/cm, while pH stayed between 7.19 and 7.86. The sodium adsorption ratio declined from 8.16 to 4.55 and the soluble sodium percentage from 52.85 to 47.45 percent, both within the permissible limits, and the salinity class improved from C4-S2 to C1-S1. Total nitrogen, total phosphorus and potassium were reduced by 70.4, 65.1 and 61.1 percent, respectively. *E. coli* and helminth eggs attained logarithmic reductions of 4.71 and 3.95 and satisfied the limits for restricted irrigation. Cadmium at 0.02 mg/L and chromium at 0.21 mg/L in the final effluent, however, remained above the recommended limits of 0.01 and 0.1 mg/L. The treated effluent is therefore suitable for restricted irrigation, but additional polishing is recommended before unrestricted agricultural use.

Keywords: faecal sludge effluent; constructed wetland; agricultural reuse; irrigation suitability; heavy metals

INTRODUCTION

Faecal sludge is the slurry that collects in on-site sanitation facilities such as pit latrines, septic tanks and soak-away pits. Its proper management covers the whole chain of collection, transport, treatment and either safe disposal or recovery of useful products. In most towns of sub-Saharan Africa, the majority of households depend on on-site sanitation, and faecal sludge is generated in amounts that often exceed the capacity of the available emptying and treatment services (Mremi *et al.*, 2025). When this sludge is released without treatment, it pollutes water sources and exposes communities to disease. The composition of faecal sludge varies widely between containments and between seasons, and this makes its treatment and reuse a demanding task (Doglas, Kimwaga and Mayo, 2021).

Waste stabilization ponds and constructed wetlands are the treatment systems most commonly used for faecal sludge in this region. They depend on natural processes driven by sunlight, micro-organisms and wetland plants, and they need little energy and few chemicals, which keeps their construction and running costs low. For this reason, they remain attractive to municipalities that operate under tight budgets (Mwamlima, Njau and Rwiza, 2025). The two systems were first designed for wastewater, but they have been adapted for faecal sludge in tropical settings and are widely held to be suitable under such conditions. When the pond and the wetland are joined in one train, the combination removes pollutants more completely than either unit working on its own.

The effluent that leaves such systems still carries nutrients, salts and other constituents, and this has drawn interest in its possible use for irrigation. Treated effluent can supply nitrogen, phosphorus and potassium to crops and can lower the demand for fresh water in dry areas (Ramakrishna and Patil, 2025). The same effluent, however, may carry a high salt load, an unfavourable sodium balance and traces of heavy metals, and any of these can harm the soil or the crop if the water is applied without care (Meiramkulova *et al.*, 2022). The suitability of an effluent for irrigation is therefore judged not only by its nutrient value but also by indices such as the sodium adsorption ratio, the soluble sodium percentage and the magnesium adsorption ratio, and by its salinity class.

Faecal sludge in Tanzania has been studied mainly in terms of its quantity, its physical and chemical composition and the performance of single treatment units (Ruhinda *et al.*, 2024). Much less attention has been given to the quality of the effluent that leaves an integrated pond and wetland system and to whether that effluent is fit for agricultural reuse. This gap matters, because the integrated systems are now being taken up by several municipalities, yet their effluent is often discharged or applied to land without a proper assessment of the risks involved.

It is from this background that the present study was carried out at Busoka Sludge Treatment Plant in Kahama. The general objective was to assess the agricultural reuse suitability of the treated effluent from the integrated waste stabilization pond and constructed wetland system. The specific objectives were to determine the physicochemical, nutrient, microbiological and heavy metal quality of the effluent along the treatment train, to evaluate the irrigation suitability indices and the salinity class of the final effluent, and to compare the final effluent with the recommended guidelines for agricultural reuse.

MATERIALS AND METHODS

study area: The study was carried out at Busoka Sludge Treatment Plant, which is found in Busoka village, Kahama Municipality, Shinyanga Region, in the north-western part of Tanzania. The plant treats faecal sludge collected from pit latrines and septic tanks within the Municipality. It consists of two anaerobic ponds, two facultative ponds and one horizontal sub-surface flow constructed wetland arranged in series. The site lies at latitude 3°47′40″S and longitude 32°32′54″E, at an elevation of about 1213 m above sea level. Kahama has a tropical climate, with air temperature between 21.34 and 23.71°C, a wet season from

November to May that receives about 417 mm of rainfall per month, and a dry season from June to September that receives about 0.16 mm (TMA, 2023). The location of the study area is shown in Fig. 1.

