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Investigation on the effective disposal of sludge from a water treatment plant

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ABSTRACT

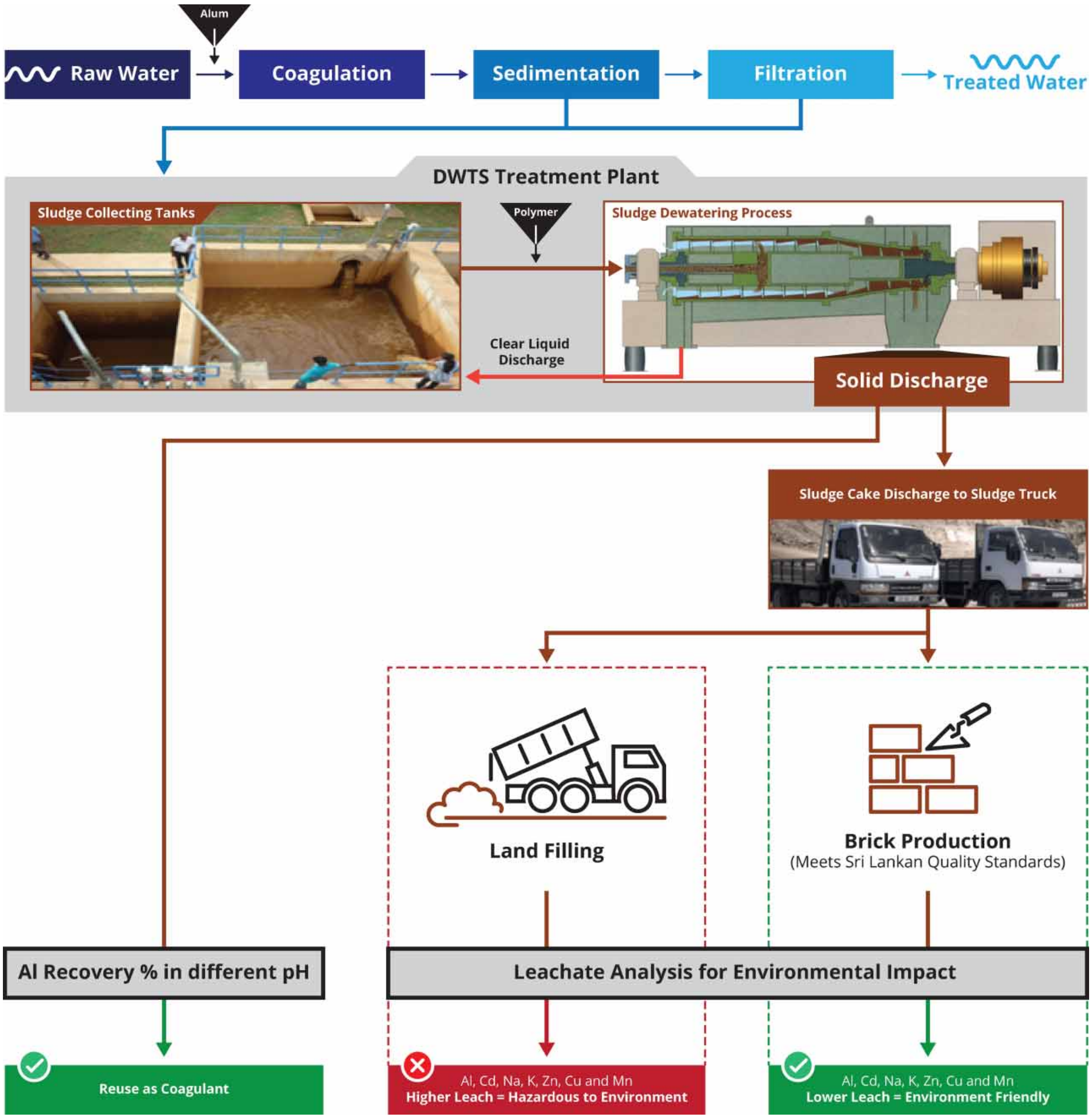
Accumulation of water treatment sludge is a major environment problem in the water purification process. Recovery of waste constituents or reuse of sludge is a cost-effective method in handling this environmental dilemma. The present study investigates the suitability of sludge in the production of bricks and recovery of aluminum from the sludge accumulated at the Biyagama drinking water treatment plant (BDWTP) in Sri Lanka. The chemical parameters of total organic carbon, pH, total nitrogen content, total phosphorous content, heavy metals, and cation exchange capacity in samples were analyzed in different turbidity periods. The aluminum recovery was investigated both by acidic and by alkaline leaching processes. A mixing ratio of 3:1 (clay:water treatment sludge) was found to be suitable for manufacturing bricks having compressive strength, efflorescence, and water absorption parameters according to SLS 39:1979. The metal composition of manufactured bricks was compared with clay and water treatment sludge. The environmental impact of current landfilling was estimated by analyzing the leachate of this sludge for COD, NO_3^-, NO_2^-, PO_4^{3-}, free NH_3, SO_4^{2-}, and metals. The heavy metal leachability of manufactured bricks was also analyzed to establish its suitability as an eco-friendly product.

