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Sequence Treatment of Sewage Sludge using Fungal Bioaugmentation and Solidification and Stabilization (S/S) Method for Disposal

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ABSTRACT

Sludge is associated with high concentrations of organic contaminants, unstable and difficult to manage. One of the methods to overcome this is by using the Solidification and Stabilization (S/S) method. However, this method is generally ineffective in treating organic compounds contained in sludge and requires additional treatment. Thus, this study evaluates the performance of the sequence treatment method of bioaugmentation and the S/S method to treat municipal sewage sludge. The fungi strain Aspergillus brasiliensis ATCC© 16404 was used in bioaugmentation treatment while Portland Cement (PC) was used as a binder for the sequence treatment. A series of laboratory tests for different ratios of S/S matrices are conducted which are a compressive strength test and a leaching test (pH, COD, and BOD test). As a result, sample C, with a ratio of 50% sludge and 50% cement, is the best ratio in this sequence treatment due to adequate compressive strength for safe disposal (above 0.35 Mpa) and also generates low COD and BOD levels. Results BOD/COD ratio indicate that all the samples after treatment show high stability. The findings improve the utilization of sludge waste for safe disposal and beneficial use, especially in the production of interlocking bricks. Partnering with manufacturers and waste companies can help integrate this method into existing facilities.

Keywords: Bioaugmentation; interlocking brick; sewage sludge; sequence treatment; solidification and stabilization method

INTRODUCTION

Rapid industrialization and urbanization have raised significant concerns regarding the disposal of sewage sludge, which is classified as hazardous waste under Malaysia's Quality Act 1974. The Department of Environment Malaysia mandates that sewage sludge must be disposed of in prescribed premises, following the Environmental Quality (Schedule Waste) Regulation 2005 (DOE 2021). Raw sewage sludge is predominantly composed of water, estimated at 85-95%, and contains pathogenic microorganisms and toxic pollutants, posing serious health risks to humans and animals (Bratina et al. 2016). Improper treatment can lead to soil and water contamination, resulting in waterborne diseases (Anjum et al. 2016). Therefore, effective stabilization and detoxification of sludge are essential to meet the Environmental Protection Agency's standards for 'class A' solids, allowing for safe disposal or repurposing as biosolids. Notably, treated sludge can be utilized in the production of interlocking bricks, which offer a sustainable option for road construction. Interlocking bricks are engineered to interlock, enhancing the stability and durability of road infrastructure. Research indicates that these bricks improve the structural integrity of masonry walls under lateral forces (Furukawa et al. 2022). Environmental assessments, including leaching studies, have evaluated the long-term safety of using interlocking bricks, such as CN bricks, in road construction (Zhang et al. 2021). This suggests that with careful material selection, interlocking bricks can serve as an environmentally friendly construction alternative.

Current sludge treatment methods, such as anaerobic digestion and landfilling, often struggle with high organic contaminant levels or leachate risks (Remmas et al. 2024). This study addresses these challenges by integrating bioaugmentation with S/S, achieving both contaminant reduction and structural stability, and setting a new standard in sludge management. Bioaugmentation involves enhancing microbial populations by introducing isolated or genetically modified microorganisms to contaminated sites, particularly when indigenous organisms are ineffective at degrading specific organic pollutants (Adams et al. 2015). However, the success of bioaugmentation can be hindered by factors such as low growth rates, insufficient inoculum sizes, and substrate demands. Selecting well-adapted strains is crucial, and in cases where local strains are ineffective, alternative strains from different sites may be employed (Raper et al. 2018). Genetic engineering can also facilitate the replication of strains to form a natural community, enhancing the degradation of pollutants.

The choice of microbial species is vital, as different organisms possess varying abilities to degrade specific compounds. For instance, a study found that the fungus *Aspergillus brasiliensis* degraded phenanthrene (PHE) by 97%, while the bacterium *Pseudomonas putida* achieved only 20% degradation within five days (Hamzah et al. 2018). This highlights the superior tolerance of fungi towards certain pollutants. However, indigenous microbial populations often struggle to degrade complex mixtures, such as petroleum, due to stress from toxic exposure.