Fig. 1: location map of the study area

study design: A quantitative field design was used to assess the quality and the agricultural reuse suitability of the treated effluent. The work involved field observation, collection of samples along the treatment train, laboratory determination of selected physicochemical, nutrient, microbiological and heavy metal parameters, and assessment of the irrigation suitability using established indices and the salinity classification.

sampling and field measurements: Samples were collected at five sequential points along the treatment train, namely the influent to the anaerobic pond (S1), the outlet of the anaerobic pond (S2), the outlet of the first facultative pond (S3), the outlet of the second facultative pond (S4) and the final outlet of the constructed wetland (S5). At each point, five grab samples were taken during every weekly visit and were combined into one composite sample for that stage, following the composite sampling procedure of APHA (2023). Sampling ran over a period of four months in order to capture seasonal variation in the performance of the system. The pH and the temperature were measured on site using a portable pH meter fitted with a probe, while electrical conductivity was measured using a conductivity meter. Quality assurance and quality control measures were observed throughout the laboratory work. The treatment train and the sampling points are presented in Fig. 2.

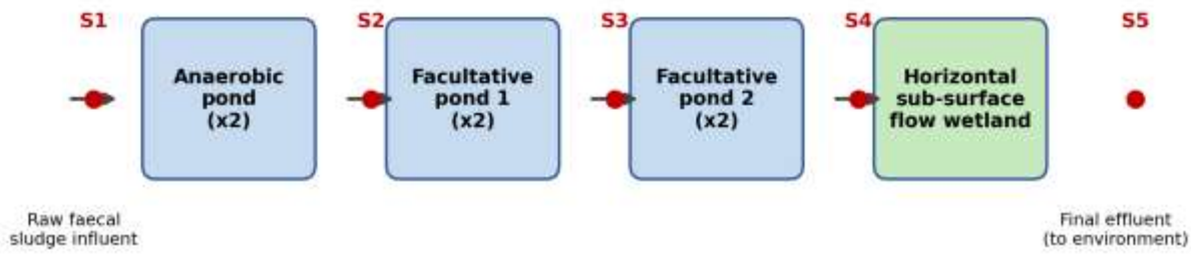

Fig. 2: schematic of the treatment train and the sampling points at Busoka Sludge Treatment Plant

laboratory analysis: The parameters determined in the laboratory included the nutrients (total nitrogen, total phosphorus and potassium), the major cations (sodium, calcium and magnesium), eleven heavy metals (cadmium, lead, chromium, copper, zinc, nickel, mercury, arsenic, cobalt, iron and manganese) and the indicator organisms (faecal coliform, total coliform, *Escherichia coli* and helminth eggs). All determinations followed the standard methods of APHA (2023), except for the helminth eggs, which were determined by the modified Bailenger sedimentation and flotation method of WHO (2006). The methods used for each parameter are summarized in Table 1.

Table 1: standard methods used for the laboratory analysis of the faecal sludge along the treatment stages

Parameter	Unit	Method (standard methods)
Total nitrogen	mg/L	Sodium salicylate method (APHA 4500-N)
Total phosphorus	mg/L	Ascorbic acid method (APHA 4500-P)
Potassium	mg/L	Flame photometric method (APHA 3500-K B)
Sodium	mg/L	Flame atomic absorption spectrometry (APHA 3500-Na)
Calcium	mg/L	Flame atomic absorption spectrometry (APHA 3111 B)
Magnesium	mg/L	Flame atomic absorption spectrometry (APHA 3111 B)
Cadmium	mg/L	Graphite furnace atomic absorption spectrometry
Lead	mg/L	Graphite furnace atomic absorption spectrometry
Chromium	mg/L	Graphite furnace atomic absorption spectrometry
Copper	mg/L	Flame atomic absorption spectrometry
Zinc	mg/L	Flame atomic absorption spectrometry
Nickel	mg/L	Flame atomic absorption spectrometry
Mercury	mg/L	Cold vapour atomic absorption spectrometry
Arsenic	mg/L	Hydride generation atomic absorption spectrometry