Key words: aluminum, eco-friendly bricks, heavy metals, water treatment sludge

HIGHLIGHTS

- Disposing sludge is a major environmental problem in the water management process.
- Recovery process of aluminum should be done prior to the sludge treatment process.
- Manufacturing of bricks using sludge is an environmentally benign (green) process.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Large quantities of sludge are generated during the drinking water treatment process, which employs coagulation, sedimentation, and filtration processes for water purification (Chen *et al.* 2010; El-Didamony *et al.* 2014). With the rapid growth of population, the demand for potable water is escalating (Ahmad *et al.* 2016; Lim *et al.* 2016). The major sources of waste are sedimentation basins and filter backwashes. Alum coagulation sludge, which is high in viscous metal hydroxides, comprises large quantities of small particles. These are among the most difficult forms of sludge to handle because of their low settling rate, low permeability to water, and thixotropic characteristics. Contamination of surface water is caused primarily by the discharge of effluents by industries. Industries discharge different pollutants in various concentrations causing a temporal variation in raw water quality. Due to this variation, it is necessary to change the dosing of chemicals, hence creating qualitative and quantitative changes in the composition of water treatment sludge (WTS; Ahmad *et al.* 2017).

Disposal of sludge from water treatment plants has become an important issue of global environmental concern due to problems relating to land and toxicity of such waste components (Nguyen *et al.* 2022). Investigations were conducted to convert sludge into a reusable resource such as fertilizer in agriculture and in brick manufacturing.

Dumping dewatered sludge into landfills is a common practice in many countries and leachate from such dumping can contaminate groundwater (Babatunde & Zhao 2007; Sales *et al.* 2011; Ahmad *et al.* 2017). Acid leaching, base leaching, ion exchange, and membranes are four of the available methods to recover aluminum from sludge (Ooi *et al.* 2018; Hassan Basri *et al.* 2019). Acid leaching is the most preferable method due to the high efficiency and low cost involved in the process. According to previous investigations, the recovery rate of aluminum from sludge was reported between 40 and 100% (Ramadan *et al.* 2008; Rodríguez *et al.* 2010; Ooi *et al.* 2018).

A number of investigations have been conducted in manufacturing bricks incorporating WTS during the last two decades (Babatunde & Zhao 2007; Chiang *et al.* 2009; Cherifi *et al.* 2011; Huang & Wang 2013; Kizinievič *et al.* 2013). However, a negative public opinion has arisen on the occupational health of brick manufacturers and end users, prompting the necessity of investigating the mobility of hazardous chemicals in bricks from sludge. It has been found that either the removal or the fixation of hazardous chemicals into the metrics is the best option to avoid potential health hazards (Huang *et al.* 2005; Chiang *et al.* 2009; Boltakova *et al.* 2017). The removal of hazardous chemicals is not practical and is costly due to the complexity and inhomogeneity between different sludge samples insinuating to rely on suitable fixation strategies to prevent the exposure.