Solidification and stabilization (S/S) are two critical processes in managing sludge. Solidification immobilizes contaminants to prevent leaching, while stabilization chemically alters contaminants to reduce their leaching potential. Solidification involves mixing waste, water, and binding agents (e.g., cement, fly ash, asphalt) to create a less permeable solid block (Wang and Zhang, 2020). In contrast, stabilization employs chemically reactive binding agents, such as limewater, to prevent contaminants from leaching into the environment. The S/S method effectively transforms waste into solid blocks, minimizing leachability but does not degrade pollutants. Therefore, integrating bioaugmentation with S/S methods can optimize sludge treatment. Bioaugmentation introduces genetically engineered microorganisms that can accelerate the degradation of organic and toxic chemicals, providing a sustainable approach to mitigate climate change impacts and enhance the removal of contaminants from soil and groundwater (Mawang et al. 2021).

Therefore, this study focuses on one of the alternative sequence treatments for sludge which is the combination of bioaugmentation method and S/S method. The research aims are as follows, (1) To analyse the trend of compressive strength and leaching (BOD, COD, pH) test for different S/S matrices based on sequence treatment. (2) To determine the best ratio of the treatment in terms of the strength and leaching behaviour for disposal as well as the potential for interlocking of road pavement. This work presents evidence that a sequence treatment approach, which involves the use of both bioaugmentation with *Aspergillus brasiliensis* and S/S method using Portland Cement, is highly efficient in reducing contaminants in municipal sewage sludge. Furthermore, this treatment method boosts the potential of the sludge to be reused as a construction material. This not only tackles environmental concerns associated with sludge disposal but also promotes sustainable waste management practices by transforming waste into an economic resource. The integration of bioaugmentation with S/S offers a novel approach by combining biological and physical-chemical processes. Bioaugmentation with *Aspergillus brasiliensis* enhances organic compound degradation, overcoming the limitations of traditional S/S methods. This hybrid approach ensures effective contaminant breakdown and structural stability, providing a unique solution in sludge treatment.

METHODOLOGY

SAMPLE COLLECTION

Two raw materials, sludge and cement, were prepared before starting the experiment. The sludge was collected from a municipal wastewater treatment plant near Kolej Mawar, Universiti Teknologi MARA (UiTM), Shah Alam. The wastewater was produced mainly from domestic activities. A weight of 10 kg of dry sludge was collected using an HDPE plastic bag and was transported to the laboratory. The sludge is stored in sealed plastic bags at room temperature until analysis begins. Portland Cement was used in the S/S method.

PREPARATION OF FUNGI

Aspergillus brasiliensis ATCC® 16404TM (formerly known as *Aspergillus niger*) was used as a bioaugmentation agent in this study which was purchased from Bio Focus Scientific Sdn Bhd, Malaysia (Ismail et al. 2020). The rationale of the strain chosen is due to its availability, which abundance of this species is reported to be found in contaminated soil, and its ability to degrade various types of pollutants (Hamzah et al. 2018). *Aspergillus brasiliensis* ATCC 16404 was revitalized from the lyophilized ampoule, based on instruction provided by the supplier. The lyophilized pallet of *Aspergillus brasiliensis* ATCC 16404 was hydrated using 6 ml sterile distilled water and stirred until suspension formed. Then, the sterile suspension was transferred into a single test tube and was left isolated for at least 2 hours at room temperature. After isolation, a few ml of suspension were dropped onto potato dextrose agar (PDA) and spread to form spores. Normally, the spores will be visible after 2 to 3 days of incubation time at 20°C (Ismail et al. 2020). Next, 10 ml saline solution was poured over an *A. brasilensis* plate, L-shaped spreader was used to lift off the spores. 1 ml fungal spore suspension was spread on Difco Potato Dextrose Agar (PDA; OXOID) plate evenly for mould regrowth, followed by 3 days incubation at 28°C to promote mycelium growth and extension for 3 days for sporulation. After 7 days, the fungal spore was transferred to sterilized distilled water to start experimental work. Prior to that, the suspension was adjusted to an absorbance within 0.9 to 1.0 at $OD_{600,}$ which resulted in 5×10^6–1×10^7 spore/ml (Ismail et al. 2020; Hamzah et al. 2020).

