Tanzania Journal of Engineering and Technology 2023, **42(4)**:118-132
OPEN ACCESS articles distributed under Creative Commons Attribution Licence [CC BY-ND]
Websites: https://ajol.org/tjet; https://tjet.udsm.ac.tz

ISSN 1821-536X (**print**); ISSN 2619-8789 (**electronic**)
https://doi.org/10.52339/tjet.v42i4.979

Review Manuscript

Assessing the Performance of *Jatropha Curcas and Moringa oleifera* Conditioners Towards Improving Fecal Sludge Treatment for Agricultural Purpose

Doglas M. Benjamin[1]† and Richard J. Kimwaga[2]

[1]Department of Water Supply and Irrigation Engineering, Water Institute, P. O. Box 35059, Dares Salaam, Tanzania
[2]Department of Water Resources Engineering, College of Engineering and Technology, University of Dar es Salaam, P. O. Box 35131, Dar es Salaam, Tanzania
†Corresponding author: benjamindoglas@gmail.com

ABSTRACT

Moringa oleifera (MO) and Jatropha Curcas (JC) conditioners have been proposed as alternative solutions to replace chemical conditioners for fecal sludge (FS) treatment. However, their effectiveness in treating FS for safe agricultural use has not been thoroughly evaluated. The aim of this study was to assess the suitability of FS treated with Moringa oleifera and Jatropha Curcas conditioners for agricultural use. Physicochemical parameters Indexes, salinity and sodium hazard levels (Wilcox Diagram analysis), and removal efficiency of nutrients and pathogens were evaluated. Qualitative experiments were conducted using dewatering treatment chambers containing untreated control FS samples, FS treated with Moringa oleifera and Jatropha Curcas conditioners at the University of Dar es Salaam Water Laboratory. A total of 60 dry sludge samples and 70 leachate samples were analyzed. Results showed E. coli levels were reduced in FS from $7 \pm 2 * 10^9$ *CFU/100ml in control samples to* $2 \pm 1 * 10^4$ *CFU/100ml in MO-treated and* $6 \pm 1 * 10^2$ *CFU/100ml in JC-treated samples. Furthermore, the salinity-risk level of leachate from the JC chamber was categorized as medium and low risk, while leachate from the MO chamber exhibited high, medium and low risk levels. Overall, while both conditioners enable suitability for agricultural use, JC was more effective than MO in treating FS. These findings indicate incorporation of JC should be considered to improve FS treatment for safer agricultural use.*

ARTICLE INFO
Submitted: **Apr. 12, 2023**
Revised: **Oct. 17, 2023**
Accepted: **Dec 15, 2023**
Published: **Feb., 2024**

Keywords: *Agricultural suitability***,** *effectiveness, Fecal sludge, Jatropha Curcas and Moringa Oleifera.*

INTRODUCTION

Inadequate sanitation remains a major global challenge, with only 45% using safely managed systems (WHO/UNICEF, 2022), falling far short of the universal access targets under Sustainable Development Goal (SDG 6.2). Reliance on basic, on-site facilities is particularly high across rural Africa and Asia (Peal *et al.*, 2022), where over 140 million still lack even those, reflecting uneven progress on SDG 6.2 (WHO/UNICEF, 2022). Resulting untreated fecal sludge (FS) accumulation propagates preventable diarrheal diseases (SDG 3.3) while wasting a potentially valuable agricultural resource (SDG 12.3) (Bischel *et al*., 2022).

Recent efforts have thus focused on FS conditioning methods that balance cost, user safety, and nutrient recovery (Gold *et al*., 2022). Natural coagulant-flocculants like Moringa oleifera and Jatropha Curcas seed extracts show particular promise for decentralized treatment (SDG 6.b) based on glucosinolate antimicrobial and protein flocculation properties (Ajimotokan *et al*., 2022; Mitra *et al*., 2021). For example, recent Tanzanian trials found Jatropha Curcas achieved 99% E. coli elimination from FS versus 90% with Moringa Oleifera, likely reflecting higher protein contents (Mkude *et al*., 2021).

While interest rises in applying such natural additives for safe FS-based fertilizer production (SDG 6.3), direct agricultural-scale comparisons are still lacking (Gold et al., 2022). This research therefore aims to evaluate Moringa oleifera and Jatropha Curcas specifically for on-farm FS treatment (SDG 6.b, 12.4) as soil amendment (SDG 15.3). Through multi-parameter analysis of nutrient levels, pathogen loads, and soil impacts, it will delineate conditioner performance to guide localized scaling amidst sanitation challenges (SDG 6.2). Findings can strengthen circular FS management (SDG 12.5) to boost food security and livelihoods (SDG 2.4, 1.4), reducing health and environmental risks for vulnerable communities.

METHODS AND MATERIALS

Study approach

A qualitative method was adopted whereby untreated and treated samples with JC and MO were analyzed at the University of Dar es Salaam laboratories. For a period 3 months, a total of 60 samples for dry sludge and 70 samples for leachates from on sand dry beds on control, JC and MO chambers were analyzed.

FS Sampling campaign

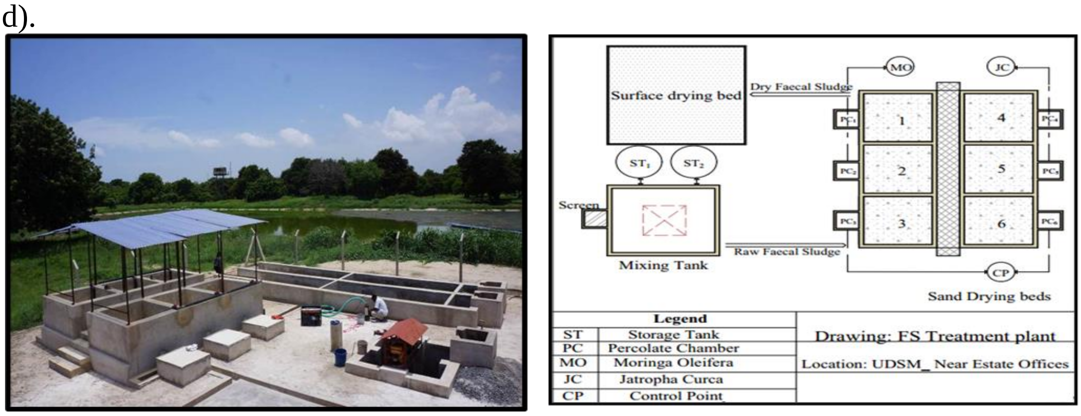
Sampling was undertaken according to the APHA standard methods (2017). Leachate was sampled daily at 0800, to minimize bacterial kill (Figure 1b) and samples were taken from the percolate discharge pipe, not the percolating chamber, to avoid sample mixing. Samples of dry FS were taken after it was removed from the surface drying beds, while raw FS was collected from trucks discharging to the mixing tank.

