Granulochemical Characterization and Valorization of Drinking Water Treatment Sludge

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ABSTRACT

Sludge from drinking water treatment plants contains heavy metals and organic micropollutants that may impact the environment and human health. This study characterizes the sludge to support eco-friendly management options. Granulometric and granulochemical analyses were performed to determine its physical, chemical, and pollution characteristics. Major elements (Al, Mg, Ca, Fe, SiO_2, NH_4^+, total nitrogen, and phosphorus) were quantified using a DR 3900 UV-VIS spectrophotometer, while heavy metals and PAHs were measured using ICP-AES and GC-MS. The sludge had an average dryness of 84%. Samples from the Me plant showed high N-P-K levels, indicating potential agricultural or material reuse. Fine sands (0.063–1 mm) and coarse silts (0.043–0.063 mm) were the most contaminated, while coarse sands were the least. Overall contamination fell within range A, reflecting low environmental risk. Brick-making tests with up to 50% sludge met standards for water absorption and compressive strength (>5MPa). These results demonstrate the potential for sustainable sludge recovery in compliance with environmental regulations.

Keywords: Drinking water treatment sludge, Granulochemical characterization, Heavy metals, PAHs, Valorization.

INTRODUCTION

Water is essential to human life and access to it is an important issue for populations. In Ivory Coast, only 61% of the population has access to drinking water, and this shortage also affects the city of Abidjan despite its industrial development. As a result, surface water, an abundant and perennial resource is widely exploited to supply large urban centers[1]. To optimize water production for domestic and industrial uses, the country relies only marginally on groundwater because drilling in basement areas often yields low flow rates[1-3].

The treatment of surface water generates various types of sludge, including hydroxide sludge, decarbonation sludge, lime sludge, and iron-manganese removal sludge. These residues

originate from filtration solids, clarification processes, spent activated carbon, saturated or spent ion-exchange resins, and regeneration solutions. Compared with groundwater treatment residues, sludge from surface water purification is generally of lower quality due to the possible presence of organic pollutants (pesticides, PAHs, PCBs), metals (Al, Fe, Cd, Hg, Cr), and biological agents. These contaminants are ubiquitous in surface waters because of their stability, persistence, and diverse source. Some of these compounds may be essential or acceptable at low concentrations, while others are undesirable, toxic, or dangerous for living organisms. Recent studies confirm that emerging inorganic and organic pollutants occur in surface waters worldwide, often at persistent and bioaccumulative levels[6]. For example, polycyclic aromatic hydrocarbons (PAHs) are classified by the U.S. EPA as probable human carcinogens and mutagenic compounds, notably benzo[a]pyrene and benz[a]anthracene[7,8]. Similarly, exposure to heavy metals can cause severe health effects, including liver and muscle damage, as shown by increased serum enzymes in fish[9-11]. In addition, ingestion of dust from lead-contaminated water-treatment sludge represents a potential risk for young children living near sludge disposal sites[12].

Given these environmental and health concerns, managing sludge derived from surface water treatment is essential for ensuring a sustainable and safe drinking-water supply system. Sludge disposal also poses practical challenges due to the difficulty of its elimination. Several management options exist[13], including landfill, discharge into stormwater networks, agricultural spreading (due to its content in mineral nutrients and organic matter), forestry applications, and use in cement works. However, the suitability of these pathways depends on several factors: the nature and toxicity of the pollutants, their degradability, and the characteristics of the sludge itself (particle size distribution, mineral composition, water content and organic matter content). These parameters can limit its direct use in certain applications.

Several studies have also reported a change in fish protein levels due to an increase in serum alkaline phosphatase, alanine transaminase and creatinine kinase levels due to exposure to heavy metals which leads to significant liver damage and muscle damage[10,11,12]. Thus, the question of managing sludge from surface

water purification seems essential to analyze the complex relationships between health, environmental protection, waste management and to ensure a sustainable approach to the production of drinking water. Moreover, the disposal of sewage sludge also poses a major problem due to the difficulty of its elimination. Several destinations are indicated for its sludge[13]. These include landfills, rainwater networks, agricultural spreading due to their richness in major mineral elements and organic matter, forestry valorization and cement works. A comprehensive physicochemical and environmental characterization is therefore necessary to determine an appropriate management strategy consistent with circular-economy principles and environmental protection. In this context, the present study aims to characterize sludge from surface water purification through granulometric, granulochemical, and mechanical analyses, and to identify potential pathways for its valorization.