The Biyagama water treatment plant in Sri Lanka purifies 360,000 m^3 of water per day and produces 8 m^3 of WTS daily. Sludge mainly consists of produce during the sedimentation process and filter backwashing, as described in Figure 1. Sludge compilation and handling of WTS is a challenge for the facility and a burden for the environment, prompting this research to investigate alternative strategies to handle WTS. Two suitable green approaches are scrutinized in this investigation, namely, the production of safe bricks and the recovery of aluminum from WTS.

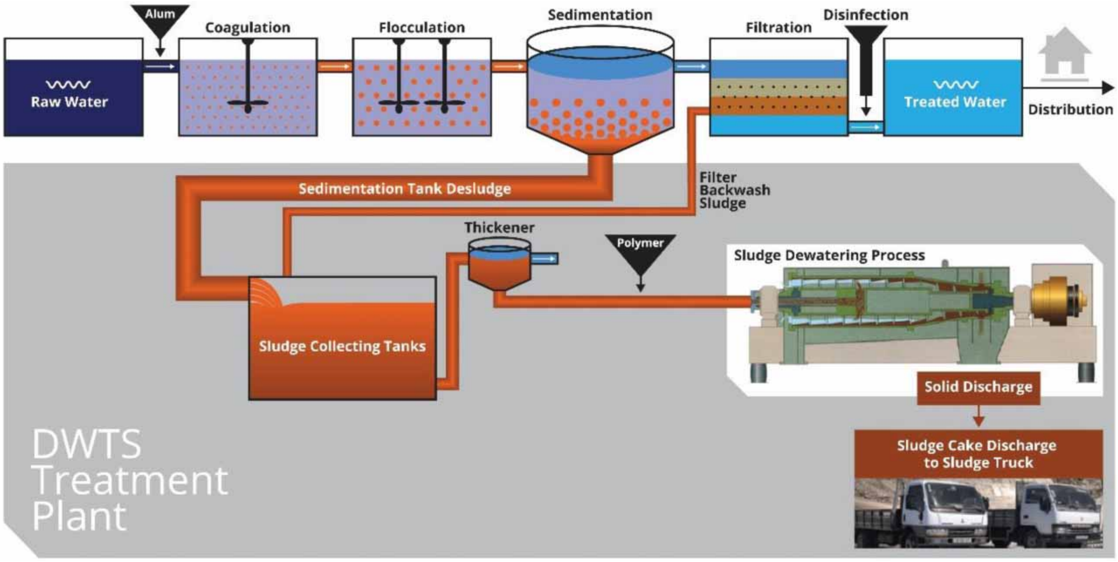


Figure 1 | Process diagram (including the sludge treatment process) of the Biyagama water treatment plant.

2. MATERIALS AND METHODS

2.1. Sample collection

Thirty samples of WTS were collected from the BDWTP during different water turbidity periods and mixed together to obtain a homogeneous sample. Three clay samples were collected randomly from a brick manufacturing site at Kelaniya, Sri Lanka, and used for manufacturing bricks. Fifty bricks were manufactured by mixing collected clay and homogeneous WTS at different ratios. A composite sample was made from a number of discrete samples that were collected from a body of brick material and combined into a single sample to consider this single sample to be a representative of the components of that body material.

2.2. Chemical characteristics of selected soil parameters in WTS

Thirty sludge samples were subjected to the determination of metal ions through a dry ashing method. In this method, about 5.0 g of WTS sample was air-dried, then grounded and passed through a 1 mm stainless-steel sieve, and then stored in a plastic bottle. Before analysis, the samples were dried at 65 °C for 48 h. About 1 g (accuracy 0.01 g) from each sample was weighed and dry-ashed. The samples were digested in an aqua-regia solution for 1 h and filtered through a 0.45 μm filter paper. The filtrate was quantitatively transferred to a 100 mL volumetric flask and topped up by adding distilled water. These solutions were stored in plastic bottles at a temperature of 4 °C till the analysis was completed. The thawed and vortexed samples were tested for As, Al, Fe, Pb, Ni, Cr, and Mn by using atomic absorption spectroscopy (AAS).

2.3. Recovery of alum

Sludge samples were collected and subjected to the alum recovery process, which consists of two main processes, alkaline extraction and acid extraction (Ooi *et al.* 2018). Five sludge samples representing various turbidity conditions were placed on a watch glass and kept for 3 h at 220 °C in an oven. Then, sludge was finely ground.