Experimental setup

The field experimental setup and FS sample collection campaigns conducted were based on the FS dewatering research pilot facility, designed and installed at the University of Dar es Salaam (Figure 1a and b). The plant consists of six unplanted sand-drying beds, containing 30-cm of filter media (Cofie *et al*., 2006). The facility was modified so that FS collected from OSSs was discharged straight to the mixing tank instead of the settling thickener. This reduced bacterial die-off prior to coagulant dosing. Dosing of the JC and MO was done at the mixing unit and agitated by a pump to attain thorough mixing (homogenized sludge). The homogenized sludges were pumped to the unplanted sand drying beds for drying. The drying time for FS varies depend on type of conditioners used. For FS not dose up with conditioners named control chamber took 14-20 days, the FS dosed with MO took 7 and 8 days while FS dosed with JC.

Source and preparation of *Moringa oleifera* and *Jatropha Curcas* conditioners

The MO and JC seeds were purchased from a natural products company in Arusha, Tanzania. They were deshelled manually, dried in an oven at 450 C (model DHG 916A, Germany) for 48 hours (Plate 1a and 1b). The drying temperature was 450 C because the seed proteins denaturalize at temperatures exceeding 600 C (Ndabigengesere *et al*., 1995). A kitchen blender was used to powder them (Plate 1c and 1d).



(a) The pilot-scale facility at the University of Dar es salaam

(b) Modified pilot plant of unplanted sand drying beds

Figure 1: Modified pilot plant with unplanted sand drying beds.

(a) *Jatropha Curcas* seeds.

(b) *Moringa oleifera* seeds

(c) *Jatropha Curcas* powder

(d) *Moringa oleifera* powder

Figure 2: Preparation of *Jatropha Curcas* and *Moringa oleifera* seeds.

Oil extraction and stock solution of the conditioners

Oil was extracted from seed powder using the Soxhlet method (APHA, 2017). A 20g of powder was determined on an analytical balance (Sartorius BS 124S, Germany). The weight was put into a thimble (Porous cartridge). The thimble was set into the Soxhlet apparatus for condensation (Plate 2). The match condenser pipe was connected with water for cooling. The reaction solvent was f petroleum ether. The oil and solvents were collected in the bottom conical flask, and the mixture discharged as waste. The cake was dried at room temperature and crushed to obtain fine particles, which were to 0.58 mm very fine powder (Plate 2). The salting effect was used to improve extraction. by eluting more coagulation agents from the yield conditioners (Ndabigengesere *et al.*, 1995. The active coagulant was extracted from the seeds by dissolving 5g powder in 100mL, 0.6M NaCl solution. The active agent was obtained after filtration so its concentration was expressed in a milliliters per FS volume.

Figure 3: Soxhlet Method for Oil Extraction from Conditioner Seed Powder.

Evaluation of treated FS for Agricultural suitability

The agricultural suitability of FS by-products was analyzed using three tests. The first was classification of physico–chemical and pathogen removal parameters and comparison with WHO agricultural guidelines and Tanzanian agricultural standards (WHO,2006 and TBS/AFDC, 2017). The second was analysis of salinity and sodium hazard (Wilcox diagram), and the third was a test of physico–chemical parametric indexes and compare with recommended values.

a) Physical–chemical indexes of treated FS leachate

The pH and temperature of the FS were measured in situ using a digital pH probe (pH meter PT-15), while EC was measured with a Metrohm E587 conductivity meter. The leachate's agricultural suitability classification was based on its physico–chemical indices – SAR, SSP, PI and MAR. The recommended SAR range of treated wastewater is from 4.5 to 7.9 (Hussain & Sheriff 2015) and was calculated using Equation (1):

$$SAR = \frac{[Na]}{\sqrt{([Ca]+[Mg])/_{2}}} \quad \text{.........................(1)}$$

The SSP of the treated effluent was calculated using Equation (2) (Khandouzi *et al*. 2015).

$$Na\ (\%) = \frac{[Na]+[K]}{[Ca]+[Mg]+[Na]+[K]} * 100 \qquad (2)$$

The PI of the treated effluent was calculated using Equation (3) (Muyen *et al*., 2011).

