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Household Production of Ceramic Water Filters in Western Rajasthan, India

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***Abstract* -- Frustum shaped clay ceramic water filters are being manufactured by the potters of the Thar Desert in India for household use. The clay composite consists of a homogeneous mixture of equal volume of clay and sawdust. A low-cost manual press, to form the clay composite into frustum shape, is developed by the present authors. This article elaborates critical investigation of the specific traditional clay-firing technique used, to achieve the required functionality and material property of the filters. Household based manufacturing of these filters is found to be markedly different from factory based production by firing process. The functional features of the clay ceramic filter, such as microbial filtration rate, flow rate, and compressive strength, are evaluated and presented. An E. coli bacteria removal efficiency of more than 99% is achieved using these clay ceramic water filters. Optimal filtration rates are achieved between ambient temperatures ranging from 30ºC - 40ºC.**

Index Terms - Ceramic Water Filter, Filter Press, Filtration, Global Health

INTRODUCTION

Water purification to acquire potable water is a major challenge for the present day civilization. Many water purification methods and technologies have been developed and employed over the years[1]. Most of these methods are cost and energy intensive and are not easily adaptable to the rural population of the developing world[2]. A very simple and effective method using water filtration through clay-ceramic pots have been used over the years in many rural parts of the developing world[1]. The ultrafine pore passages with high tortuosity in the clay material trap most of the non-soluble contaminants and bacteria (> 99%). A reasonable volumetric production (> 600 ml/hr) of safe potable water can be obtained by this method[3]. A nonprofit organization "Potters for

Peace" based in Boulder, Colorado, USA has been promoting the clay ceramic pot impregnated with a colloidal silver lining in central America since the early 1980s. The water filter propagated by Potters for Peace is viewed as one of the most sustainable solutions for household drinking water purposes[4,5]. This technology is famed due to its ability to showcase considerable reduction in diarrhea cases[5–7]. India has the largest diarrhea related mortality[8]. Diarrhea is caused by ingestion of microbe contaminated water.

Potters from Western Rajasthan, India are well acquainted with the manufacturing of off-white water storage pots[9]. Percolating decontaminated/filtered water drips down these off-white water pots[10] which can be collected and used as potable water. Filtration by gravity is a low cost, energy efficient operation[1]. Frustum shaped ceramic water filters have showcased log removals of 2 to 4 while filtering water contaminated with microbes such as E. Coli[1,11–13]. This filtration technology, however, does not perform well in case of virus filtration[12]. Plappally carried out an extensive review on clay ceramic based water filters[14]. Plappally and Lienhard reviewed cost and microbial filtration efficacy of these clay ceramic water filtration devices[1]. Hunter asserted that these clay ceramic water filters are most effective long-term water filtration solutions for households in developing nations[15].

During emergencies like tsunami and floods in Sri Lanka and Dominican Republic, such clay ceramic filters were used for ensuring drinkability of water[16]. These filters had a frustum shape with a height of 26 cm and a base diameter of 20 cm[17]. This frustum shaped 10-15 liter capacity water filter is sufficient for drinking water requirements of a nuclear families[18,19]. The literature on hydraulic modeling suggests a filtration rate of 1-3 liters per hour through these filters[1,4,20].

Potters are a pertinent facet of rural India. Potter can be equipped with the clay ceramic water filtration technology of Potter for Peace to provide one-stop solution for drinking water purification[18,21]. A nonprofit organization "Rupayan Sansthan" introduced this technology with a name G-Filter in Western Rajasthan[22–24]. The G-Filter was introduced keeping in mind skill development, local accessibility, potter community sustenance, and inexpensive and efficient rural water services in Western Rajasthan[25]. G-Filter is found to be a solution for drinking water woes of dispersed communities with no-piped water supplies[26]. One impediment for G-Filter sustenance is whether local people are willing to pay for G-Filters when other drinking water options are available [27]. Furthermore, various other energy intensive point of use water filtration technologies and bottled water have already entered households in India[28], despite long term health risks due to human ingestion of toxic leachants from polyethylene terephthalate bottles[8,29].

A typical G-Filter is shown in Fig. 1. A 20 liter clay container supports a 9 liter filter receptacle and cools the filtrate collected within. The clay container is made using the traditional technique for manufacturing water storage pots[9].