THE SEQUENCE TREATMENT

A sequence treatment method was used, and the sewage sludge was treated for 7 days using the bioaugmentation method, followed by the S/S method. Briefly, the sludge was treated with fungal suspension (10% v/w) and aerated manually for 7 days before the treated sludge was mixed with cement according to the mixing ratios as shown in Figure 1. Three major steps are involved in preparing S/S matrices: mixing, casting, and curing as shown in Figure 2. Meanwhile, the sequence method was conducted by mixing treated sludge with Portland cement. Prior to the mixing step, a mixing ratio was prepared as shown in Table 1. The samples underwent 5 minutes of mixing before casting. In the casting process, the samples were transferred into 150x150x150mm cube mold with 3 layers of manual compaction (50 blows). Lastly, the curing process is necessary to enhance the strength development and durability of the S/S matrices. The samples were cured at controlled temperature and humidity for 14 days, 28 days, and 60 days in distilled water. Cement without sludge was prepared to act as a control. All samples were prepared in triplicate to ensure repeatability and reliability.

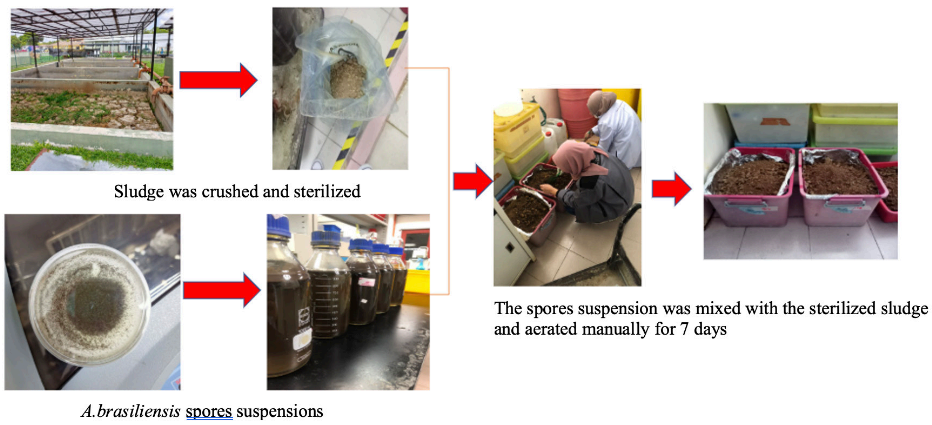

FIGURE 1. Biougmentation process before S/S method was carried out

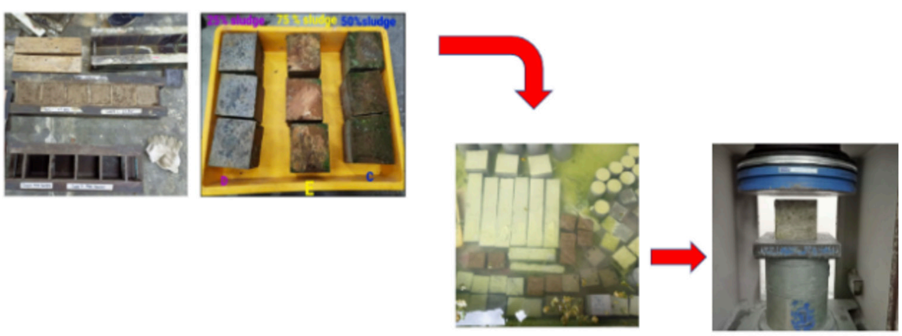

FIGURE 2. S/S method for different ratios of Portland cement and sludge starting with mixing, casting, curing and compression test