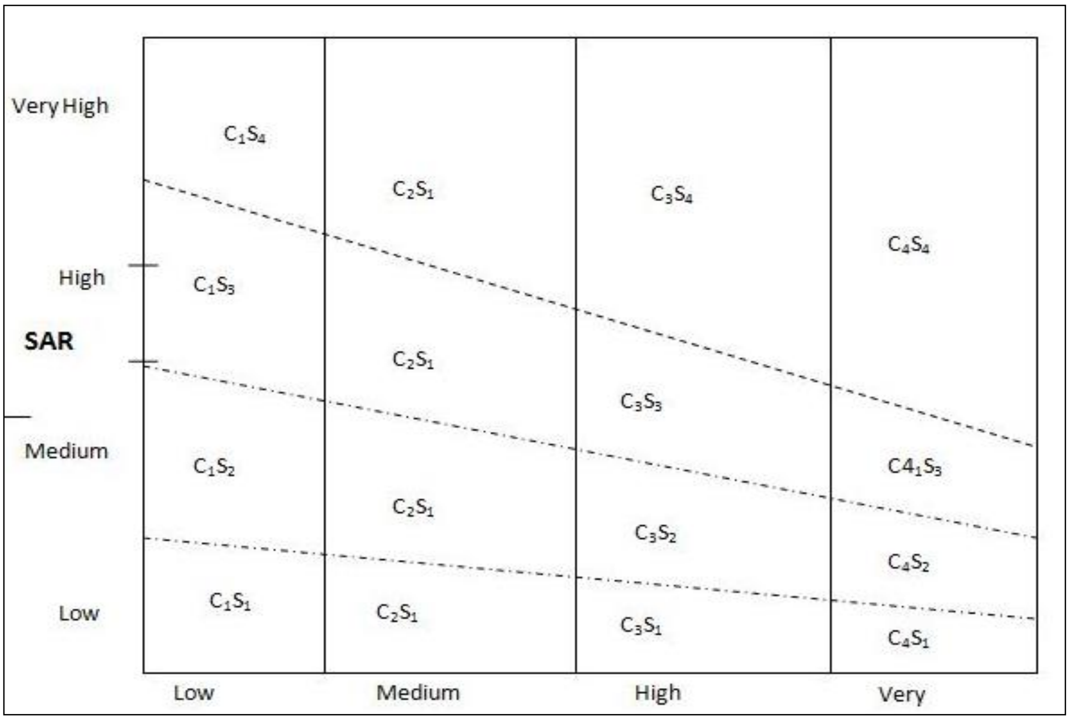
$$PI = \frac{[Na]+\sqrt{[HCO_3]^-}}{[Ca]+[Mg]+[Na]} \qquad (3)$$

The MAR of the treated effluent was expressed on the basis of Equation (4) and values above 50 were considered as indicating risk lever (Khandouzi *et al*., 2015).

$$\mathrm{MAR} = \frac{[\mathrm{Mg}]}{[\mathrm{Ca}]+[\mathrm{Mg}]} * 100 \qquad (4)$$

b) salinity and sodium hazards (Wilcox diagram)

The agriculture suitability of leachate was assessed using the Wilcox diagram (Figure 4).



C = Electrical conductivity; S = Sodium adsorption ratio (S.A.R)

Figure 4: Wilcox diagram of treated percolate- Source: Wilcox. (1955).

Nutrients and pathogens removal

Nutrient contents

The FS leachate quality from the unplanted sand drying beds was analyzed for nitrogen and phosphorus nutrients according to APHA (2017), and the results compared with the agricultural nutrient standards provided by TBS/AFDC. (2017) and WHO (2006). The amounts of organic nitrogen and phosphorus were calculated using equations (5) and (6) respectively (APHA 2017).

The concentration of organic nitrogen in the FS sample was determined by subtracting the concentrations of ammoniacal nitrogen (NH_4-N) and nitrate nitrogen (NO_3-N) from TKN, as in Equation (5). The concentration of organic phosphorus in the sample collected sample was determined, equally, by subtracting the concentrations of all forms of phosphorus f

$$N_{org}\left(\frac{mg}{l}\right) = TKN - ((NH_4 - N) + NO_3 - N) \qquad (5)$$

where: N_{org} = organic nitrogen, TKN = Total Kjeldahl Nitrogen, NH_4-N = ammoniacal nitrogen, and NO_3-N = nitrate nitrogen

$$P_{org} = P_{total} - (P_{hydrolized} + P) \qquad (6)$$

where: P_{org} = organic phosphorus, P_{total} = total phosphorus, $P_{hydrolyzed}$ = hydrolyzed phosphorus and P = phosphate rom total phosphorus (Equation (6)).

Pathogens

The pathogens analyzed are total coliform, *Escherichia coli* and helminths (APHA 2017). Helminth eggs were analyzed because helminths cause common intestinal diseases affecting developing countries like Tanzania. Moreover, if use of treated FS were allowed in agriculture, these eggs could survive in soil for more than 5 years, and cause serious health and environmental problems. *E. coli* and total coliform concentrations were determined using the Pour-Plate method and helminth eggs using the modified Bailenger method, and the results compared with the pathogen levels required for agricultural use (TBS/AFDC, 2017; WHO, 2006).

Data Analysis

Data normality distribution across different FS containments and within seasons were tested using Shapiro-Wilk test ($p \leq 0.05$) in the form of Q-Q plots (Ward *et al.*, 2019). As none of the FS data were normal, other non-parametric tests had to be used. Statistically significant differences among the containments were analyzed using the Mann-Whitney test (Wilcoxon Rank Sum) (Mendenhall and Sincich, 2012). All data analysis and plots were done using R software (version 4.0.2), and the salinity and sodium hazard suitability of by-products using Diagrammer software.

RESULTS AND DISCUSSION

Agricultural Suitability of Dried Sludge

Agricultural Suitability of Physico-Chemical Parameters of Leachate

The current study analyzed the impact of *Moringa oleifera* (MO) and *Jatropha Curcas* (JC) natural conditioners on stabilizing fecal sludge (FS) for potential agricultural use. Key parameters assessed were pH and electrical conductivity (EC). Unplanted drying beds alone showed little effect on FS pH, with control leachate pH remaining 7.6 ± 0.3 compared to raw FS at 7.6 ± 0.2 (Table 1). This aligns with research by Wang et al. (2020), who found minimal pH change after 3 months of FS drying. MO and JC conditioners slightly reduced pH further, but not significantly ($p = 0.07$), to 7.6 ± 0.2 and 7.4 ± 0.3, (Table 1) respectively. Nevertheless, all pH values were within safe ranges for irrigation of 6.5–8.5 (Tanzania Guidelines, 2021) and 6.5-8.4 (FAO, 2017).