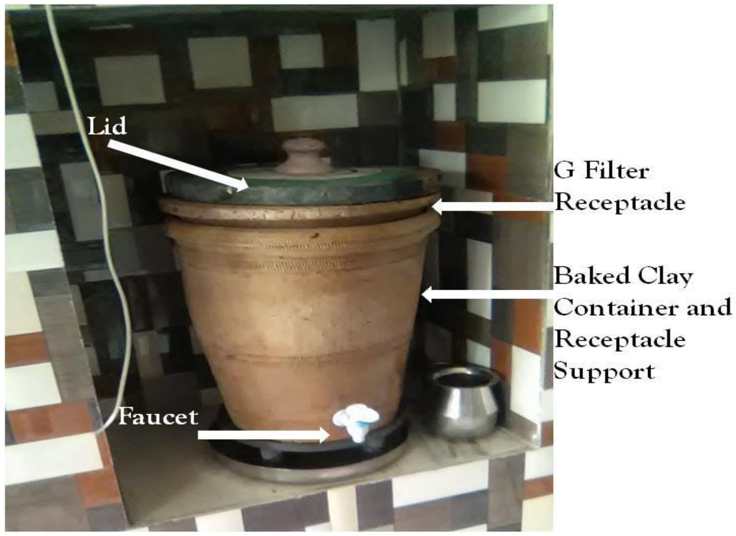

FIGURE 1
THE G FILTER SETUP IN A HOUSE AT BANAD VILLAGE, JODHPUR

In India, pottery is a community based profession[30,31]. This skill is passed from generation to generation. The imminent thought of possible loss of family profession due to the adaptation of other water filtration/purification methods, prompted researchers working towards this ceramic water filter project to arrest the feasibility of a cottage industry based factory for clay-ceramic water filter production[32,33]. The objective of this project will be to preserve and continue the community profession and instill the factory based water filter manufacture[34] technology to the local potter community. In western Rajasthan, traditionally the potters practice open firing and an up-draught open hearth furnace[31,35] for firing the filter, which will differ from the factory mode of water filter manufacture[18,36,3,37].

This article reports the process of clay ceramic water filter manufacturing by potter households in western Rajasthan, India. This includes studying local (Rajasthan potters) know-how of processing raw materials and sintering clay artifacts and substituting it for factory mode of filter production processes practiced in different locations of the world[37–40]. Finally the clay ceramic filters manufactured as proof-of-concept are assessed for its microbial removal effectiveness and load bearing capacities.

METHODOLOGY

Forming the Soil to a Shape

The potters in Western Rajasthan are acquainted with rotating wheel based pottery[41]. The process of manufacture of the clay ceramic water filter receptacle is distinct. Pottery in Western Rajasthan is still untouched by mechanization[42]. Salty raw clay is mined from Raital and Mokalsar near Jodhpur, Rajasthan[31], which - is then powdered[30]. The women folk (irrespective of the location of potter across India) sieve the clay using a household sieve (3 mm × 3 mm). Potter for Peace recommends a sieve size in the range 0.18 mm-2 mm[43]. If the salt content in the clay is not sufficient (0.02% by volume), additional salt is added into the clay[29]. Addition of salt is considered to make the clay ceramics more load bearing, whiter in color, and functionally better refrigerators of water [31]. Local artisans believe that addition of salt in clay influence the sintering rates of clay ceramics. Traditionally, equal volumes of soil and organic matter (saw dust) are kneaded together to manufacture structurally stable construction materials in Western Rajasthan[44]. Sieving of sawdust is performed with the same sieve used to for the powdered salty clay. This is analogous to the Potter for Peace method of preparing the clay-sawdust mixture for manufacturing the filter greenware[3,45]. In this study, a uniform mix of sawdust and salty clay taken in equal volumes is added with water, equivalent to 70% by volume of the mix, to form the disk shaped composites. The composite is kept overnight a moist cloth covering[46]. The composite is press-formed to frustum shape using a 30 ton press (MEC Ltd, India)[4]. The frustum shaped aluminum molds (used to press form the green wares) are covered with a 96 in diameter plastic bag to prevent formed green body from sticking to the mold wall[14]. It should be noted that several versions of frustum shaped water filter presses are available and are being used around the world[18,38,47]. A photograph of the indigenous filter press built to make a nine liter filter green body of the composite mix is shown in Fig. 2.

FIGURE 2
THE CERAMIC WATER FILTER PRESS DEVELOPED IN THE LABORATORY (COURTESY: Y&CO, JODHPUR, RAJASTHAN, INDIA)

The green ware thus formed is 23 cm high and has a base diameter of 25.5 cm. These dimensions were set according to a commercially available plastic bucket of 38 cm height. The green ware separator illustrated in Fig 2 was utilized to retrieve the filter green ware. The filter green ware

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once formed was kept for 2 days in ambient conditions and then dried under direct sunlight for 3 days in this work. The age of drying, its rate and methodology influences the structure and function of the final sintered ceramic being produced[48].