2.3.1. Solubilization tests in an acidic and basic medium

Approximately 1.0 g of a dry sludge sample was added into each 50 mL of 0.05 M sulfuric acid and the pH was monitored. The suspension was stirred using a magnetic stirring plate for 45 min. The prepared sample was kept overnight and filtered quantitatively using a 55 μm filter paper. The same procedure was followed with a 1.0 M NaOH basic solution.

The filtrate was transferred into a 500 mL volumetric flask and brought to the final volume by using distilled water. Then, the pH of filtrate was measured by using a pH meter and stored in a clean plastic bottle at 4 °C till the completion of the analysis.

2.3.2. Solubilization tests in a distilled water medium

Approximately 5 g of dry sludge was added into 500 mL of distilled water and the above procedure was followed for the suspensions.

2.3.3. Determination of total aluminum using the acid digestion method

Approximately 16 mL of aqua-regia solution was added into 2.5 g of a dry sludge sample and the suspension was stirred for 2 h while heating at 300 °C. The prepared sample was kept overnight and filtered using a 55 μm filter paper, quantitatively transferred into a 500 mL volumetric flask, brought to the final volume by using distilled water, and stored in a clean plastic bottle at 4 °C till the analysis. The Al content was determined according to the HACH DR 2800 Spectrophotometer procedure manual, Method 8012.

The percentage of Al^{3+} recovery was calculated using the following equation:

$$\text{Aluminum recovery (\%)} = \frac{\text{Al in supernatant after acidification/alkalization} \times 100}{\text{Al in raw sludge after acid digestion}}$$

2.4. Brick production, testing, and evaluation of sustainability

2.4.1. On-site manufacturing

WTS was mixed with clay. After thoroughly mixing sludge, clay, and water, the bricks were molded using a steel mold and assembled bricks were stacked in the field for air drying. In dry seasons, 3 or 4 days of air drying is sufficient before burning. Then, these bricks were loaded into the kiln and burnt with wood fire for 12–14 h. Burnt brick was allowed to cool.

2.4.2. Test samples of manufacturing bricks

WTS was mixed with clay in proportions of 25%:75% and 50%:50% by volume. As controls, clay bricks were prepared without using WTS. For each test, 50 bricks were prepared using a mixture of sludge and clay, kept for air drying for 4 days together with normal bricks, and then loaded to the kiln for burning. After cooling and visible inspection for cracking, the bricks were subjected to the testing of dimensions, compressive strength, water absorption, and efflorescence.

2.5. Leachability of WTS

2.5.1. Preparation of water samples

Five dry WTS samples (each weighing 5.0 g) were placed in plastic containers and 250 mL of distilled water was added to each container and placed in a jar tester for 1 and 18 h, respectively, for settling. Then, 100 mL of the supernatant in each sample was withdrawn and a nitric acid digestion method was used. The solutions were stored in plastic bottles at 4 °C till testing. The thawed samples were vortexed and tested for metal ions by using AAS.

Five dry sludge samples of weight 5.0 g were placed in a glass beaker and 250 mL of distilled water was added to each container and placed on a jar tester for 1 and 18 h, respectively, to settle the particles. Then, the supernatant of each sample was pipetted out and stored in clean plastic bottles at 4 °C for the determination of inorganic parameters and COD.

2.5.2. Chemical parameters of leachate

Six different samples were subjected to an analysis of inorganic and COD. Each anionic parameter was analyzed with respect to program numbers at selected wavelengths with different spectrophotometric methods listed in Table 1, and a standard solution series was prepared for each parameter for quantification. The COD value was determined by the open reflux method.