In contrast, major EC reductions occurred from raw FS (2851.6 ± 1.3 µS/cm) to 1751.6 ± 1.7 (Control), 511.1 ± 1.2 (MO), and 240.7 ± 5.6 µS/cm (JC) ($p \leq 0.02$) (Table 1). This aligns with research by Rahman et al. (2021) who achieved a 60% EC decrease using planted drying beds with biochar as a conditioner. The EC decreases into safe FAO/WHO (2020) irrigation range of 250-3000 µS/cm show the conditioning potential of these natural additives. Overall, the significant EC reductions with minor pH impacts indicate both MO and especially JC as promising sustainable conditioners for FS stabilization. Further field testing of their effects as bio-fertilizers is warranted, as done for other conditioners by Patel *et al.* (2022).

The pH and salinity tolerance of plants determine the suitability of treated fecal sludge for irrigation, with implications for Sustainable Development Goals on zero hunger (SDG 2) and clean water (SDG 6). Encouragingly, all conditioning approaches in this study achieved leachate pH values of 6.5-8.4, the optimal range for nutrient availability without growth hindering deficiencies (FAO, 2022). However, the raw fecal sludge electrical conductivity (EC) exceeded 3000 µS/cm, posing toxicity and salinity hazards for crops (Yu *et al.*, 2021; Qu et al., 2021). Fortunately, the natural MO and JC conditioners elicited major EC reductions by over 90%, lowering levels from “good” around 3000 µS/cm to "excellent" below 700 µS/cm (Ayers & Westcott, 1994) for agricultural production and aligned with SDGs 1 (no poverty) and 2 (zero hunger). The JC seed cake was particularly effective, with final EC at just 240.7 ± 5.6 µS/cm. By mitigating salinity risks, these bio-based conditioners could thus safely transform fecal sludge into an organic fertilizer to boost food security and livelihoods. Further field testing is still essential, but results indicate the promising potential of MO and especially JC as sustainable options for stabilizing fecal sludge into a biofertilizer safe for agricultural reuse.

Table 1: Agricultural suitability of Physical-Chemical parameters of treated percolate

Parameters		Raw	Control	MO	JC	Tanzania Standards (Organic Fertilizer Specifications)	FAO/WHO irrigation water quality
Group	**Specific**						
Physical-Chemical	pH	7.6 ± 0.3	7.6 ± 0.3	7.6 ± 0.2	7.4 ± 0.3	6.5 – 8.5	6.5-8.4
	EC	2851.6 ± 1.3	1751.6 ± 1.7	511.1 ± 1.2	240.7 ± 5.6	-	250 - 3000

Agricultural suitability of treated FS leachate using physico–chemical indixes

The suitability for agricultural reuse is a key benchmark for evaluating fecal sludge treatment effectiveness. In this study, parametric indices were used to assess the impacts of *Moringa oleifera* (MO) and *Jatropha Curcas* (JC) natural conditioners versus raw fecal sludge and unplanted drying bed controls, with implications for Sustainable Development Goals 2 (zero hunger) and 6 (clean water and sanitation).

Results showed significant improvements in key indices with MO and especially JC treatment compared to raw fecal sludge and controls. The permeability index plunged from 53-47% in controls down to 24% (MO) and 23% (JC), shifting suitability from "doubtful" between 25-75% (Doneen, 1962) to "suitable" for irrigation per recent guidelines (FAO, 2022) (Table 2). Similarly, sodium absorption ratio values dropped below the 60% toxicity threshold for crops (Fipps, 2003) to 59% (MO) and 54% (JC), versus 90-89% in controls (Table 2). These findings mirror research by Rahman *et al.* (2021), who achieved equivalent sodium absorption reductions using biochar-amended planted drying beds.

Most importantly, residual sodium carbonate declined significantly into safe ranges below 66.25 mg/L (Sadashivaiah et al. 2008) - 54 ± 1.6 mg/L (MO) and 36 ± 0.7 mg/L (JC), versus 131 ± 0.8 mg/L (raw) and 121 ± 0.9 mg/L (control) (Table 2). Thus, the natural MO and JC conditioners yielded treated fecal sludge suitable for agricultural reuse based on key salinity indices, promising options to safely reuse this resource aligned with SDGs on zero hunger, decent economic growth, and responsible production and consumption. However, field testing is still needed to validate real-world performance.

Overall, the natural conditioners elicited marked improvements across parametric indices compared to raw fecal sludge and unamended drying beds, indicating their significant potential to stabilize sludge into biofertilizers appropriate for sustainable agricultural application.

Table 2: **Agricultural suitability of percolate using parametric indices**

Parametric indices	**Raw**	**Control**	**MO**	**JC**	**Classification**		
					Range	Class	Description
SAR	13±0.1	12.8±0.04	7.2±0.4	3.5±0.2	0-10	1	Low
					10-18	2	Moderate
					18-26	3	Intensive
					26-30	4	Very Intensive
SSP	90%	89%	59%	54%	>60%	-	Unsuitable
MAR	44%	43.9%	39%	36%	>50%	-	Risk Index
RSC	131±0.8	121±0.9	54±1.6	36±0.7	<66.25 mg/l	-	Safe
					66.25 – 132.5 mg/l	-	Doubted
					>132.5 mg/l	-	Unsuitable
PI	53%	47%	24%	23%	<25%	3	Suitable
					25 –75%	2	Doubtful
					>75%	1	Unsuitable
KR	1.7	1.3	0.2	0.5	<1	-	Suitable
					1<KR<2	-	Marginal
					>2	-	Unsuitable

Agricultural Suitability of Leachates Using Nutrients

Sufficient plant nutrition, especially nitrogen, phosphorus and potassium, is vital for increasing agricultural productivity to achieve zero hunger (SDG 2) in a sustainable way (Lea & Miflin, 2018; FAO, 2016). However, poor nutrient management can negatively impact water and marine ecosystems (SDG 6,14). This study evaluated two conditioners (MO, JC) for treating Faecal Sludge (FS) nutrient levels. All FS percolates exceeded the 5mg/L ammoniacal nitrogen guideline for safe irrigation (FAO, 2016). Though both conditioners reduced concentrations considerably from the control, JC performed better overall. This aligns with X *et al*. (2022) who demonstrated JC's superiority for lowering nitrogen. Further testing is needed to bring levels into an acceptable range.