TABLE 1. Mixture's Ratio in S/S matrices

Sample	Raw sludge (%)	Treated sludge (bioaugmentation) (%)	Portland cement (%)	Water content (g)	Sample weight (g)
A (control)	-	-	100	0.45	250
B (control)	-	100	-	0.45	250
C	-	50	50	0.45	250
D	-	25	75	0.45	250
E	-	75	25	0.45	250
F(control)	100	-	-	0.45	250

COMPRESSIVE STRENGTH TEST

After the curing process, the compressive strength of the samples was measured according to ASTM C67M21. The compressive strength was measured using a compressive testing machine and determined by dividing the maximum load at failure by the sample cross-sectional area. For analysis, USEPA 1968 recommended that the S/S cube have a minimum strength of 0.35 Mpa for the method to be successful and safe to dispose of in landfills, indicating whether bonding is sufficient. This value justifies that the treated waste should have at least as much strength as the soil surrounding the disposal location if this minimal value is met (USEPA, 1989). In extend, the results obtained can be used to estimate the minimum requirement for the application of treated sludge as road pavement materials alternative following standard (BS 56281:1992 Code of practice for the use of masonry – Part 1: Structural use of unreinforced masonry) (Institution BS, 1992).

LEACHABILITY TEST

A leachability test was conducted to measure the leachability of the S/S matrices. This test was conducted on 14, 28, and 60 days following the curing period. The sample sludge cubes were crushed to a maximum size of 9.5 mm following the standard method. To stimulate the earlier leaching stage, the mixture of crushed samples and leachate with a ratio of 1:10 was used based on the European leaching protocol (EN British Standard, 2002). The bottles were agitated at 30 rpm within 18 hours. Then, 7 µm fibre filters were used to extract leachate and to be stored in a cold room. This leachate extraction was used for COD, BOD, and pH tests. A Chemical Oxygen Demand (COD) test was conducted using Spectrophotometer DR600 equipment. The value represents the total oxygen used in water to oxidize pollutants. The Standard Method based on EPA600/479020, USEPA Method 410.1 was used in conducting this test. The Biological Oxygen Demand (BOD_5) test was conducted based on The Standard Method BOD5 APHA 5210 with a condition of 5 days, incubated in the dark at 20°C temperature. The pH test was conducted using a pH meter according to The Standard Method 4500H+ Braid and Bridgewater, 2017).

STATISTICAL ANALYSIS

Statistical analysis was performed using a two-way ANOVA without replication to evaluate the significance of the effects of sample composition and curing time on compressive strength, BOD, COD, pH, and COD:BOD ratio. The analysis was conducted at a significance level of $P<0.05$, indicating that differences were considered statistically significant if the p-value was less than 0.05. This method was chosen to assess the interaction between the two independent variables (sample composition and curing time) and their individual effects on the dependent variables.

Uncertainty in compressive strength and leachability results was addressed through reporting standard deviations. Potential sources of variability, such as binder homogeneity and curing conditions, were minimized through rigorous experimental controls.

RESULTS AND DISCUSSION

THE COMPRESSION STRENGTH

The strength for different samples based on specified S/S matrices was tested after the 14th, 28th and 60th days of curing using a compressive strength testing machine. Figure 3 summarizes the results for compressive strength tests in the 14th, 28th and 60th days of curing. A minimum strength of 0.35 Mpa is advised to determine whether bonding is sufficient. If this minimal value is met, the treated sludge should have at least as much strength as the soil surrounding the disposal location (USEPA, 1989).

Based on Figure 3, all samples recorded an increasing trend of compressive strength as the curing duration increased. Sample A (100% cement) yields the highest compressive strength (37.14 MPa) on the 60th day of curing.

Meanwhile, sample D cement yields the highest compressive strength (19.62 Mpa) among the sequence treatment samples. This might be related to the S/S matrices ratio, as sample D contains the least treated sludge content (25%) compared to the amount of treated sludge in samples B (100%), C (50%) and E (75%).