Table 1 | Spectrophotometric conditions for the analysis using HACH DR 2800

No.	Parameter	Method	Range (mg/L)	Wavelength (nm)
01	Sulphate	Sulfa Ver 4	2–70	450
02	Phosphate	Phos Ver 3	0.02–2.5	880
03	Ammonia	Nessler	0.02–2.5	425
04	Nitrate	Cadmium reduction	0.3–30.0	500
05	Nitrite	Diazotization	0.002–0.3	507

2.5.3. Determination of total metals in brick samples and leachate

2.5.3.1. Determination of total metals in brick samples. About 20.0 g of WTS and clay samples that were used for manufacturing bricks and manufactured brick samples were air-dried, then grounded and passed through a 1 mm stainless-steel sieve, and then stored in plastic bottles. Each sample was dried at 65 °C for 48 h prior to the analysis. About 1 g (accuracy 0.01 g) from each sample was weighed in a crucible. Then, the dry ashing method was used (Hseu 2004) and digested in an aqua-regia solution. Then, the solution was filtered through a 0.45 μm filter and quantitatively transferred to a 100 mL volumetric flask. The solution was then stored in plastic bottles at 4 °C. The thawed samples were vortexed and tested for metal ions by using AAS.

2.5.3.2. Determination of total metals in brick suspensions. Three manufactured brick samples were placed in plastic containers and 3 L of distilled water was added to each container and kept 18 h, respectively, for settling. Then, 100 mL of the supernatant in each sample was pipetted out followed by the nitric acid digestion method using analytical grade nitric. During acid digestion, each supernatant was added with 2 mL of concentrated nitric acid and heated in a hot plate at 90–95 °C until the volume reduced to 15–20 mL. Then, the solution was filtered using a 0.45 μm filter and volume up to 100 mL. The solution was stored in plastic bottles at temperatures less than 4 °C till the analysis was completed. The thawed samples were vortexed and tested for metals ions by using AAS.

2.6. Statistical analysis

Thirty water treatment sludge samples were collected during different turbidity seasons in Kelani River. The statistic tool R i386 3.2.1 box-plot analysis, Shapiro-Wilk normality test and non-parametric and parametric test was performed for the data set to determine our data was match with standard values.

3. RESULTS AND DISCUSSION

3.1. Chemical characteristics of clay and waste treatment sludge

The clay samples collected were mainly composed of laterite-based soil and characterized by water-insoluble oxides such as Fe_2O_3, Al_2O_3, SiO_2, and TiO_2. Among them, SiO_2 was the most dominant oxide followed by

Fe_2O_3 and Al_2O_3 (Nayanthika *et al.* 2018). The selected analyzed total metal content in the clay samples is presented in Table 2.

Table 2 | Total metal content in WTS, bricks, and clay in mg/kg

Metal	Total metal content (mg/kg)		
	WTS	Clay	Brick
Mn	728	0	250
K	5	13	19
Fe	5,950	4,024	5,325
Cd	0.03	0.10	0.15
Pb	49,070	119,040	179
Al	167,166	54,114	99,467
Cr	140	329	580
As	233	98	53
Ni	2	2	4

WTS had Mn, Al, and As compared with clay samples, clay was rich in K, Cd, Pb, and Cr compared with WTS, and the bricks formed intermediate levels depending on the mixing composition. Based on the data, it was clear that the recovery of Al prior to the formation of the bricks and the fixing of hazardous metals into the bricks were the best options for the effective use of sludge with minimum effect on the environment.

3.2. Recovery of Alum

According to the scatter plot distribution (Figure 2), the best acidic medium pH range was 1–2 and the maximum amount of aluminum-recovered percentage was 60.4% with a stirring time of 4 h and a settling time of 24 h. The maximum recovery of aluminum at pH of 13 was 87.4% with a stirring time of 90 min and a settling time of 45 min. But according to the summarized data in the basic medium, the maximum extracted recovery percentage was 82.6% with a stirring time of 4 h and a settling time of 24 h.

3.3. Determination of brick quality

After a visible inspection for cracking, no cracks were observed in WTS after it was mixed with clay in proportions of 25%:75% samples. Dimensions, compressive strength, water absorption, and efflorescence were tested in this sample, and the results are given in Table 3. The results of manufactured bricks were compared under the handmade category with the requirement of SLS 39:1979. Except for the parameter of dimensions, all other required parameters complied with all types of constructions under the Type II category. The bricks that were manufactured by using 100% clay were measured under laboratory conditions, and the results of the dimensions were found to be the same as those of WTS that was mixed with clay in proportions of 25%:75% samples. For brick manufacturing, the manufacturer had used a traditional molder and dimension errors existed in the molder.