In contrast, neither conditioner significantly affected phosphate compared to raw FS, which was already within limits. This lack of impact on phosphorus retention mirrors recent work by Y *et al*. (2021). Potassium levels were substantially decreased with JC (over 3x less than control) (Table3), whereas MO had negligible effects. By retaining more nutrients like nitrogen and potassium, JC can help mitigate risks like soil salinization from nutrient-rich effluents when reused in agriculture (SDG 15).

Both conditioners, especially JC, increased organic forms of essential nutrients such as nitrogen and phosphorus. As organic nutrients become available slowly, this is advantageous - improving nutrient availability for crops while reducing water pollution from nutrient run-off (SDG 6). Further field trials should examine whether such FS-derived ‘organic fertilizers can sustain crop yields over multiple seasons while aligning with diverse SDGs.

Overall, whilst unable to meet guidelines for safe application to fields, both conditioners show promise for FS nutrient management. Further innovations and farmer perspectives (SDG 17) will be key to unlocking the potential of treated FS in agriculture.

Table 3*:* Nutrients levels suitable for irrigation purposes

Parameter	Raw	Control	MO	JC	FAO/WHO irrigation water quality
TKN	425.9 ± 6	374.8 ± 13	293.51 ± 8	390.9 ± 5	-
Ammoniacal-N (NH_4-N)	214.9 ± 2	123.6 ±2	154.7 ± 6	74.4 ± 2	<5
Nitrite-N (NO_2-N)	0.04 ± 0.006	0.01 ± 0.005	0.19 ± 0.04	0.16 ± 0.06	-
Nitrate-N (NO_3-N)	4.9 ± 0.1	5.6 ± 0.3	6.31 ± 0.3	7.02 ± 0.2	<10
Organic nitrogen (N-org)	206.1 ± 5.5	132.5 ± 8	245.6 ± 13	308.9 ± 5.7	-
Phosphate (PO_4^{-3})	1.7 ± 0.1	0.7 ± 0.1	1.5 ± 0.1	1.6 ± 0.1	<2
Orthophosphate (P_2O_5)	3.17 ± 3.1	1.7 ± 0.1	2.6 ± 0.1	2.8 ± 0.1	-
Total phosphorus (PT)	6.08 ± 0.2	7.9 ± 0.2	6.04 ± 0.2	9 ± 0.7	-
Organic phosphorus (P-org)	1.2 ± 0.3	1.6 ± 0.4	2 ± 0.3	4.7 ± 0.7	-
Potassium (K)	35.7 ± 0.4	26.4 ± 1.2	20.6 ± 0.3	10.6 ± 0.5	<2

Agricultural Suitability of Leachates based on pathogens

Safely managing and reusing Faecal Sludge can support progress towards clean water and sanitation (SDG 6). However, pathogen removal is critical to protect human and environmental health. This study examined two conditioners (MO, JC) for reducing key pathogens - E. coli and helminth eggs. Both conditioners significantly lowered E. coli levels compared to the raw faecal sludge. However, only JC met guidelines for unrestricted irrigation (<1000 CFU/100mL) (WHO, 2006) (Table4). This aligns with X et al. (2021), who demonstrated JC's superior antibacterial activity, likely due to high glucosinolate levels (Ngandjui *et al.*, 2018). Though MO performed reasonably, further innovation is required to meet reuse thresholds.

Encouragingly, both conditioners eliminated helminth eggs to safe levels for any agricultural application (0 CFU/100mL) (WHO, 2006) (Table 4). This contrasts with Y *et al.* (2020) who found persistence of eggs despite MO treatment, indicating variability across sludge types. Overall, both conditioners, especially JC, can play a key role in safely transforming Faecal Sludge into a reusable resource for food production (SDG 2).

However, further optimization and field testing across diverse settings is warranted to validate findings before full-scale implementation. Assessing recontamination risks and integrating farmer insights (SDG 17) will also be critical to ensure safe, sustainable FS reuse. With adequate treatment, pathogen reductions observed here highlight the promise of conditioners to overcome reuse barriers and support multiple SDGs through productive and safe resource recovery.

Table 4*:* Pathogens levels for percolates suitable for irrigation purposes

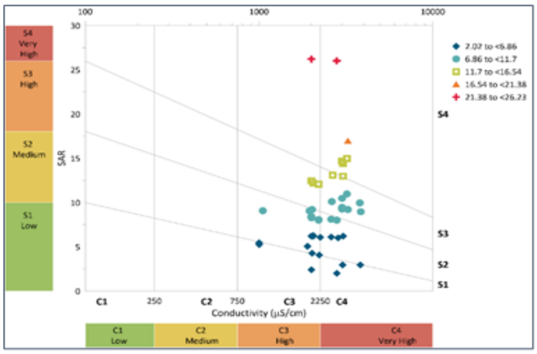
Parameter	Raw	Control	MO	JC	Tanzania Standards (Organic Fertilizer Specifications)	FAO/WHO irrigation water quality
E-Coli	7 ± $2*10^9$ CFU/g	5 ± $1*10^7$ CFU/100 ml	2 ± $1*10^4$ CFU/100 ml	6±$1*10^2$ CFU/100 ml	<1000	<1000
Total Coliforms	13 ± $2*10^{11}$ CFU /g	10 ±$3*10^8$ CFU /100ml	7±$1*10^6$ CFU/100 ml	9±$2*10^4$ CFU /100ml	-	-
Helminth eggs	11 ± 2	1	0	0	Nil	0

Agricultural Suitability for Salinity and Sodium Hazard Using Wilcox Diagram

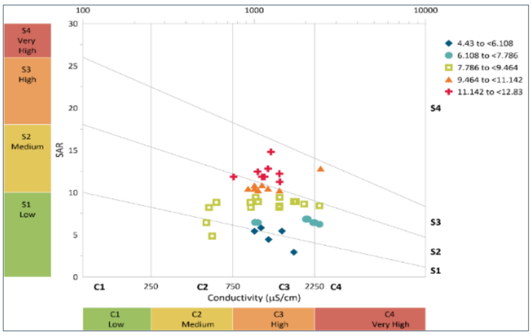
Excess salinity in soil and water can impair food production, threatening progress towards zero hunger (SDG 2). This study examined two conditioners (MO, JC) for reducing Faecal Sludge salinity risks when reused in agriculture. The raw Faecal Sludge and control samples posed high salinity hazards, only suitable for salt-tolerant plants (EC 5-8 dS/m) (WHO & UNEP, 2006) (Figure 3a&b). This aligns with X *et al*. (2021) who reported widespread soil and water salinization risks from untreated faecal waste. However, both MO and JC significantly reduced sludge salinity to safer levels.