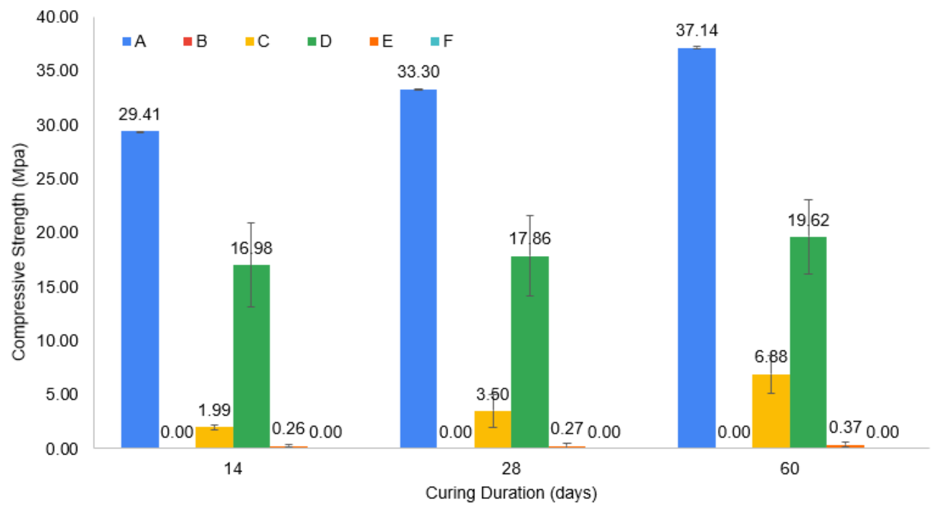

FIGURE 3. Comparative Compressive Strength of the S/S matrices in the 14th, 28th and 60th days. The compressive strength for Sample A (100% Portland cement) shows the highest while the sequence treatment (Sample C, D, and E), sufficiently complies with the minimum strength for disposal (0.35 Mpa) according to USEPA (1989). Error bars show a standard deviation for a triplicate sample

Besides, this might be due to the presence of less sludge in sample D, which functions as a replacement for sand, which is usually used in ordinary concrete bricks and helps increase the strength of the cube. Based on the study by Bu et al. (2017), increasing the portion of sand in the cement mortar strength to be within the right amount can help increase the strength of the mortar. Meanwhile, Sample E failed to achieve 0.35 Mpa on the 14th and 28th day of curing, which is the minimum requirement for safe disposal of sludge based on USEPA, (1989), but barely passed the requirement with 0.37 Mpa on the 60th day of curing. Several reasons can be related to this statement. Firstly, it might be due to the increasing organic matter in the sludge, which resulted from fungi addition during the bioaugmentation treatment and consequently retarding the hydration of the cement and delaying the solidification of the sample. Next, the organic matter in the sewage sludge is prone to shrinkage when it is dry, which leaves more air space in the specimen. Therefore, the specimen becomes porous, reducing the cube strength (Yang et al. 2022; Acarturk et al. 2024). The high water content in the sludge also significantly reduces the strength due to the air void formation as the water dries during the curing process (Thukkaram and Kumar 2024).

Therefore, it can be concluded that sample D (75% cement and 25% treated sludge) is suitable for generating high-strength brick compared to the other ratio. But in terms of economic purposes, sample C may be the best ratio to be adopted in the sequence treatment as it not only uses lesser Portland Cement and increases the use of sludge as a sustainable source but is also able to yield adequate compressive strength for safe disposal purposes at early as 14th day of curing period (1.99 Mpa). These findings also have proven that municipal sewage sludge (sample C) can become a substitution for sand in concrete mixture and has high potential to be developed as a sustainable interlock used for road pavement in the future with 6.88 Mpa at the 60th day of curing. This finding complies with a minimum compressive strength for interlocking bricks according to the standard BS 56281:1992 Code of Practice for Use of masonry– Part 1: Structural use of unreinforced masonry (Institution BS, 1992). This finding was aligned with Ribeiro et al. (2024) who found that the additional 50% water treatment plant sludge into soil-cement mixtures resulted in compression strength within the range of 2.5 to 9.3 MPa. Our findings also align with studies showing that material composition significantly affects brick properties. Previous research highlights that natural fibre and SFW additions can improve or reduce compressive strength and density, respectively (Suraya Hani et al. 2024; Yusof et al. 2024). These findings emphasize the importance of balancing material content to optimize the strength and durability of interlocking bricks.