Parameter	Unit	Method (standard methods)
Cobalt	mg/L	Flame atomic absorption spectrometry
Iron	mg/L	Flame atomic absorption spectrometry
Manganese	mg/L	Flame atomic absorption spectrometry
Faecal coliform	CFU/100 mL	Membrane filtration, selective medium, 44 to 45 °C (APHA 9215-D)
Total coliform	CFU/100 mL	Membrane filtration, selective medium, 44 to 45 °C (APHA 9215-B)
Escherichia coli	CFU/100 mL	Membrane filtration, selective medium, 44 to 45 °C (APHA 9215-G)
Helminth eggs	eggs/L	Modified Bailenger sedimentation and flotation (WHO, 2006)

Keys: CFU = colony forming units; APHA = American Public Health Association

irrigation suitability indices: The suitability of the treated effluent for irrigation was judged from the sodium adsorption ratio, the soluble sodium percentage and the magnesium adsorption ratio. The sodium adsorption ratio was computed using Equation (1).

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad (1)$$

where: Na^{+}, Ca^{2+} and Mg^{2+} are the sodium, calcium and magnesium concentrations (meq/L)

The soluble sodium percentage was computed using Equation (2).

$$SSP = \frac{Na^{+}}{Na^{+} + K^{+} + Ca^{2+} + Mg^{2+}} \times 100 \quad (2)$$

where: Na^{+}, K^{+}, Ca^{2+} and Mg^{2+} are the sodium, potassium, calcium and magnesium concentrations (meq/L)

The magnesium adsorption ratio was computed using Equation (3); a value above 50 is taken as a risk to the soil.

$$MAR = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} \times 100 \quad (3)$$

where: Ca^{2+} and Mg^{2+} are the calcium and magnesium concentrations (meq/L)

The salinity and the sodium hazard of the effluent were further assessed by plotting the electrical conductivity against the sodium adsorption ratio on the irrigation water classification diagram, which separates water into classes that range from low to very high on each axis (Wilcox, 1955). The classification framework is shown in Fig. 3.

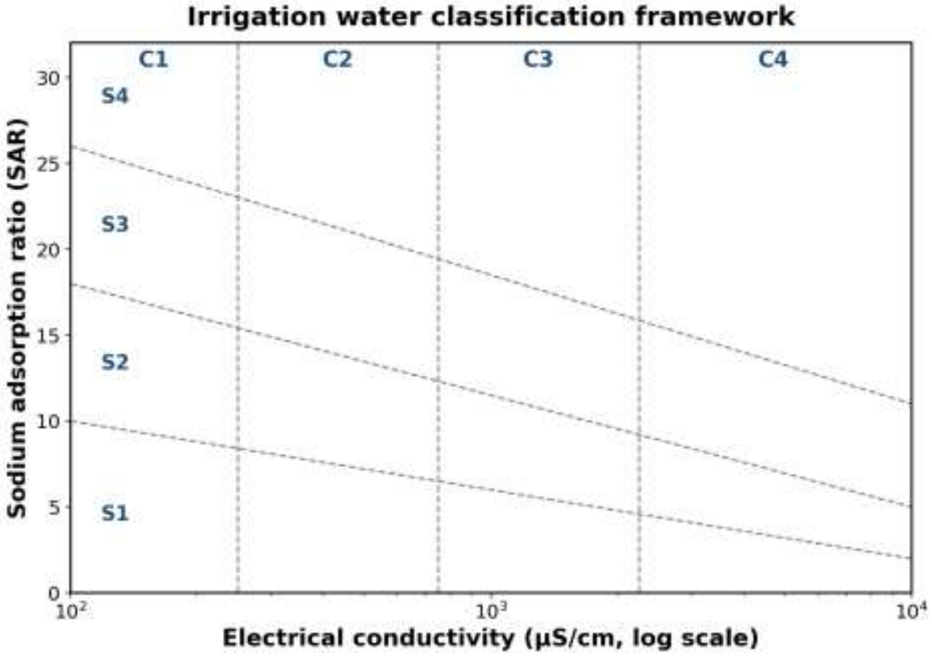

Fig. 3: irrigation water classification framework used to assess the salinity and the sodium hazard (after Wilcox, 1955)

data analysis: The laboratory results were summarized as concentrations at each treatment stage. The removal efficiency and the logarithmic reduction of each parameter were computed from the influent and the final effluent values. The results were then compared with the recommended limits for agricultural reuse given by WHO (2006) and by the Tanzania Bureau of Standards.