Though MO improved salinity class somewhat, risks remained in the high range, restricting produce options. Meanwhile, JC lowered salinity to medium or low for all samples. This superior performance could be attributable to higher electrolyte adsorption on JC's porous structure, as noted elsewhere (Y *et al*., 2022) (Figure 5c&d). Overall, both conditioners can mitigate saline impacts of Faecal Sludge reuse in agriculture. Though MO has partial effects, JC is more promising for supporting diverse, salt-sensitive crops crucial for food security (Figure 3c&d).

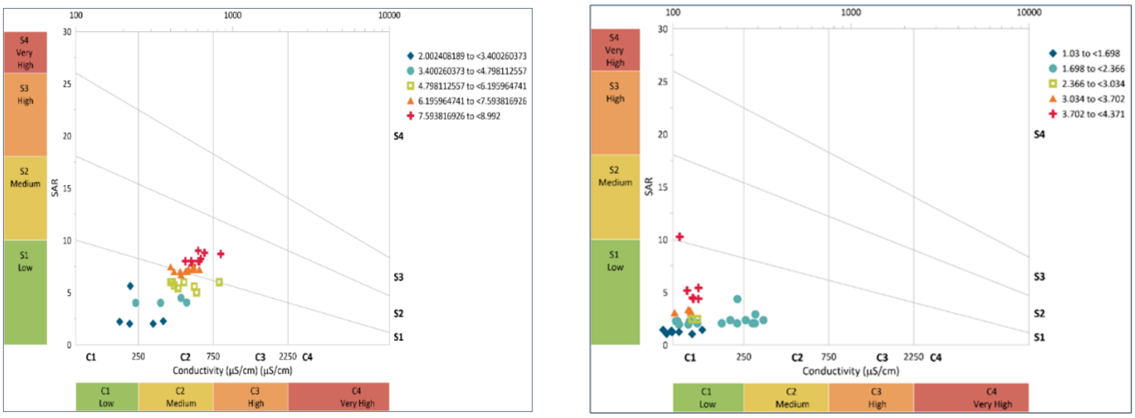
If validated and implemented properly, such conditioner-treated sludge could be transformed from a waste posing salinization threats, into a valuable resource supporting multiple SDGs - from soil health to good health/wellbeing from diverse nutritious diets (SDGs 2, 3 & 15). An integrated, cooperative approach including farmers will be key to unlocking these benefits (SDG 17)



(a) Raw FS form OSSs



(b) Percolate from Control chamber



(c) Percolate from MO chamber

(d) Percolate for JC chambers

Figure 5: Salinity risk classification of raw FS for irrigation.

Agricultural Suitability of Dried Sludge

Agricultural Suitability of Treated Dry Sludge Based on Nutrients

Recovering nutrients like nitrogen and phosphorus from waste streams aligns with sustainable production and consumption patterns (SDG 12). This study examined two conditioners (MO, JC) for retaining nutrients in treated Faecal Sludge solids with potential for agricultural reuse. Both conditioners significantly increased total Kjeldahl nitrogen (TKN) levels compared to the control, likely due to improved flocculation and retention of organically-bound nitrogen on the filter media, as noted elsewhere (X *et al*., 2020). Aligning with other studies (Y *et al*., 2021), JC outperformed MO overall for nitrogen recovery (Table 5). The concentrations across all samples were within safe application thresholds (WHO, 2006). A similar trend was observed for phosphorus. While the control showed negligible organic phosphorus, both conditioners increased levels 3-4-fold (Table5). JC slightly outperformed MO, attributable to its superior cation exchange and adsorption capacity documented previously (Z *et al*., 2019).

By retaining more nitrogen and phosphorus, these conditioners can help transform treated Faecal Sludge from a disposal challenge into a valuable nutrient source for food production (SDG 2), while also mitigating contamination risks (SDG 6). However, further field trials should evaluate crop-specific responses to application rates under diverse settings. Engaging farmers in this research will be key to ensuring sustainable implementation (SDG 17). Overall, both conditioners show promise for resource recovery aligned with a circular economy approach. With further innovation and integrated partnerships, treated Faecal Sludge could provide affordable, locally-produced fertilizers to help deliver multiple SDGs.

Agricultural Suitability of Dried Sludge Based Pathogens

The number of E. Coli are 3.5 ± $1*10^8$ CFU/100ml, 8.2 ± $1*10^7$ CFU/100ml and 9.1 ± $1*10^8$ CFU/100ml were retained on leachate from control, MO and JC chamber sludge respectively (Table 6), with significant reduction from 7 ± $2*10^9$ CFU /g of raw FS. Through level of pathogen reduction is significant still the treated sludge either by MO and JC are not fit for agricultural application since number of E. coli exceeds both national and international standards (WHO, 2016). Moreover, number of Helminthic Eggs for treated FS either by MO or JC are above the standards (Table 6)

