Supporting information

Moringa oleifera f-sand Filters for Sustainable Water Purification

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f-sand preparation procedure for column tests

Procedure This detailed description below provides an example of how an *f*-sand column at specified conditions was prepared. Fully packing a sand column (1.6 cm I.D. and 10 cm L) required 25 g sand with a size of 106 µm. 3 grams of ground seed was added into 600 ml water for 5 min, generating a seed concentration of 0.005 g/ml, followed by filtration of the seed extract through a 1.5 µm glass fiber filter and then a 0.2µm cellulose acetate filter. The filtered seed extract (600ml) was then mixed with 25 g sand for 5 min. This generated a seed loading of 5.6 g/m^2. The supernatant was then discarded and *f*-sand was used for packing after rinsing with DI water three times. To pack the column, the *f*-sand slurry was quickly poured into the glass column and gently mixed in the column to remove any trapped bubbles before packing overnight by gravity-fed DI water.

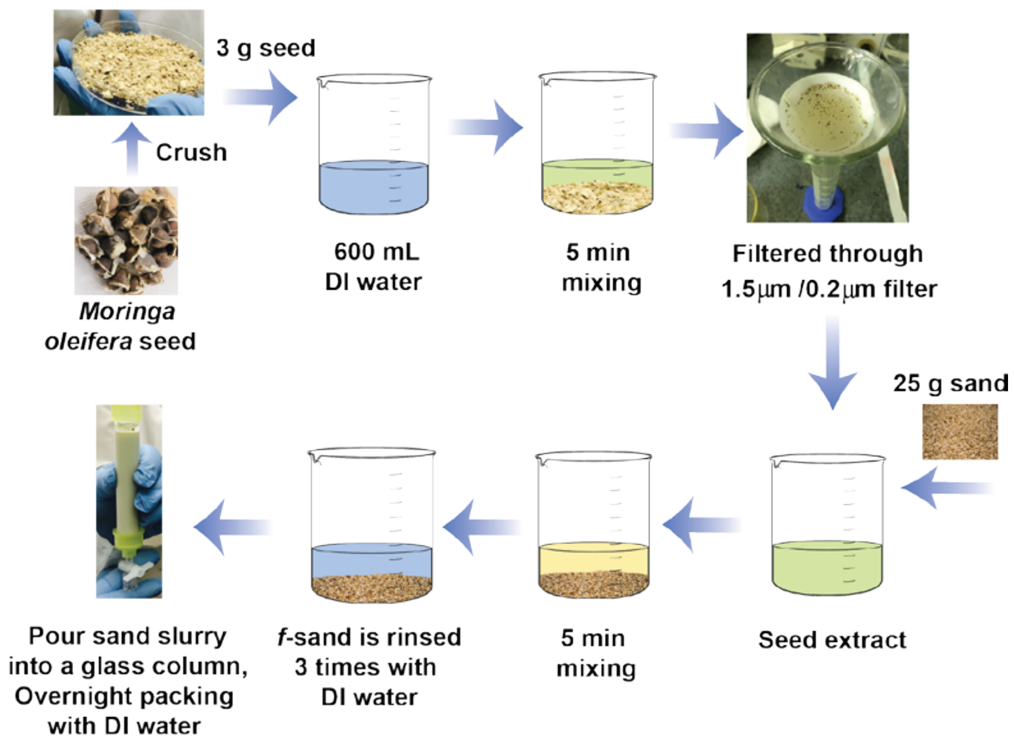

Figure S1. Procedure of preparation of an *f*-sand column using *Moringa* seeds. Image was created using Adobe Illustrator.

Experimental details For column experiments with different seed loadings, only seed amount was changed while the volume seed extract volume and sand amount remained constant, as presented in **Table S1**. For experiments with different collector sizes, we first determined roughly 26 g sand was used to fill the glass column. Seed extract concentration (0.005 g/ml) and seed loading (5.6 g/m^2) was kept constant throughout different collector size experiments, while seed amount (g) and seed extract volume (ml) was then determined as presented in **Table S2**.

Table S1. Details of *f*-sand column preparation for column experiments at different seed loadings.

Seed/surface area (g/m^2)	Seed concentration (g/ml)	Seed (g)	Seed extract (ml)	Sand (g/ml)
1.12	0.001	0.6	600	
5.59	0.005	3	600	0.042
11.17	0.01	6	600	

Table S2. Details of *f*-sand column preparation for column experiments at collector sizes.