Firing Process Development

Once dried, the green ware is fired in a vertical open hearth furnace (circular shape) of 5 ft radius and 5 ft height[31]. This up draught firing furnace as illustrated in Fig. 3 was introduced in Jodhpur in 1960s[31]. The firing and heating chamber is separated by used truck leaf spring blades. The size of the firing box is 0.4572 m × 0.4572 m. Volume of the heating chamber is 1.75 times of the firing chamber. The green-wares and the furnace are covered with rubbles of pottery to achieve this volume ratio. The kiln wall is tied using an iron belt to improve its structural integrity[49]. The green wares are kept 0.61 m above the ground in inverted position while firing[31,49]. The local potters fired the dried green ware at the same temperature as they used to traditionally fire pure clay flower vases. These temperatures are similar to those set in factory mode sintering[17,50].

FIGURE 3
THE UP-DRAUGHT FURNACE SAR VILLAGE, JODHPUR, RAJASTHAN, INDIA

Locally available cow dung cakes, organic waste (dried twigs or leaves), waste wood, and sawdust are used as fuel for the furnace[31]. The firing should be performed at a temperature range that precludes cracking possibility. During the sintering trials, some of the filter green wares cracked due to thermal stress[51,52]. Potters from the three villages reported this observation with a frequency of 1 in every 45 filter green-wares fired.

In order to monitor the temperature variation in the furnace, continuous measurement of the temperature variation in the furnace during the firing process was conducted with an IR thermometer and K type thermocouple capable to measure in the range -50°C – 1850°C (HTC IRX-68). K type thermocouples were placed inside the furnace at different points to get an overall average time history of the temperatures during the firing process. The measured sintering temperature time history, which precludes the emergence of cracking, is plotted in Fig. 5. The firing time illustrated in Fig. 4 (~230 min.) is comparatively shorter compared to factory based ceramic water filter firing thus conserving lot of energy and fuel[37,39]. Firing forty five filter green bodies consumes 100 kg of wood and 100 kg of sawdust in an updraught (5 ft by 5ft) furnace[31]. Once the firing process is completed, the filters are retrieved after overnight cooling. The filters are left unglazed and utilized for the field experiments.

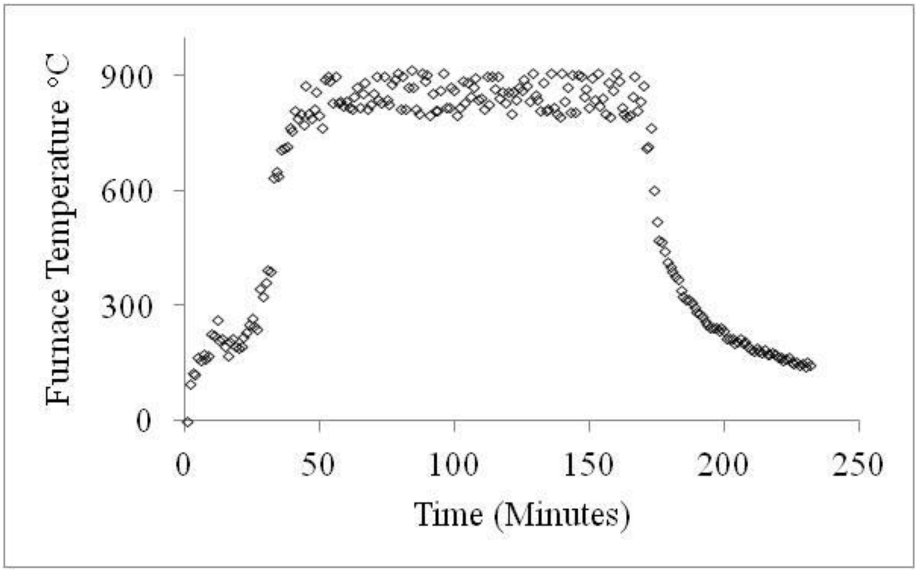

FIGURE 4
TIME HISTORY OF MEASURED OVERALL TEMPERATURE VARIATION IN THE FURNACE THAT PRECLUDES CRACKING OF THE FILTERS

FUNCTIONALITY ASSESSMENT OF THE MANUFACTURED FILTERS

Various functionalities of the manufactured G Filter were systematically evaluated. The volumetric filtration rate, compressive load bearing capability, and microbial removal rates were tested and quantified to assess the characteristics of the water filters. These are discussed in the following sub-sections.