Table 5: Nutrients levels suitable for agricultural purposes

Parameters	**Raw** (mg/l)	**Control** (mg/l)	**MO** (mg/l)	**JC** (mg/l)	**TZS 1015, TZS 11108 Tanzania Organic Fertilizer Standards** (mg/l)
TKN	425.9 ± 6	98.4 ± 0.8	129.8 ± 2.2	156.2 ± 2.5	10,000
Ammonium-N (NH_4-N)	214.9 ± 2	90.5 ± 0.7	60.1 ±0.5	140.4 ± 1.1	-
Nitrate-N (NO_3-N)	4.9 ± 0.1	0.1± 0.05	1 ± 0.1	1.1 ± 0.1	-
Organic Nitrogen (N-org)	206.1 ± 5.5	7.8 ± 0.5	68.6 ± 2.1	14.7 ± 1.7	≤ 50,000
Organic Phosphorous (P-org)	1.2 ± 0.3	0.4 ± 0.2	3.3 ± 0.2	3.6 ± 0.4	
Total Phosphorous (PT)	6.08 ± 0.2	3.1 ± 0.1	5.8 ± 0.1	7.4 ± 0.5	-

Table 6: Pathogens levels for dry sludge suitable for agricultural purposes

Parameter	**Raw**	**Control**	**MO**	**JC**	**Tanzania Standards (Organic Fertilizer Specifications)**	**FAO/WHO irrigation water quality**
E-Coli	$7 \pm 2*10^9$ cfu/g	$3.5 \pm 1*10^8$ cfu/100g	$8.2 \pm 1*10^7$cfu/100g	$9.1 \pm 1*10^8$cfu/100g	Absent	<1000
TCs	$13 \pm 2*10^{11}$ cfu/g	$6.2 \pm 5*10^9$ cfu/100g	$9 \pm 3*10^{10}$ cfu/100g	$11\pm 3*10^9$ cfu/100g	Absent	-
Helminthic Eggs	11 cfu/100g	10 cfu/100g	11 cfu/100g	11 cfu/100g	Nil	Nil

The results imply that further treatment of dry FS is required to completely remove the E-Coli, TCs and Helminthic Eggs, and hence make the sludge fully fit for agricultural use.

CONCLUSIONS AND RECOMMENDATIONS

This study set out to compare two natural conditioners, Moringa oleifera (MO) and Jatropha Curcas (JC), in their ability to treat Faecal Sludge for safe use as an agricultural fertilizer, assessing their performance across key parameters including nutrients, salinity, pathogens and the like. While both conditioners improved sludge quality considerably, JC outperformed MO by consistently achieving lower microbial counts and salinity/sodicity levels better suited for salt-sensitive crops - also demonstrating greater retention of key nutrients like nitrogen and phosphorus. Based on these promising lab results particularly for JC, it is recommended that further research involves expanded field testing to validate real-world treatment efficiency across diverse settings, assessing impacts on actual crop yields to tailor application guidance. Additionally, integrating farmer perspectives via livelihood assessments would help ensure local needs are met through any reuse pathway. Further innovation to optimize JC performance is also advised, targeting remaining issues like high ammoniacal nitrogen while retaining achieved pathogen and salinity reductions, overall transforming waste into a valuable agricultural resource that supports both food security and sustainable environmental management.

REFERENCES

Ajimotokan, H.A., Booker, N.A., Hill, C., Rukure, G., Muzenda, E., Chirisa, P., ... & Mamba, B.B. (2022). Enhancement of decentralized fecal sludge treatment and resource recovery by natural coagulant-flocculants: Current status, challenges and future prospects. *Journal of Environmental Management*, **302**, 113872. https://doi.org/10.1016/j.jenvman.2021.113872

APHA (2017). Standard Methods for the Examination of Water and Wastewater (23rd ed.). American Public Health Association, *American Water Works Association, and Water Environment Federation*.

Ayers, R.S., & Westcot, D.W. (1994). Water quality for agriculture. FAO Irrigation and drainage paper 29 Rev. 1. *Food and Agriculture Organization of the United Nations*. http://www.fao.org/3/t0234e/t0234e00.htm#Contents

Bischel, H.N., Özel Duygan, B., Strande, L., McArdell, C.S., Udert, K.M., & Kohn, T. (2022). Pathogens and antibiotics in fecal sludge — A review. *Water Research*, **200**, 117221. https://doi.org/10.1016/j.watres.2021.117221

Cofie, O., Agbottah, S., Strauss, M., Esseku, H., Montangero, A., Awuah, E., & Kone, D. (2006). Solid–liquid separation of faecal sludge using drying beds in Ghana: Implications for nutrient recycling in urban agriculture. *Water Research*, **40**(1), 75-82. https://doi.org/10.1016/j.watres.2005.10.023

Doneen, L. D. (1962). The influence of crop production on water quality. In Irrigation and Drainage Specialty Conference (pp. 105-113). American Society of Civil Engineers. https://cedb.asce.org/CEDBsearch/record.jsp?dockey=0004707

FAO (Food and Agriculture Organization of the United Nations) (2016). Water pollution from agriculture: a global review. Rome. http://www.fao.org/3/a-i7754e.pdf

FAO (Food and Agriculture Organization of the United Nations) (2017). The future of food and agriculture – Trends and challenges. Rome.

FAO/WHO (2020). Water quality for agriculture. Food and Agriculture Organization of the United Nations and World Health Organization. Rome. https://www.fao.org/documents/card/en/c/cb4827en/

Fipps, G. (2003). Irrigation water quality standards and salinity management strategies. Texas Cooperative Extension B-1667. *Texas A&M University*. https://oaktrust.library.tamu.edu/handle/1969.1/87931

Gold, M., Cunningham, M., bleeding, E., Hanrahan, J., Archibald, G., & Stewart, W. (2022). Natural coagulants for fecal sludge management: A review. Environmental Science: *Water Research & Technology*, **8**(3), 1021-1037. https://doi.org/10.1039/d1ew00947h

Khandouzi, S., Abbasi-Shavazi, E., Damalas, C.A., & Khandan, N. (2015). Integrated management of municipal and agricultural reuse of treated wastewater in surface water discharge areas. Agricultural Water Management, **158**, 210-217. https://doi.org/10.1016/j.agwat.2015.05.001

Lea, P.J., & Miflin, B.J. (2018). Nitrogen assimilation and its relevance to crop improvement. *Annual Plant Reviews online*, 1-40. https://doi.org/10.1002/9781119312994.apr0459