3.4. Evaluation of the environmental sustainability of manufactured bricks

3.4.1. Leachability of WTS

The leachate capability of 1 kg of WTS was estimated and it contained nitrate (2,150 mg/kg), nitrite (50 mg/kg), sulfate (16,000 mg/kg), phosphate (2,200 mg/kg), ammonia (370 mg/kg), and COD (2,800 mg/kg) (Table 4). Also, a relatively high concentration of heavy metals Pb (0.2 mg/kg), Cd (0.1 mg/kg), Cr (0.9 mg/kg), and Ni (1 mg/kg) were leached into the environment. Micronutrients like Fe (4 mg/kg), Zn (0.5 mg/kg), and Cu (0.1 mg/kg) (Table 4) were also present in the leachate.

The chemical parameters varied with the raw water quality, amount of chemical dosing, and time of retained sludge in the sedimentation tanks such as the percentage of the sedimentation values opening, desludging time,

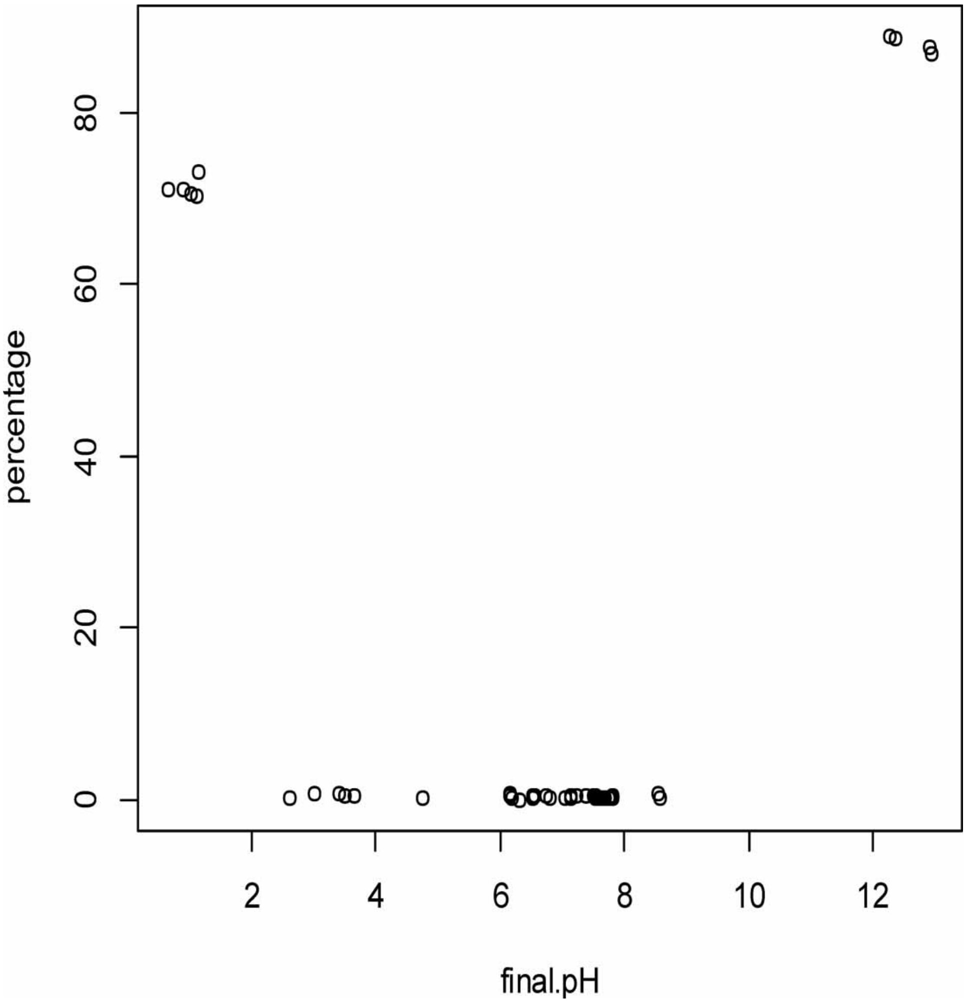


Figure 2 | Impact of final pH on Al recovery.