MATERIALS AND METHODS

Sludge characterization
Sampling

The sludge sampled is that already dehydrated and stored on the sludge unloading site of the Me water purification plant in Ivory Coast. The choice of the area to be sampled was made in relation to its proximity to the Abidjan metropolitan area. Thus, four (4) samples were taken using a plastic material in the first 20 centimeters of the mud column. At each sampling point, a plastic container with a capacity of 10 L each was filled and identified. These containers were then sent to the institute's laboratory specialized in this type of analysis.

Physical characteristics of sludge
Humidity, dryness and consistency

Sludge is made up of water and dry matter, the percentage of water in the sludge is called moisture content and the mass percentage of dry matter is called dryness. Determination of dryness required weighing ($m = 10$ g) of mud in a cup of empty mass m_0. Then, the sample was placed in an oven at 105°C for 2 hours. After this step, the sample was removed from the oven and placed in a desiccator for 4 hours. After drying, the sample was weighed again to obtain the new mass (m_1).

$$S = \frac{m}{m_{1-m_0}}$$

At the same time, the humidity level will be calculated as follows: H = 100% - S

With H: humidity (%) and S: dryness.

The percentage of VSM (volatile suspended matter) is the part of the dry matter that can easily be biodegradable, hence the existence of microorganisms in this sludge.

VSM (%) = $((m_2-m_3))/m_2$ m2: mass of dry matter at 105°C; m_3: mass of material calcined at 505°C

Quantities of sludge

The following formula was used to estimate the total quantity of sludge produced during drinking water production[10].

With:

B = V. (0.8Al + MES + A)
B: sludge produced (kg/day)
V: volume of treated water (dam³/day)
Al: dose of coagulant $Al_2(SO_4)_3$ (mg/L)
MES: suspended solids in raw water (mg/L)
A: other added reagents (mg/L) (polymer A100, quicklime, activated carbon)

The volume of parameters considered in the quantification of the sludge volume is presented in Table 1.

Table 1: Quantity of sludge estimation parameters

Parameters	Volume (mL)	Concentration used (mg/L)
Dose of coagulant Al_2O_3	2.80	70.0
MES		77.00
A: Other reagents added (mg/L)		
Polymer A100	0.20	0.60
Quicklime	0.83	20.00
Activated carbon	0.16	3.20
Volume of Treated water = 5607.00 m³/h = 137.56 dam³/j		

Granulometry and granulochemistry of sludge

40 L of dry sludge were used to carry out particle size and particle chemistry studies. The particle size analysis was carried out on three of the four containers using a vibrating gyratory sieve with a diameter of 45 cm. The dry sludge was sieved in the presence of water (wet sieving). At the end of this operation, the sludge was separated into eight different particle size fractions, i.e > 4 mm; $2 < x \leq$ 4mm; $1 < x \leq 2$mm; $0.5 < x \leq 1$mm; $0.25 < x \leq 0.5$mm; $0.125 < x \leq 0.25$ mm; $0.063 < x \leq 0.125$ mm; $0.045 < x \leq 0.063$mm. These fractions were obtained using sieves whose mesh width corresponds to the desired particle diameter. Fractions were collected in suitable containers then placed in an oven at 60°C until they were completely dried. They were then weighed to determine the moisture content of each fraction. After sieving, the dried sludge from each container was grouped into three types of sand (coarse sand, fine sand and coarse silt). The three types of sand were taken after sieving for subsequent analyzes allowing an initial granulochemical characterization (determination of the metal content, PAHs).

Chemical characteristic of the sludge
Sample preparation

For the determination of these parameters (Ca, SiO_2, Al and Fe), the procedure for preparing the filtrate consisted on the one hand of grinding 100 g of dry mud contained in each container in a mortar, then sifted through a sieve of 250 μm mesh. On the other hand, 10 g of the sieved sample were introduced into an Erlenmeyer flask, to which 100 mL of distilled water was added. The mixture is kept stirring at 2000 rpm for three minutes, at 26±2°C. The contents of the Erlenmeyer flask were filtered using filter paper over a beaker followed by the dosage according to Dana *et al.,*[14]. The analyzes were carried out on the filtrate obtained.

Dosage of major elements (Ca, SiO_2, Al and Fe)
Assay methods are listed in Table 2.