Collector size, specific surface area	Seed concentration (g/ml)	Seed (g)	Seed extract (ml)	Sand (g/ml)
106 µm, 0.021 m^2/g	0.005	3	600	0.0042
256 µm, 0.0091 m^2/g	0.005	1.3	256	0.098
512 µm, 0.0045 m^2/g	0.005	0.6	128	0.196

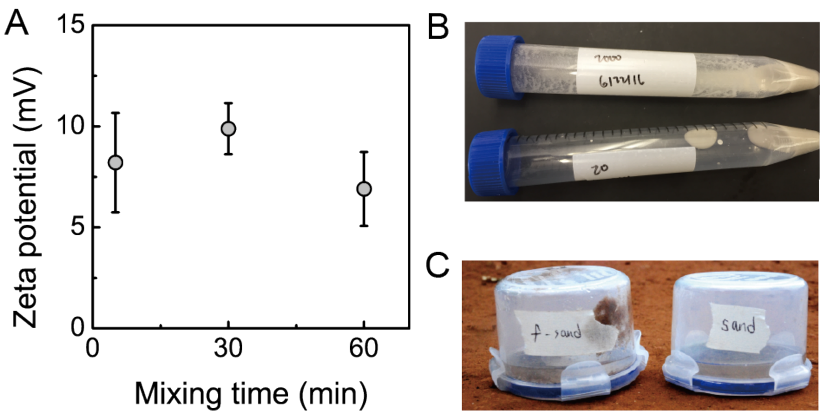

Figure S2. (A) Five minute mixing time for glass beads and 0.005 g/ml and 5.6 g/m^2 moringa serum is sufficient to yield charge reversal of sand, resulting in the surface potential of 8.2$\pm$2.4 mV. Mixing time up to 30 min only led to an increase in zeta potential to 9.8$\pm$1.3 mV. 3μm SiO_2 particles (original surface potential of -42 mV) are used as substitute for sand in order to eliminate settling challenges during zeta potential measurements of 106 μm glass beads. (B) A simple "stick test" can quickly be used to determine the effectiveness of charge reversal of sand by *Moringa* seed protein. *f*-sand coated with 2.3 g/m^2 moringa seed stuck on the side of the plastic tube (upper image) due to positive surface potential, compared to *f*-sand coated with 0.02 g/m^2 moringa seed (lower image) showing no sticking effect. (C) Stick test was performed in Kigali, Rwanda using locally available sand and moringa seeds (left:*f*-sand, right:regular sand). This test can be done with plastic or glass containers in the field to quickly determine the optimal seed dosage given various sizes of sand material. Both photos (B and C) were taken by one of the authors (Emma Clement).

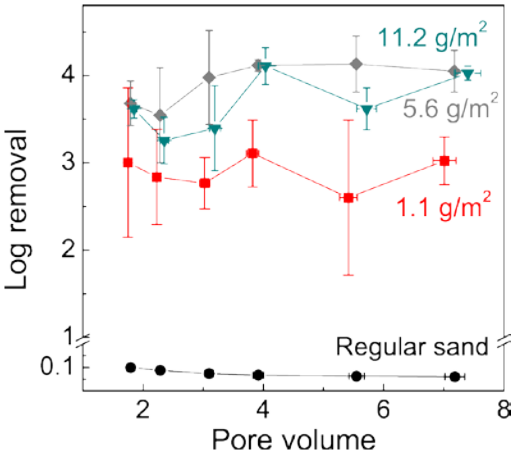

Figure S3. Log removal of *f*-sand column coated with various amounts of *Moringa* seed over 2-8 pore volumes. Removal values at each pore volume are an average of triplicate experiments. Experimental conditions:1 μm polystyrene particle at a concentration of 10^6/ml, 1mM NaCl, 1.6 ml/min with 106 μm glass beads.

Calculation of predicted log removal

$$\text{Log removal}_{\text{pred}} = -\log_{10}[e^{\frac{-3(1-\varepsilon)L\,\eta_0\alpha}{2d_c}}] \qquad \text{Equation (1)}$$

$$\sigma_{\text{log removal}} = -\log_{10}(e)\left(\frac{-3(1-\varepsilon)L\,\eta_0}{2d_c}\right)\sigma_\alpha \qquad \text{Equation (2)}$$

Interaction energy calculation

The electrostatic interaction energies were calculated using equation (4) developed by Hogg *et al.*[1]:

$$\phi_{EDL} = \pi\epsilon_0\epsilon_r a_p\left\{2\psi_p\psi_c \ln\left[\frac{1+e^{-kh}}{1-e^{-kh}}\right] + (\psi_p^2+\psi_c^2)\ln[1-e^{-2kh}]\right\} \qquad \text{Equation (3)}$$

Where ϵ_0 is the dielectric permittivity in vacuum, ϵ_r is the relative dielectric permittivity in water, a_p is the particle radius, ψ_p and ψ_c are the surface potential of particle and glass beads (collector) experimentally determined as zeta potential, k is the inverse of debye length and h is the separation distance between particle and collector. The van der Waals interaction energies were calculated using equation (5)

$$\phi_{VDW} = -\frac{Aa_p}{6h}\left[1+\frac{14h}{\lambda}\right]^{-1} \qquad \text{Equation (4)}$$

Where A is the Hamaker constant and a value of 1×10^{-20}J was used for the polystyrene-water-quartz system[2]. λ is the characteristic wavelength of the dielectric (100 nm[3]).