RESULTS AND DISCUSSION

physicochemical characteristics of the effluent: The pH of the effluent ranged from 7.19 to 7.86 across the treatment stages and stayed near neutral to slightly alkaline, which is the range that favours the microbial activity responsible for treatment in ponds and wetlands. The temperature was stable, between 27.22 and 27.95°C, and reflects the warm tropical conditions of the area that support biological treatment. Electrical conductivity dropped from 2482.75 µS/cm in the raw influent to 249.25 µS/cm in the final effluent, a reduction of about 90 percent. This large fall shows that the dissolved salt load was greatly reduced as the sludge moved through the train. It may be explained by the settling of particulate salts in the anaerobic pond, the uptake of ions by the biomass in the facultative ponds, and a combination of plant uptake and adsorption on the substrate in the wetland. A similar improvement in the salt content of pond effluent after further natural treatment was reported by Meiramkulova *et al.* (2022) for stabilization pond effluent in Dar es Salaam. The measured values are summarized together with the irrigation indices in Table 3.

cations and irrigation suitability indices: Sodium, calcium and magnesium all decreased between the raw influent and the final effluent. Sodium fell from 625 to 241 mg/L, calcium from 250 to 117 mg/L and magnesium from 118 to 58 mg/L. The sodium adsorption ratio decreased from 8.16 to 4.55 and stayed within the excellent class for irrigation, which is below 10. The soluble sodium percentage decreased from 52.85 to 47.45 percent and remained within the permissible limit of 60 percent, which points to a low to moderate sodium hazard. The magnesium adsorption ratio ranged from 42.41 to 48.07 percent and stayed below the critical value of 50 percent, so the magnesium content is not expected to impair the movement of water through the soil. The excellent sodium adsorption ratio indicates a low sodicity hazard, although the permissible sodium percentage suggests that sodium could build up slowly under continuous irrigation, particularly on fine-textured soils, so the soil should be checked from time to time. These results are presented in Table 3.

Table 3: summary of the physicochemical parameters and the irrigation suitability indices of the effluent

Parameter	Raw influent (S1)	Final effluent (S5)	Permissible limit	Remark
Electrical conductivity (µS/cm)	2482.75	249.25	–	reduced by about 90%
Sodium (mg/L)	625	241	–	reduced
Calcium (mg/L)	250	117	–	reduced
Magnesium (mg/L)	118	58	–	reduced
Sodium adsorption ratio	8.16	4.55	below 10	excellent, within limit
Soluble sodium percentage (%)	52.85	47.45	below 60	permissible
Magnesium adsorption ratio (%)	48.07	42.41	below 50	within limit
Salinity class (Wilcox)	C4-S2	C1-S1	C1 to C2 / S1	suitable for irrigation

pH ranged from 7.19 to 7.86 and temperature from 27.22 to 27.95 °C across all the treatment stages.

nutrient content of the effluent: Total nitrogen, total phosphorus and potassium were reduced as the sludge passed through the system. Total nitrogen fell from 39.35 to 11.67 mg/L, a removal of 70.4 percent; total phosphorus from 23.18 to 8.09 mg/L, a removal of 65.1 percent; and potassium from 94.43 to 36.75 mg/L, a removal of 61.1 percent. The sharpest fall in nitrogen took place between the anaerobic and the facultative ponds, where anaerobic digestion and uptake by micro-organisms are most active, while most of the phosphorus was removed in the wetland through uptake by plants and adsorption on the substrate. The nutrients that remained in the final effluent still hold value for crops, since nitrogen, phosphorus and potassium are the main elements supplied by fertilisers, and their presence can lower the amount of chemical fertiliser a farmer needs to buy. A comparable nutrient value in treated faecal sludge intended for land application was reported by Ramakrishna and Patil (2025). The reduction in nutrients before discharge also lowers the risk of enrichment and oxygen loss in any receiving water body. The nutrient concentrations in the raw influent and the final effluent are shown in Fig. 4.