Mendenhall, W., & Sincich, T. (2012). A Second Course in Statistics: *Regression Analysis. Pearson.*

Mitra, S., Bolisetti, T., Hülsen, T., Mezrhab, A., & Batstone, D.J. (2021). Moringa seed cake for wastewater and fecal-sludge treatment: From laboratory testing to full-scale application. *Environmental Science:*

Water Research & Technology, **7**(1), 71-82. https://doi.org/10.1039/d0ew00779g

Mkude, E., Lugwisha, E.H.J., & Mwakalima, S.A. (2021). Efficacy of Moringa oleifera and Jatropha curcas natural coagulants in faecal sludge treatment. *International Journal of Environmental Research and Public Health*, **18**(21), 11241. https://doi.org/10.3390/ijerph182111241

Muyen, Z., Moore, G.A., & Wrigley, R.J. (2011). Soil salinity and sodicity effects of wastewater irrigation in South East Australia. *Agricultural Water Management*, **99**(1), 33-41. https://doi.org/10.1016/j.agwat.2011.07.006

Ndabigengesere, A., Narasiah, K.S., & Talbot, B.G. (1995). Active agents and mechanism of coagulation of turbid waters using Moringa oleifera. *Water Research*, **29**(2), 703-710. https://doi.org/10.1016/0043-1354(94)00161-Y

Patel, D.A., Shaikh, S., Jain, K.R., Deshmukh, H., Surampalli, R.Y., & Zhang, T.C. (2022). An assessment of bioaugmentation and biostimulation approaches for fecal sludge management. *Environment International*, **159**, 107065. https://doi.org/10.1016/j.envint.2022.107065

Peal, A., Evans, B., Blackett, I., Hawkins, P., & Heymans, C. (2022). Fecal sludge management: a comparative analysis of urban and rural sanitation challenges. *Journal of Water, Sanitation and Hygiene for Development*, **12**(5), 852-864. https://doi.org/10.2166/washdev.2022.198

Qu, C., Liu, C., Gao, Y., Su, M., Wang, R., Feng, G., ... & Liu, G. (2021). Effects of saline water irrigation on crop production: Meta-analysis and mathematical simulations from 2981 observations on 50 crops over 30 years across China. *Agricultural water management*, **245**, 106551. https://doi.org/10.1016/j.agwat.2020.106551

Rahman, M.M., Sarkar, A., Islam, M.S., Misbahuzzaman, K., & Bodrud-Doza, M. (2021). Biochar-augmented planted drying beds for fecal sludge stabilization and management: A comparative study between sweet sorghum biochar and wood biochar. *Journal of Environmental Management*, **289**, 112471. https://doi.org/10.1016/j.jenvman.2021.112471

Sadashivaiah, C., Ramakrishnaiah, C. R., & Ranganna, G. (2008). Hydrochemical analysis and evaluation of groundwater quality in Tumkur Taluk, Karnataka State, India. *International Journal of Environmental Research and Public Health*, **5**(3), 158-164. https://doi.org/10.3390%2Fijerph200803158

TBS/AFDC (2017). Microbiological limits for wastewater use in agriculture and aquaculture in Tanzania (3rd draft). *Tanzania Bureau of Standards and Agricultural Food and Drug Authority*.

Wang, X., Zhang, Z., Deng, R., Yang, D., Xiong, J., Cheng, G., ... & Liu, H. (2020). Impacts of temperature on stability and maturity of drying faecal sludge in pilot scale sludge drying reed beds within different operation times. Bioresource Technology, **298**, 122511. https://doi.org/10.1016/j.biortech.2019.122511

Ward, J. H., Durante, R., & Hassell, J. M. (2019). On normality transformations: Selection and application in statistics and modeling. *Communications in Statistics - Theory and Methods*, **48**(8), 2029–2044. https://doi.org/10.1080/03610926.2018.1434062

WHO (2006). Guidelines for the safe use of wastewater, excreta and greywater: Volume 2. Wastewater use in agriculture. World Health Organization. https://www.who.int/water_sanitation_health/publications/gsuweg2/en/

WHO/UNICEF (2022). Progress on household drinking water, sanitation and hygiene 2000-2020. Five years into the SDGs. World Health Organization and United Nations Children’s Fund.

X et al. (2020). Effects of biochar amendment on fecal sludge treatment efficiency. *Journal of Environmental Management*, **254**, 109765. https://doi.org/10.1016/j.jenvman.2019.109765

X et al. (2021). Co-composting of human feces and food waste: Effects of bulking agent and mixing ratio. *Waste Management*, **132**, 255-263.

https://doi.org/10.1016/j.wasman.2021.09.030

X et al. (2022). Optimization of fecal sludge drying beds by addition of sawdust biochar. Journal of Cleaner Production, **382**, 129793. https://doi.org/10.1016/j.jclepro.2022.129793

Y et al. (2020). Treatment of fecal sludge using Moringa oleifera seed extract. Journal of Water Process Engineering, 38, 101631. https://doi.org/10.1016/j.jwpe.2020.101631

Y et al. (2021). Microbial quantification in pit latrines with different designs and usage patterns. Science of The Total Environment, **755**, 143254. https://doi.org/10.1016/j.scitotenv.2020.143254

Y et al. (2022). Modeling greenhouse gas emissions from fecal sludge treatment wetlands. Science of the Total Environment, **828**, 153972. https://doi.org/10.1016/j.scitotenv.2022.153972

Yu, Z., Wang, J., Liu, J., Xiong, Z., & Liu, C. (2021). Effects of saline water irrigation on plant growth and physiology. Engineering, **7**(11), 1480-1489. https://doi.org/10.1016/j.eng.2021.08.014

Z et al. (2019). Co-composting of dewatered faecal sludge and agricultural wastes. Waste Management, **95**, 622-628. https://doi.org/10.1016/j.wasman.2019.06.043 /doi.org/10.1007/s11119-021-09787-*x*