Table 2: Assay method and necessary reagents

Elements	Analysis mode Reagents	Reagents used
Ca	Spectrophotometry (DR 3900)	Calcium indicator sachet (CalVer 2)
		Potassium Hydroxide
SiO_2	Spectrophotometry (DR 3900)	Molybdate Reagent Réactif
		Citric Acid Reagent
		Amino Acid Reagent
Al	Spectrophotometry (DR 3900)	Reagent for the analysis of Aluminum in sachets (AluVer 3)
Fe	Spectrophotometry (DR 3900)	Reagent for iron analysis in powder sachet (FerroVer)

Nutrient dosage

The filtrate obtained, at the end of the sample preparation, is thus used for the analysis of nitrogen (N), phosphate, potassium (K), magnesium (Mg) and ammonium (NH_4) in the mud.

These elements are determined by the DR3900 spectrophotometer and their Hach barcode are presented in Table 3.

Table 3: Method for determining elements of a fertilizing nature

Elements	Determination method (Hach barcode)
Nitrogen	LCK 138
Phosphate	LCK349
Potassium	LCK 228
Magnesium	LCK 326
Ammonium	LCK 302

Digesting and dosage of metals

Before the ICP-AES analysis, the pre-treated sludge samples (10 g) are mineralized in teflon tubes using 3 mL of hydrofluororic acid (HF) pure concentrated (48%) with the 'Regal water (1/3 HNO3 + 2/3 HCL) according to the MA method. 205-MET/P 1.0 of the Center for Environmental Analysis of Quebec[15]. Chemical analyzes including digestion and ICP-AES analysis were carried out in doubles.

Determination of HAP contents

To extract HAPs, 10 g of unknown mud sample dried in the 60°C oven was used. Then, 25 mL of dichloromethane (CH_2Cl_2) were added to the samples and positioned in an ultra-sound bath for about 25 to 30 minutes. After the addition of the recovery stallion (Pyrene D-10), the extracts were purified by the addition of silica gel mixed with a Benzo (A) Pyrene D-12 solution. Depending on the quantity of added silica gel, a known volume of dichloromethane was added to the mixture, then homogenized for a while. After a short rest time, a volume (V = 3 mL) of supernatant was taken[16]. To this the internal stallion (phenanthrene-d10) before analyzes by gaseous phase chromatography coupled with mass spectrometry (GC-MS). Gas chromatography condition of polyaromatic hydrocarbons analysed was indicated in Table 4.

Table 4: Gas chromatography condition of polyaromatic hydrocarbons

GC	HP6890 Powered with HP chemstation rev. A09.01 software
Column	HP-I
Column Lenght	30 m
Column ID	0.25µm
Column film	0.25µm
Injection Temperature	250.00°C
Detector Temperature	350.00°C
Detector	FID
Initial Temperature	60.00°C
First rate	15.00°C/min for 14.00 min, maintained for 4.00 min
Second rate	10.00°C/min for 5.00 min, maintained for 3.00 min
Mobile phase	Nitrogen
Nitrogen column pressure	30.00 psi
Hydrogen pressure	28.00 psi
Compressed air pressure	32.00 psi

Brick manufacturing with sludge
Materials collection

Materials collected are the dry sludge from drinking water production (collected in the form of aggregates and then crushed to obtain a small grain size and finally sieved) and conventional sand (drainage sand harvested in the sea). Cement was used as a binder in this process.

As part of this study, we have examined the feasibility of replacing conventional sand with sludge from drinking water production in the manufacture of bricks. To do this, the mixture (sand, cement and water) has obeyed the NF DTU 20.1 standard which establishes the rules for the realization of masonry walls of small elements. The different formulations adopted are recorded in Table 5.

Table 5: Formulation of different mixtures

Samples	witness	I	II	III	IV
% sludge	0	25	50	75	100
% sand	100	75	50	25	0

Calculation of the proportion of each element for brick making

To make 1 m³ of mortar: it takes 250 kg of cement, 200 liters of water and 1 m³ of sand.

For 10x14x8 test pieces, the unit volume is 1120 cm³ or 0.00112 m³. Thus, the quantities necessary to make a brick of 10x14x8 cm are determined as follows:

-Ciment: 250 kg* 0.00112 m³/1 m³ = 0.280 kg of cement per brick.

Water: 200 liters *0.00112 m³/ 1 m³ = 0.224 liters (or 224 mL) of water per brick.