Table 3 | Comparison test results of manufactured bricks with the requirement of SLS 39:1979

		Type II		
Description	**Type I**	**Grade I**	**Grade II**	**Manufactured bricks**
Method of manufacture	Wire cut machine made	Handmade	Handmade	Handmade
Average compressive strength not less than (N/mm^2)	10	4.8	2.8	5.98
Use in locations	Load-bearing multi-storied	Two-storied constructions	Single-storied constructions	All types of type II category
Maximum water absorption (%)	18	28	28	22.7
Efflorescence	Slight	Moderate	Moderate	Nil
Dimension	–			
Length (mm)		5,280 ± 75 mm		4,896
Breadth (mm)		2,520 ± 40 mm		2,664
Height (mm)		1,560 ± 40 mm		1,296

and frequency (Husillos Rodríguez *et al.* 2011). A significant variation in sulfate concentration was observed in different samples, which varied between 100 (mg L^{-1}) and 600 (mg L^{-1}) due to different levels of alum dosing in various turbidity conditions.

Table 4 | Measured inorganic, organic chemical, and heavy metal parameters of sludge leachate

	NO_3^--N	NO_2^--N	PO_4^{3-}	NH_3-N	SO_4^{2-}	COD	Pb	Cd	Cr	Fe	Zn	Cu	Ni
Sample number	**Mean (mg L^{-1})**												
4	50	0.7	38	7	300	40	0.005	0.003	0.013	0.029	0.006	ND	0.020
15	50	0.1	47	5	100	56	0.001	0.001	0.017	0.038	0.007	0.001	0.017
18	60	0.4	43	9	200	72	0.002	0.002	0.016	0.015	0.012	0.002	0.025
21	30	2.5	49	11	600	48	0.001	0.001	0.019	0.030	0.010	0.004	0.019
26	70	1.2	42	5	400	64	0.013	0.001	0.022	0.285	0.013	0.004	0.020
Average	43	0.98	43.8	7.4	320	56	0.004	0.002	0.017	0.080	0.010	0.003	0.020
Amount leached (mg/kg)	2,150	50	2,200	370	16,000	2,800	0.2	0.1	0.9	4.0	0.5	0.1	1.0

3.4.2. Determination of the leachate of manufactured bricks

The metal content of the leachate samples was determined, and only quantifiable amounts of Pb were found in Sample 1 (0.19 μg/kg) and in Sample 2 (0.32 μg/kg). No leachate was found for Al, Cd, Na, K, Zn, Cu, and Mn.

The mean value of the cation exchange capacity (36.7) represents clay loam grade in soil texture category and can be further categorized into elite type by considering the clay category. The results obtained indicated the presence of various types of metals in varying concentrations and also emphasized that heavy meals were present in the brick samples (Table 2). Pb and As metals were in relatively low percentage when compared with raw materials due to evaporation at high temperatures in the kiln. The metal K was high in the brick samples due to contact with dry ash during the manufacturing process.

The result of manufactured bricks demonstrated that sludge can be used to produce good-quality bricks for various engineering applications in construction and building by fulfilling the SLS 79:2003 standard. Sludge clay burnt bricks can be successfully produced using water treatment plant sludge as a supplement for clay. The proportion of sludge in the mixture was affecting the quality of brick. The heavy metal leachability of manufactured bricks was also analyzed and it was found that more than 99% of heavy metals were fixed in these bricks; therefore, the manufacture of bricks is an environmentally benign process.

4. CONCLUSION

This investigation mainly focused on the recovery of alum and manufacturing bricks. The recovery of the aluminum percentage in WTS was comparatively low due to the effect of polymer. Therefore, the recovery of aluminum must be done prior to the sludge treatment process. Leachate analysis confirmed that 99% of the heavy metals present in the sludge firmly bound to the manufactured bricks. The metal content of the leachate samples was determined, and only quantifiable amounts of Pb were found in Sample 1 (0.19 μg/kg) and in Sample 2 (0.32 μg/kg). No leachate was found for Al, Cd, Na, K, Zn, Cu, and Mn. Therefore, the manufacture of bricks using sludge is an environmentally friendly process.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare that there is no conflict.

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