Flow Measurement

The discharge from the G- filter is measured in fully filled condition. Prior to flow measurement experiment, the filters were soaked and saturated with ultra-pure water[4]. The filtrate was collected from four distinct filters manufactured at Banad, Sar, and Salawas villages in Jodhpur. These filters slightly differ in raw materials, construction methods, and firing process depending on the locality of production. A graduated beaker was kept beneath each of the fully filled water filters suspended from a test frame. These four filters were randomly selected. The filtrate is the water, which is collected during the first hour of filtration running in a fully filled condition. The time measurement was performed using a digital stop watch (Casio® A158WA-1DF). The water was collected from the four filters on different days of the year to simulate distinct ambient temperature conditions.

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Percolation rates of water from the four selected G Filters is plotted in Fig. 5 as a function of the ambient temperature[53]. In the first hour, the fully filled filters produce an average of 600-950 ml of filtrate[54]. Similar results have been observed in other frustum shaped ceramic water filter variants across the globe[20,50]. These filtrate productions were in the range 1-3 l/hr[1]. From Fig. 5, it is observed that the maximum percolation rate occurred at temperature range between 30°C-40°C. Water filtration rate vary with local ambient temperature. All filters showcased a dip in filtration rates when the ambient temperature goes beyond 35°C (except for filter 1) as illustrated in Fig. 5.

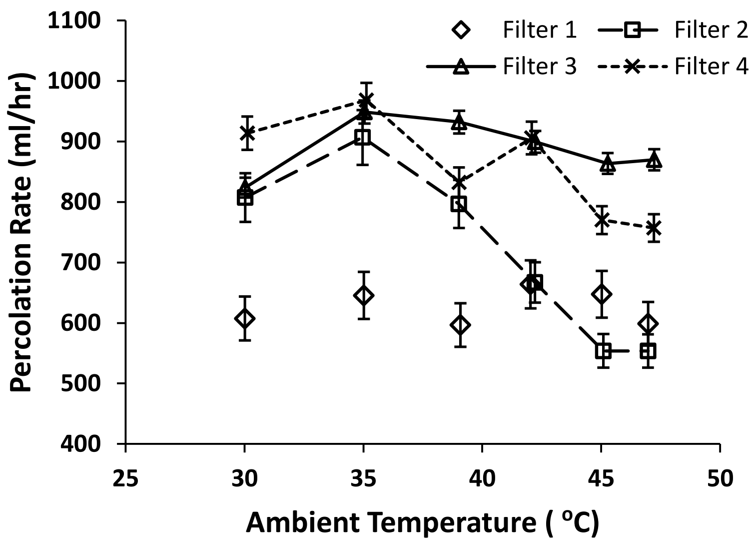

FIGURE 5
THE PERCOLATION RATE OF THE G-FILTER (n=11) IN COMPLETELY FILLED CONDITION AS A FUNCTION OF THE AMBIENT TEMPERATURE

Compressive Strength

For brittle ceramics, the compressive strength is approximately fifteen times the tensile strength[48]. The compressive tests were performed according to the ASTM 1358 standards[17]. Propagation of cracks in ceramics during compressive loads is parallel to axis of applied compressive load[55]. The specimens for the strength tests were prepared from the circular base of the eleven randomly selected sintered G filters. A static axial load at a rate of 0.1 Ns^{-1} is applied to the 35 mm long sample with a cross section of 15 mm × 15-mm[17,50]. The samples were tested for compression on a Universal Material Testing Machine (Model EZ-50, Lloyd Instruments, Germany). It should be noted that inherent cracks or inhomogeneity in the porous clay ceramics increase during compression resulting in powder formation[48,55,56]. The applied compressive loads overcome the strong chemical bonding between the sintered material particles to form these powders[57]. Tests were conducted at a temperature of 300 K and a relative humidity of 20-25%. It is known that compressive failure stress of clay ceramic materials is a polynomial function of their densities[56]. It is therefore pertinent to observe the little variations in density owing to craftsmanship of the potters from Banad, Sar and Salawas villages. Therefore density also was calculated by dividing the mass of the 35 mm thick ceramic sample to its geometrical volume. Mass of the samples are measured using a digital weighing balance (Citizen CG3S, M/s Indian Equipments Co., Jaipur, India).