Sand: 1 m³ *0.00112 m³/1 m³ = 0.00112 m³ de sand or 1m³ is 1500 kg of sand so it takes 1.68 kg of sand per brick. Thus, to make a brick of dimension 10x14x8 cm, we needed 280 g of cement, 224 mL of water and 1680 g sand.

Pressure and porosity test
Calculation of Water Absorption Rate
The water absorption rate is calculated as follows.

$$Tabs = \frac{P_i - P_s}{P} \times 100$$

Tabs: absorption rate
P_i: weight of the brick after immersion
P_s: weight of the dry brick

Capillary Absorption
Capillary water absorption is essential to estimate the porosity and durability of the construction materials produced. Capillary water absorption was performed according to NF EN 1015-18 standards. The following equation was used to calculate capillary absorption: $Q/A = S\sqrt{t}$

Where Q is the amount of water absorbed (kg) by the specimen, A is the surface (m²) of specimen in contact with water, t is the contact time(s) and S the sorptivity coefficient of specimen ($kg \cdot m^{-2} \cdot s^{-1/2}$).

Mechanical resistance
The resistance test was carried out under compression according to standard NF EN 772-1. This test consisted of determining the maximum compressive pressure that each category of brick could withstand before breaking.

RESULTS

Physical characteristics of sludge
The average dryness being 84% then the deduced humidity rate is 16%. This mud is called solid mud because it has a dryness between 25 and 85% (Table 6).

The percentage of VSM obtained (18.27%) from the sludge shows that it contains microorganisms.

Table 6: Physical characteristic of sludge

Parameters	Values
pH	6.84 ± 0.36
Conductivity (µS/cm)	94.00± 3.60
humidity (%)	16.00± 2.04
dryness (%)	84.00± 3.44
VSM (%)	18.27 ± 2.95

Sludge particle size
Table 7 presents the particle size distribution of the sludge samples collected from the drying bed of the Me water treatment plant. The aim of granulometry is to study the size of the particles in the sludge but also their distribution. The sludge studied is composed of 76.97% coarse sand, 19.74% fine sand and 0.594% coarse silt (Table 7).

Table 7: Sludge particle size

Sludge particle size (mm)	Relative weight (%)	CLASSIFICATION
> 4	34.11	COARSE SAND
2< X < 4	26.93	
1< X < 2	15.93	
0.5 < X < 1	9.65	FINE SAND
0.25<X < 0.5	5.72	
0.125 < X < 0.25	2.66	
0.063 < X < 0.125	1.71	
0.045 < X < 0.063	0.594	COARSE STRINGERS

Chemical characteristic of sludge
Nutrients
The results show that sludge from the Me water purification plant contains nutrients in significant quantities (Table 8). It has within it different minerals that plants need for their development (N-P-K).

Table 8: Concentration of nutrients in sludge

Parameters	Concentration (mg/kgDM)
Nitrogen	3.20 ± 1.21
Phosphate	1.40 ± 0.8
Potassium	4.03 ± 0.94
Magnesium	2.38 ± 0.04
Ammonium	3.10 ± 1.04

Trace elements incorporated during the drinking water process
Table 9 presents concentrations of these elements. The results show a high concentration of silica (13.97 mg/kg.DM) compared to other elements.

Table 9: Trace elements incorporated during the drinking water process

Parameters	Concentration (mg/kg.DM)
Aluminum	6.31 ± 0.12
Calcium	5.04 ± 1.61
Silica	13.97 ± 2.30
Iron	2.29 ± 0.13

Granulochemical characterization of the sludge

Fine sands (0.063<x<1mm) and coarse

silts (0.043<x<0.063mm) are the most contaminated while coarse sands are the least. However, copper, lead and zinc recorded significant values. This trend is also observed regarding PAHs contents. Although these values were obtained, the characterization carried out in the laboratory shows the absence of metal and PAHs contamination in range A when considering the sludge in its entirety (Table 10).