The integration of bioaugmentation with the S/S method for sewage sludge treatment and interlocking brick production faces several challenges for industrial-scale applications. Variability in sludge composition may require adjustments to the process, increasing complexity and cost. Regulatory compliance and public perception may also pose challenges due to concerns over residual contaminants. Scaling up will require process optimization, economic feasibility studies, and efficient, automated systems to ensure commercial viability.

THE LEACHABILITY TEST

THE COD REMOVAL

Figure 4 illustrates the comparative COD level of different S/S matrices in the 14th, 28th and 60th days. Based on the figure, sample F (untreated sludge) recorded the highest COD level (758 mg/L), which can represent a control sample for the bioaugmentation method. The high COD reading shows that the raw sludge contains high organic and inorganic contaminants, requiring high oxygen levels to oxidize chemically.

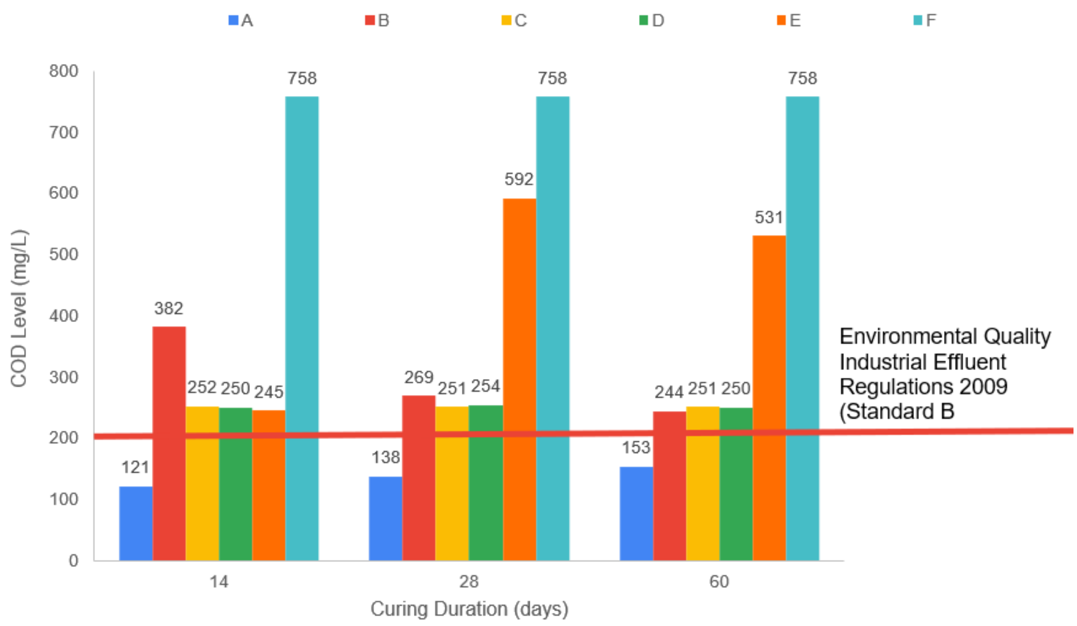

FIGURE 4. The concentration of COD in leachate from the leaching test of the bricks on the 14th, 28th and 60th day of curing. The red line shows the acceptable concentration level of COD in effluent according to the Environmental Quality Industrial Effluent Regulation 2009 (Standard B) (DOE, 2021).