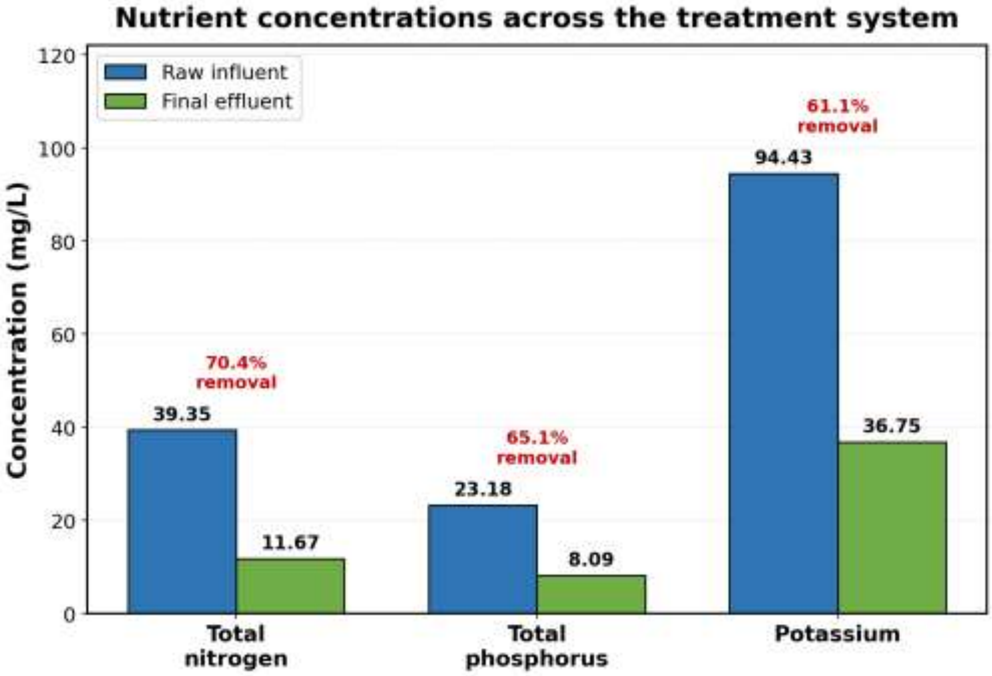

Fig. 4: nutrient concentrations in the raw influent and the final effluent

pathogen reduction: The raw faecal sludge carried very high numbers of indicator organisms. *E. coli* was 8.02×10^6, faecal coliform 1.15×10^6 and total coliform 3.30×10^7 CFU per 100 mL, while helminth eggs were 356 per litre. These numbers fell at every stage, and the final effluent contained 1.55×10^2, 1.77×10^2 and 7.70×10^4 CFU per 100 mL and 0.04 helminth eggs per litre. This gave logarithmic reductions of 4.71 for *E. coli*, 3.81 for faecal coliform, 3.63 for total coliform and 3.95 for helminth eggs. The anaerobic and the facultative ponds gave the largest share of the removal through settling, digestion and exposure to sunlight, while the wetland provided the final polishing. The helminth eggs count of 0.04 per litre in the final effluent met both the restricted limit of one egg per litre and the stricter unrestricted limit of 0.1 egg per litre set by WHO (2006), and the *E. coli* count met the restricted irrigation limit of 10^3 CFU per 100 mL. The residual total coliform shows that some further polishing would be needed before the effluent could be used without restriction. A similar level of helminth and faecal coliform removal in waste stabilization ponds and constructed wetlands has been reported by Mwamlima, Njau and Rwiza (2025) and by Dang and Nguyen (2025). The full set of values is given in Table 2.