Compressive strength of ceramic filter material depends on the heterogeneous material character[58]. The eleven G Filter green wares in the up draught kiln contain pre-existing non-elastic deformation or crack forming inhomogeneity (completely oxidizable organics)[17,57]. The compressive strength of the tested specimens are plotted in Fig. 6 as a function of the density of the specimens in which, a derived equation for a polynomial fit of the data with high goodness of fit (R) is also reported. The polynomial relationship of the compressive strength σ_c of the G Filter material with its density ρ conforms to similar relationships derived by other researchers[14,17]. It is to be noted that the density of ceramic filter material depends on the manufacturing process and sintering parameters[59]. An increase in the density of the clay ceramics accompanies an increase in the compressive strength of the ceramic[59].

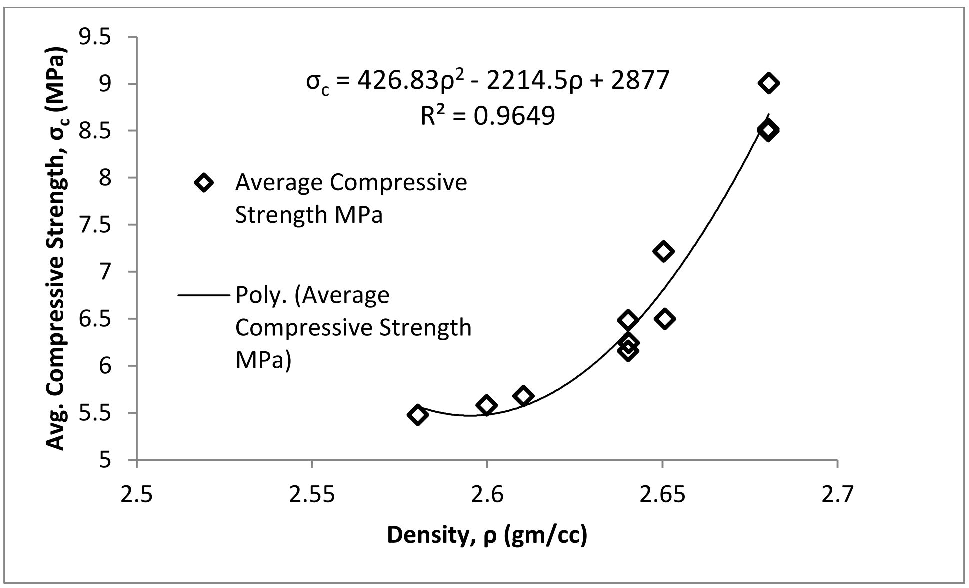

FIGURE 6
COMPRESSIVE STRENGTH AS A FUNCTION OF DENSITY OF G FILTER MATERIAL [50]

Microbial Filtration

E. coli (Escherichia coli) is an indicator bacterium for occurrence of bacterial pathogens and also for fecal contamination[60,61]. E. coli concentration tests in the pre- and post-filter water samples were conducted according to ISO 9308-1:2014 framework[59]. One Shot® TOP10 E. coli (Thermo-Fisher Scientific, India) cells (similar to the E. coli DH10B strain) was used for spiking the concentration in the ultra-pure water. The pure water was supplied by M/s Tomar Scientific, Jodhpur, India. This brand of E. coli is commonly available for laboratory experiments such as cloning, and plasmid propagation (Thermo-Fisher Scientific, India)[62]. One Shot® TOP10 E. coli strain was grown in Miller's LB Broth at ambient condition overnight[62]. Concentrated solution of the E. Coli, diluted with 3 liters of microbial contaminant free distill water was stored until use at -75°C. This solution was prepared prior to the day of the filtration tests. The pre-filtrate sample was prepared by spiking required E. Coli stock (mentioned above) into a constantly stirred 30 liters water tank. The experimental set-up is diagrammatically represented in Fig 7. The complete microbial filtration test set up is kept within a plastic structure. The initial one liter of the filtrate was discarded to prevent initial dilution of filtrate due to their saturation. Saturated filter receptacles are used to simulate operational conditions of the filter. The beaker is cleaned with ethanol followed by rinsing with deionized water and 500 ml of filtrate was collected. The number of viable cells in the contaminated water within the G filters and the filtrate was determined by proper dilution in ultrapure water. Further plating was performed on Miller's LB agar plates. These plates were kept overnight in incubators at 37^{o}C. The colonies were counted after incubation at 37^{o}C and this information was used to calculate viable cells in the respective water samples.