Saturation model equation

Eqn 5 was used to calculate the maximum fraction (*f*) of sand area that is occupied by particles at breakthrough, which is defined as the fractional converage when N/N_0 exceeds 0.1.

$$f = \frac{A_s N_s}{J_p V_b A_p} \qquad \text{Equation (5)}$$

where A_s is the surface area of one sand particle, N_s is the total number of sand particles in the column, J_p is the flux of influent particles, V_b is the volume filtered at breakthrough and A_p is the cross-section area of an influent particle.

Interaction area calculation of sphere and rod-shape bacteria

The interaction area between spherical polymer particle with a diameter $(2r)$ of 1 µm is estimated using euqation[4]:

$$A = 2\pi r \kappa^{-1} \qquad \text{Equation (6)}$$

The interaction area between rod-shape bacteria with a diameter of 1.2 µm and a length (L) of 3.7 µm is estimated using this Eqn:[4]

$$A = 2L\sqrt{r\kappa^{-1}} \qquad \text{Equation (7)}$$

Where κ^{-1} (nm) is the Debye length[4] in 1 mM NaCl. The calculation was under the assumption of the distance between particle or bacteria and sand surface is equal to the Debye length. The sand surface is considered a flat surface given the significant size difference between particle and sand.

Considerations for selecting collector size and flow rate for lab scale column experiments

Collector size We justify our choice of collector size in our study according to a previous scale-down analysis of granular activated carbon that suggests a proper scaling between the small and large column empty bed contact time (EBCT) can be determined from the ratio of adsorbent particle sizes:[5]

$$\frac{EBCT_{sc}}{EBCT_{lc}} = [\frac{d_{sc}}{d_{lc}}]^2 \qquad \text{Equation (8)}$$

where $EBCT_{sc}$ and $EBCT_{lc}$ are EBCT of small and large columns, which can be calculated from column volume divided by superficial velocity. d_{sc} and d_{lc} are adsorbent (collector in our case) particle size. The equation is under the assumption that the porosity, bulk densities and capacities are identical in the two scales and that intraparticle diffusivities do not change with particle size. We considered a slow sand filter and a rapid sand filter at the typical full scale, and used **Eqn 8** to perform scale-down analysis to calculate collector size given the column dimension and flow rate used in our study. Media diameter, filter length and flow rate used the calculated collector size is presented in **Table S1**. The scale-down collector size ranges from 0.03-0.075 mm considering a slow sand filter and ranges from 0.7-1.6 mm considering a rapid sand filter. We chose to use 0.1-0.6 mm collector size for our study.

Table S3. Scale-down collector sizes were calculated from the design parameters of full scale slow sand filter and rapid sand filters.

	Full scale slow sand filter (low, high)	Small column scale down from slow sand filter	Full scale rapid sand filter (low, high)	Small column scale down from rapid sand filter
Filter Length (cm)	90, 150	10	60, 180	10
Flow rate (m/h)	0.05, 0.2	0.48	5, 15	0.48
Collector size (mm)	0.3-0.45	0.03, 0.075 (low, high)	0.5, 1.2	0.7, 1.6 (low, high)

Flow rate Head loss calculations show that the collector size and flow rate used in this study were reasonable for a small-scale filter and comparable with the large scale sand filters. Head loss or the minimal head required is calculated using the equations below[6]. For a flow at Darcy flow regime at Re<1, H_L (m) is calculated based on Poiseuille's law:

$$\frac{H_L}{L} = \frac{K_k \mu S^2 v}{\rho_W g \varepsilon^3} \qquad \text{Equation (9)}$$

where K_k is Kozeny coefficient (unitless) which is an empirical coefficient and assumed to be about 5 for spherical media[7]. S is the specific surface area ($\frac{6\,(1-\varepsilon)}{d}$, m^{-1}), ε is column porosity, v is superficial velocity (m/s), μ and ρ_W is viscosity and density of water.

Table S4. Superficial velocity (v) and head loss of the filtration experiments with various collector sizes and flow rates. The values suggest the flow rates of filtration experiments were similar and higher than a slow sand filter, and were at Darcy flow regime that generated a head loss lower than a typical slow sand filter.