On the 14th day of curing, all four treated sludge samples (sample B, C, D and E) showed a major reduction of COD level by almost 50% reduction when compared to the COD concentration in Sample F. Sample B was able to reduce almost 50% of COD concentration (382 mg/L) at the 14th day when compared with sample F. This proves that the bioaugmentation method individually is effective in degrading organic contaminant in the sludge. However, the COD level in sample B was slightly higher than in other treated samples (C, D, E). This might be due to the high content of sludge, which indicates a greater amount of oxidizable organic and non-oxidizable inorganic material in the sample. On the 28th day of curing, the reduction of COD concentration for samples B, C, and D managed to achieve a COD reduction beyond 50%, but sample E unexpectedly recorded an increase in COD level compared with sample E on day 14.

The finding aligns with Adams *et al.* (2015), which emphasizes that microbial activity is directly affected by the number of contaminants in the waste and temperature. The present microbial may be toxically affected due to a high number of contaminants in the waste, while induction of microbial degradation enzymes may terminate in a low number of contaminants. Meanwhile, on day 60, the COD concentration of sample E started to decrease slightly, which might be due to less organic matter leaching from the sample after a certain period of curing. Heidarzadeh et al. (2021) discovered that a prolonged curing duration can improve the stability of the sample and decrease the leaching of organic matter.

Overall, it is identified that sample B results in the lowest COD level and the highest percentage of COD reduction after 60 days, which indicates a high degradation rate of contaminant by the fungi and proves that bioaugmentation is a great method in reducing COD levels, especially the organic matter. Furthermore, fungi bioaugmentation was found to be least effective on the sequence treatment using sample E (75% treated sludge: 25% cement) as the COD and BOD concentrations were increased with the longer duration of curing.

The further treatment of the S/S method used in samples C, D and E also helps in decreasing the trend of COD level over time. The S/S method is not designed to remove the contaminant, instead, it is immobilizing and traps the contaminants by binding them into a less permeable solid block and helps to reduce the leachability of the contaminants in sludge. This shows that the S/S method successfully reduces the leaching ability by transforming the sludge into less permeable material towards water. Therefore, sample C is considered as the best mixing ratio (for COD reduction) after compared to sample D, although both recorded low and almost similar COD levels after treatment, Sample C utilized more sludge compared to sample D. Unfortunately, all the samples recorded were beyond the acceptable level based on the Environmental Quality Industrial Effluent Regulations 2009 (Standard B) (DOE, 2021) which conclude that the sequence treatment was less effective to hold the inorganic matter. Therefore, it was suggested that self-curing agents such as artificial lightweight aggregate (LWA), porous superfine powders, superabsorbent polymers (SAP), polyethylene glycol (PEG), natural fibres, and artificial normal weight aggregate (ANWA) are required to overcome the mobilization of inorganic pollutants (Hamzah et al. 2022).

THE BOD REMOVAL

Meanwhile, in Figure 5, the BOD level of sample F (raw sludge) was recorded to be 30 mg/L which acts as a control. On 14 days of curing, sample C recorded the lowest BOD level (0.52 mg/L) and the highest BOD level was dominated by sample E (63.93 mg/L).

The same pattern continues during day 28 while on day 60 of curing, sample D recorded the lowest BOD level among others. This might be because sample D contains the least amount of sludge compared to another sample. From day 14 to day 60, it was observed that sample E unexpectedly recorded a higher BOD level than sample F (raw sludge). Factors such as the presence of pathogenic bacteria and increased quantities of biodegradable organic components in the treated sludge.