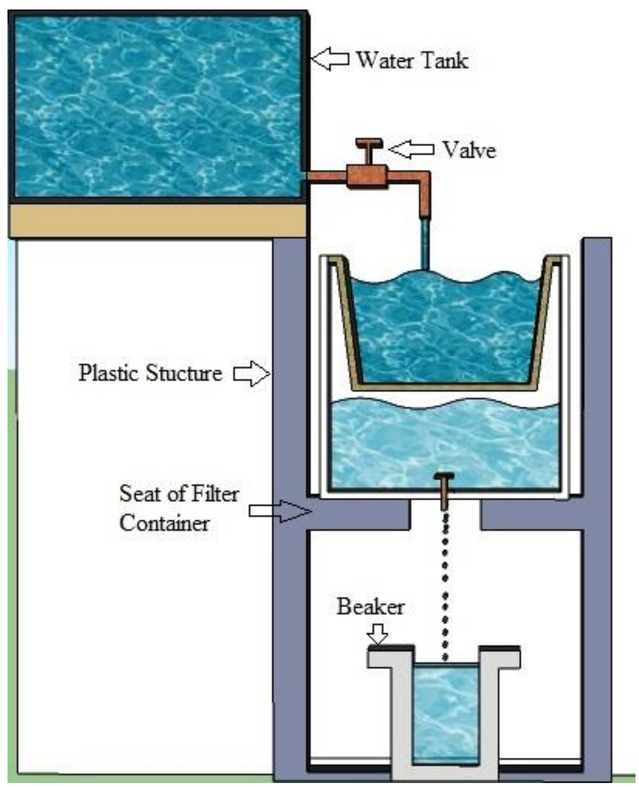

FIGURE 7
SCHEMATIC PRESENTATION OF THE MICROBIAL FILTRATION SET-UP

The numbers of viable cells in the pre- and post-filter suspensions were counted. The efficiency of E. coli filtration was calculated as[18],

$$\eta_{E.Coli} = 1 - N_f / N_{pf} \tag{1}$$

where N_f is the number of viable cells per milliliter of filtrate and N_{pf} is the number of viable cells per milliliter in the pre-filter sample. The log reduction value is defined as [14,18],

$$LRV = log_{10}(N_{pf} / N_f) \tag{2}$$

Physical Removal of E. coli

A contaminated water suspension with almost around 10^8cells/ml was used in the pre-filter sample. Similar levels of contamination (10^6-10^8 cells/ml) have been observed in the Yamuna river water, which is a major source of drinking water in Northern India[63]. This fecal coliform contaminant level is far beyond the drinking water quality standards set by World Health Organization (WHO)[64]. The E. coli filtration experiments were performed on the three G Filter. Each of these G Filters were tested four times using a produced contaminated solution of E.coli as mentioned above. Table 1 shows the efficiencies of the three G filters tested.

TABLE I
RESULTS OF E. COLI FILTRATION EFFICIENCY OF THE G FILTERS

Pre-filter Concentration (No. of Cells/ ml)	Filtrate Concentration (No. of Cells/ ml)	Pre-Filter Conc./Filtrate Conc.	Efficiency ($1-N_f/N_{pf}$)	Log Reduction Value (*LRV*)
6.0×10^8	1.6×10^6	375.0	0.9973	2.5
4.0×10^8	6.0×10^6	666.6	0.9985	2.8
2.4×10^8	4.5×10^6	533.3	0.9981	2.7

CONCLUSION

Household mode of manufacturing G filters is discussed. This mode of manufacturing varies from the factory mode [18,19,33,65]. These clay ceramic filters are considered to be one of the sustainable drinking water procuring solutions in developing countries[66]. Women folk of the potter families in India are knowledge bearers of the type and size of clay for specific pottery artifact. These filters are sintered using the indigenous firing technique. The instantaneous filtration rate through the G Filter is ambient temperature dependent. The maximum filtration rate of G Filter was observed between the temperature range of 30^{o}C and 40^{o}C. Manufactured filters with low density materials have lower compressive strength. It is reiterated that a polynomial function exists between the density and compressive strength of the G Filter material[17]. The microbial treatment efficacy of such filters is at par with clay ceramic water filter produced in factories elsewhere[5,38]. The implication is that potter households dispersed at different location in Western Rajasthan and across India can locally and individually manufacture G filters and distribute to their surroundings. This reduces the cost of transporting water filters to remote locations in rural India.

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