Table 2: concentration and removal of the indicator organisms along the treatment stages

Sampling point	*E. coli* (CFU/100 mL)	Faecal coliform (CFU/100 mL)	Total coliform (CFU/100 mL)	Helminth eggs (eggs/L)
Raw influent (S1)	8.02×10^6	1.15×10^6	3.30×10^7	356
Anaerobic pond outlet (S2)	7.28×10^5	7.77×10^5	4.80×10^6	85
Facultative pond 1 outlet (S3)	5.33×10^4	6.10×10^4	2.02×10^6	39

Sampling point	*E. coli* (CFU/100 mL)	Faecal coliform (CFU/100 mL)	Total coliform (CFU/100 mL)	Helminth eggs (eggs/L)
Facultative pond 2 outlet (S4)	3.96×10^3	4.82×10^2	2.20×10^5	0.1
Final effluent (S5)	1.55×10^2	1.77×10^2	7.70×10^3	0.04
Removal efficiency (%)	99.99	99.98	99.77	99.99
Log_{10} reduction	4.71	3.81	3.63	3.95

Keys: CFU = colony forming units; S1 to S5 = sampling points along the treatment train

heavy metals in the effluent: The treatment system lowered the concentration of most heavy metals to within the recommended limits for irrigation water. Iron fell from 8.65 to 0.62 mg/L, zinc from 1.78 to 0.13 mg/L, copper from 0.45 to 0.03 mg/L and mercury from 0.009 to 0.0009 mg/L. The removal was high for copper at 93.3 percent, lead at 93.0 percent, iron at 92.8 percent and zinc at 92.7 percent, and these metals are removed mainly through uptake by the biomass, adsorption, settling and assimilation by the wetland plants. Nickel, cobalt, arsenic and mercury were each removed by more than 80 percent. Cadmium and chromium, however, were removed by only 53.5 and 54.3 percent, and their final concentrations of 0.02 and 0.21 mg/L remained above the recommended limits of 0.01 and 0.1 mg/L. Manganese, at 0.18 mg/L, stayed within the limit of 0.2 mg/L. The poor removal of cadmium and chromium can be linked to the near-neutral pH of the effluent, at which chromium tends to remain as a poorly adsorbed oxide species and at which the uptake of cadmium is hindered by competition from the abundant calcium and magnesium ions (Meiramkulova *et al.*, 2022). The build-up of cadmium is of particular concern, because cadmium that enters the soil through irrigation can accumulate and find its way into crops, as has been shown for soils under long-term wastewater irrigation (Shahid *et al.*, 2023). Heavy metals in faecal sludge applied to land have likewise been flagged as a risk that calls for monitoring (Odirile *et al.*, 2024). A further polishing step, such as chemical precipitation or the use of an adsorption medium, is therefore needed before the effluent is used for unrestricted irrigation. The heavy metal results are summarized in Table 4.

Table 4: concentration, removal and compliance of the heavy metals in the final effluent

Heavy metal	Final effluent (mg/L)	Removal (%)	Limit (mg/L)	Remark
Cadmium (Cd)	0.02	53.5	0.01	exceeds limit
Chromium (Cr)	0.21	54.3	0.1	exceeds limit
Copper (Cu)	0.03	93.3	0.2	within limit
Zinc (Zn)	0.13	92.7	2.0	within limit
Iron (Fe)	0.62	92.8	5.0	within limit
Lead (Pb)	–	93.0	0.1	within limit

Heavy metal	Final effluent (mg/L)	Removal (%)	Limit (mg/L)	Remark
Mercury (Hg)	0.0009	90.0	0.001	within limit
Manganese (Mn)	0.18	–	0.2	within limit

Recommended limits for trace elements in irrigation water (WHO, 2006). Nickel, cobalt and arsenic were each removed by more than 80% and met the recommended limits.