Collector size (μm)	Flow rate (ml/min)	v (m/h)	Head loss (m)
106	1.6	0.48	0.13
	3.2	0.95	0.25
	7	2.09	0.55
106	1.6	0.48	0.13
256			0.02
512			0.005

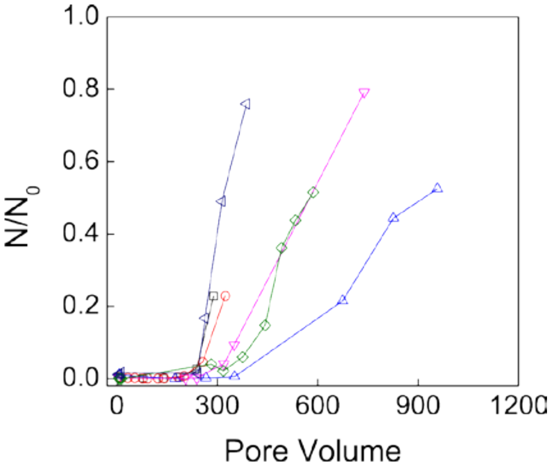

Figure S4. Breakthrough curves of 3-day column filtration experiments using a column with a dimension of 5 cm L and 1 cm inner diameter run at 0.7ml/min with 10^7/ml 1 µm polystyrene particles. Six repeated runs were presented. This data was used to calculate the fractional coverage (*f*) at breakthrough.

Scale up analysis Two different scales were considered for scale up: 5-person household scale for point-of-use, and 1000-person community scale. Filter flow rate was first determined based on the amount of people served for each scale assuming 2L per day of drinking water. In addition we specified a sand diameter of 0.5 mm. The specific diameter and length of the column was then determined in order to meet two requirements: 1) reasonable head required and 2) 4 log removal of 1 µm particles at a concentration of 10^4 /ml concentration. The amount of sand was then calculated based on the porosity (0.37) while the mass of seeds was calculated using 5.6 g seed/m^2 sand area. The lifetime of the filter based on saturation was then calculated using 4% maximum fractional coverage (*f*). Finally the head loss was calculated using an non-linear Forchheimer flow equation when Re>1:

$$\frac{H_L}{L} = \frac{K_v(1-\varepsilon)^2 v\mu L}{\rho_W g d \varepsilon^3} + \frac{K_I(1-\varepsilon)v^2 L}{\rho_W d \varepsilon^3} \qquad \text{Equation (10)}$$

where K_v is the head losss coefficient due to viscous forces and K_I is the head loss coefficient due to inertial forces. We used typical values for sand, K_v=110 and K_I =2^6, for our calculations.

Log removal increases with column diameter due to decreased superficial velocity and increased collector efficiency. Log removal also increases with column length given the CBF model (**Eqn 2** in manuscript). Yet column diameter and length are disproportional to each other due to given a fixed column volume. Analysis shows that, in order to meet both requirements, column volume has to be scaled large enough to generate the dimensions shown in **Table S3**.

The minimal volume was found to reach breakthrough in 140 years given our fraction of coverage of 4%. Therefore, in reality, the longevity of the column will not depend on the column capacity but rather depend on the duration and stability of adsorbed protein over extended period of time.

Analyses also suggest that the column filtration rate will be operated at low Re number <1, and with very small head required (<0.1 m). It was also found that the column with a larger media size such as 0.8 mm would result in a column (community scale) dimension providing too small of required head (0.008 m with a dimension of 1 m diameter and 1.6 m long) or too large of a scale (1.6 m head loss but a dimension of 0.2 m diameter and 12.5 m long) that is unrealistic for implementation in the field.

Table S5. Scale up specifics of *f*-sand filter. Two different scales were considered: 5 people household scale for point-of-use, and 1000 people community scale. Assumptions: 2 L/ day/person, porosity 0.39. 1 µm particle at 10^4 /ml concentration, sand size 0.5 mm, fraction of coverage: 4%, filter will not reach breakthrough in 140 years, although filters are assumed to be replaced every three months based on protein stability and effectiveness with sand being reused. Unit price of locally sourced sand is \$0.018/ kg[8].

Design parameters		**Point of use (5 people)**	**Community based (1000 people)**	**Typical slow sand filter**	**Rapid sand filter**
Treatment capacity	Daily output (L)	10	2000	NA	NA
	Yearly output (L)	3650	730,000	NA	NA
	Flow rate (L/d)	10	2000	NA	NA
	Filtration rate (m/h)	0.21	0.22	0.05-0.2	5-15
Column specifics	Filter volume (m3, porosity 0.39)	0.002	0.41	NA	NA
	Media diameter (mm)	0.50		0.3-0.45	0.5-1.2
	Filter diameter (m)	0.05	0.70	NA	NA
	Filter length (m)	1.04	1.06	0.9-1.5	0.6-1.8
	Log removal	4.1	4.2		
	Minimal head (m)	0.03	0.03	0.9-1.5	1.8-3
Sand and seed consumption	Total sand (kg)	2.1	423	NA	NA
	Cost of sand/ person/ year (\$, Unit price: 0.018\$/kg)	0.03		NA	NA
	Total seed (kg)	0.054	42.91	NA	NA
	Seed kg /person/ year	0.043		NA	NA

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