Table 10: Granulochemical characterization

Chemical element (mg/kgDM) /Sludge fraction (mm)	As	Cd	Cr	Cu	Ni	Pb	Hg	Zn	HAP
Coarse sand >1	0.60	0.03	0.03	4.21 ±0.06	0.75±0.11	4.06 ±0.12	0.30	8.44± 0.30	0.01
Fine sand0.063 <X<1	1.34±0.12	0.28±0.01	1.80 ±0.34	5.09 ±0.25	1.7±0.02	3.96±1.02	0.30	9.40±1.52	0.30
Coarse silts 0.043 <X < 0.0632.70 ± 0.60	0.48±0.25	2.53 ±0.21	5.44 ± 0.11	2.07±0.04	7.60±0.82	0.30	12.06±2.02	0.20	
Medium content	2.02	0.38	2.16	4.91	1.50	5.20	-	9.96	0.25
Criteria A17,18	6.00	1,50	85.00	40.00	50.00	50.00	0.20	110.00	< 0.10
Criteria B 17,18	30.00	5.00	250.00	100.00	100.00	500.00	2.00	500.00	--
Criteria C 17,18	50.00	20.00	800.00	500.00	500.00	1000.00	10.00	1500.00	-

Quantification of the mud produced and manufacturing of bricks

Quantification of the sludge produced

The results show an estimated sludge production of 21.569 kg/day, which amounts to an annual production of 7,872.685 kg/year.

Brick manufacturing

Figure 1 present variation of sludge-sand mixtures used for brick-making tests. Samples show different proportions of water treatment sludge and sand: 100% sludge, 75% sludge+25% sand, 50% sludge+50% sand, 25% sludge+75% sand, and 100% sand. These mixtures were tested to evaluate the effect of sludge content on brick properties such as compressive strength and water absorption.

100% Sand

25% sludge + 75% Sand

50% sludge + 50% Sand

100% sludge

75% sludge + 25% Sand
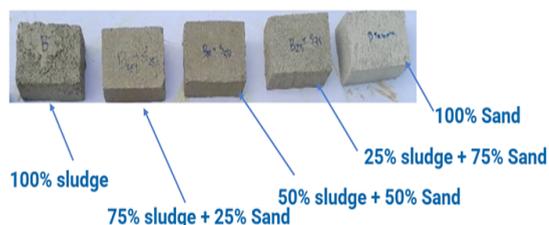
Fig. 1. Variation of sludge-sand mixtures used for brick-making tests

Absorption test

The results show that the higher the sludge content in the brick, the more water it absorbs (Table 11).

The different sorptivity coefficients of the samples deduced from the equation are presented in the table below. They are very low from 50%, which is consistent with the different low heights of the water rising by capillarity on the brick.

Table 11: Brick absorption test and Capillary Absorption height

Sample	Witness	I	II	III	IV
% sludge	0	25	50	75	100
% sand	100	75	50	25	0
Tabs (%)	3.47	8.86	10.12	11.31	11.86
Capillary Absorption (cm)	8.60	5.10	4.20	3.00	2.90
Sorptivity coefficient of the sample	1.45	0.85	0.70	0.50	0.48

Brick resistance

The different samples were compressed using a hydraulic press in order to see at what load each sample could break.

Compressive strength tests (Fig. 2) of each brick show that the mixtures give good results up to 75% mud incorporation. On the other hand, the 100% mud brick was only able to withstand a pressure of 0.925 MPa. The higher the sludge rate in the dosage, the lower the compressive strength (Figure 2).
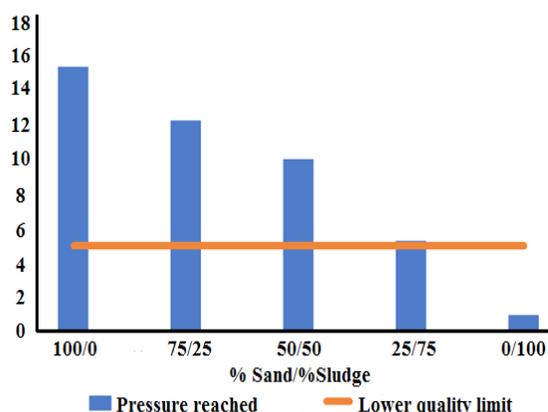
Fig. 2. Results of resistance tests of manufactured bricks

DISCUSSION

Agronomic Valorization

The analyzed sludge contains appreciable amounts of major nutrients, including nitrogen (N), phosphorus (P), and potassium (K), as well as acceptable levels of heavy metals (contents<range A). Consequently, it exhibits good agronomic quality with respect to NPK content[19,20]. Nitrogen is a key element influencing plant productivity, phosphorus contributes to growth, disease resistance, and effective fertilization, and potassium supports flowering, fruit development, and enhances plant resilience to stress. Together, these three nutrients are essential for proper plant development[19].