salinity and sodium hazard classification: The position of the effluent on the irrigation water classification diagram improved markedly along the treatment train. The raw influent, with an electrical conductivity of 2482.75 µS/cm and a sodium adsorption ratio of 8.16, fell in class C4-S2, that is very high salinity with a medium sodium hazard, and was unsuitable for irrigation. The conductivity and the sodium adsorption ratio decreased through the anaerobic pond (1539.25 µS/cm and 7.04), the first facultative pond (748 µS/cm and 5.65) and the second facultative pond (453.5 µS/cm and 4.86). The final effluent, with a conductivity of 249.25 µS/cm and a sodium adsorption ratio of 4.55, reached class C1-S1, that is low salinity with a low sodium hazard, which is suitable for irrigation without restriction. The movement from C4-S2 to C1-S1 confirms that the salinity and the sodium hazard were brought under control, with the constructed wetland acting as the main polishing stage. The trend agrees with the report of Meiramkulova *et al.* (2022), in which stabilization pond effluent of a very high hazard class was improved after further natural treatment. Even so, the slow build-up of sodium under continuous irrigation cannot be ruled out, and the soil should be monitored from time to time (Shahid *et al.*, 2023). The classification of the effluent at each stage is shown in Fig. 5.

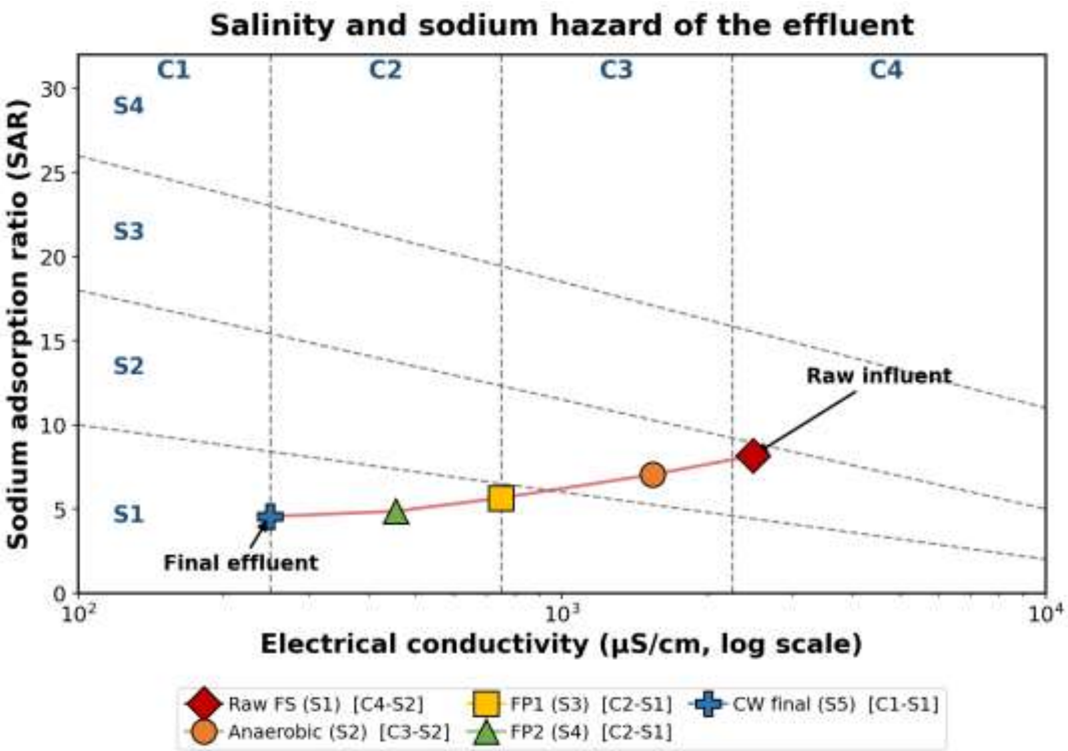

Fig. 5: salinity and sodium hazard classification of the effluent along the treatment stages

Conclusion: The integrated waste stabilization pond and constructed wetland system at Busoka turned raw faecal sludge into an effluent that is largely fit for agricultural reuse. The system lowered the salt load, the sodium hazard and the load of indicator organisms to within the limits set for restricted irrigation, and it improved the salinity class of the water to one suitable for use on the land. The nutrients retained in the effluent add to its value as a source of plant food. The main shortcoming was the incomplete removal of cadmium and chromium, which stayed above the recommended limits. It is recommended that a polishing step be added to bring these two metals down before the effluent is used without restriction, that the receiving soil be monitored for salt and metal build-up, and that the ponds and the wetland be maintained regularly so that the treatment stays efficient.

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