Several studies have highlighted that wastewater treatment sludge can be significant source of fertilizing elements. For instance, Lyndon *et al.,*[21] reported substantial concentrations of N, P, and K in sludge while remaining within heavy metal thresholds. Research on lettuce demonstrated that sludge application improved nitrogen and phosphorus uptake by plants without exceeding regulatory limits. Specifically, the study by Lyndon *et al.,*[21] in Kumasi indicated nitrogen contents around 4% and phosphorus levels between 2–3% in sewage sludge, confirming its agronomic potential.

Beyond NPK, the sludge contains high levels of ammonium and organic matter, which provide microbial biomass that can be mineralized to meet plant nutrient needs. Magnesium, although a minor fertilizer, plays an important role in photosynthesis and facilitates nutrient transformation, assimilation, and migration. Overall, the results indicate that drinking water sludge is nutrient-rich and can serve as both a fertilizer and a soil amendment.

Additionally, the presence of slaked lime used during water softening raises the pH due to the formation of precipitated carbonates, partly explaining the relatively high calcium content. Calcium and magnesium pass easily through the treatment process because they are poorly flocculated due to the high solubility of their hydroxides. The lime generates an exothermic reaction leading to partial evaporation of water in the sludge, and calcium ions interact with the coarse silt fraction, increasing the sludge dryness (84%). These ions also improve structural stability by agglomerating fine particles. Despite the basic nature of lime, the analyzed sludge shows a neutral pH and a volatile organic matter content of 18%, which makes it unsuitable for backfill purposes.

Heavy-Metal and PAHs Risk

Although the sludge is nutrient-rich, its use raises environmental concerns due to heavy metals. The estimated daily production and cumulative sludge over 15 years (118,090.275 t) could pose pollution risks if not recovered. Burial of this volume would occupy approximately 16 hectares, potentially threatening groundwater due to leaching of PAHs and heavy metals that may bioaccumulate[4,7].

Flocculation-decantation and sand filtration in water treatment can eliminate microflocs of metals complexed or adsorbed on organic matter. However, the sludge analyzed still contains fine silt fractions with high metal content, which could be mobilized into the water table, particularly in acidic conditions. These findings emphasize the importance of controlled reuse strategies to minimize environmental and health risks.

Brick Performance

The sludge analyzed has a high silica (SiO_2) content due to the sand used in filtration, which provides quality raw material for brick manufacturing. Silica indicates the presence of quartz, which acts as a degreaser and increases the fraction of coarse sand (>76%), leading to higher water absorption in earth building bricks. Mixtures of 75/25 and 50/50 construction sand to sludge gave respective absorption rates of 8.86% and 10.12%, compared to 3.47% for control bricks[22,23]. This increase is

attributed to reduced cohesion and larger pore sizes within the bricks.

The sludge contains low-cohesion soil (19.74% fine sand, 0.594% silt), yet the formulations produced good mechanical performance. Conventional solid bricks require mechanical resistance between 5 MPa and 40 MPa depending on use[24]. Since raw earth bricks are less resistant to weather than fired bricks[25], baking the designed bricks at temperatures above 500°C is recommended.

Using sludge in brick or concrete production offers a dual benefit: valorization of sludge while reducing environmental risks associated with disposal. This approach contributes to sustainable waste management and aligns with environmental protection goals.

CONCLUSION

The management of sludge from drinking water treatment represents a significant challenge for preserving the environment and promoting sustainable management. With a view to guaranteeing effective management of this sludge while minimizing their impact on the ecosystem, different approaches have been explored, in particular the valorization of sludge for the production of bricks, their use in agricultural spreading, as well as the possibility of create a landfill.

The results showed that converting sludge into bricks offers a promising solution for reducing waste while creating a useful construction material.

These results will help reduce the number of natural resources taken for the construction of buildings. However, a study aimed at carrying out thermographic and acoustic tests is necessary in order to know these performances. Furthermore, spreading sludge on agricultural land can be beneficial as an organic amendment, given the significant presence of nutrients (NPK). Nevertheless, an experimental study of testing the use of sludge in spreading is recommended to estimate their effectiveness in improving the fertility of agricultural soils.

Given that the composition of Portland cement impacts the environment through CO_2 emissions, other studies are underway to find environmentally protective binders.

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