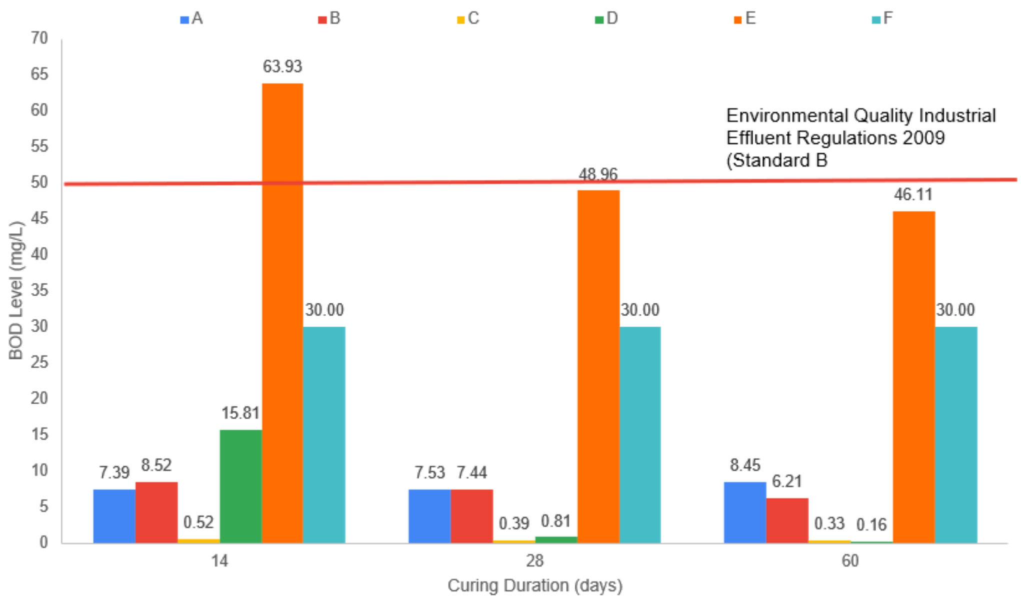

FIGURE 5. Concentration of BOD in leachate from leaching test of the bricks on the 14th, 28th and 60th day of curing. The red line shows the acceptable concentration level of BOD in effluent according to the Environmental Quality Industrial Effluent Regulation 2009 (Standard B) (DOE, 2021).

Muter et al. (2022) found that the proportion of *Salmonella enterica* and *Escherichia coli* was higher in treated sludges than in raw sludge. The rise in pathogenic bacteria may potentially contribute to the release of organic materials, resulting in elevated levels of biochemical oxygen demand (BOD) in the treated sludge. In addition, Pilli et al. (2020) observed a substantial rise in the Soluble Chemical Oxygen Demand (SCOD) of sludge following treatment, as compared to untreated sludge in its raw state. The increase in soluble chemical oxygen demand (SCOD) suggests a greater presence of easily degradable organic molecules in the processed sludge, potentially leading to an elevated biochemical oxygen demand (BOD) release.

Therefore, the sequence treatment can decrease BOD levels over time, showing positive reactions by fungi in degrading pollutants with different rates according to the ratio used. Considering samples from day 60 as the final indicator of BOD level, all investigated samples (B, C, D, and E) passed the permissible limit as the BOD level, which is below 50 mg/L according to the Environmental Quality Industrial Effluent Regulations 2009 (Standard B) (DOE, 2021). Therefore, the sequence treatment of bioaugmentation and S/S method is considered successful in reducing the BOD level with sample C, which is considered the best ratio to be adopted in reducing BOD content using this treatment method.

THE STABILITY OF LEACHATE

The BOD to COD ratio is a measurement used to describe the organic composition of leachate and can be used as an indicator to evaluate the level of pollution in rivers and landfills (Lee and Nikraz, 2014). It is also used as an indicator of degradation of organic matter in landfills. It can be interpreted that a higher BOD/COD ratio indicates high biodegradability or a high amount of organic matter in leachate that needs to be degraded and vice versa. Andrio et al. (2019) emphasize that a BOD/COD ratio above 0.5 indicates high biodegradability of leachate and pretreatment is not necessary (to remove inorganic compounds). The BOD/COD ratio will decrease parallel to the ageing of the landfill. It is also believed that the lower the BOD/COD ratio, the more stable the waste is which leads to the stability of leachate (Ilmasari and Yuzir, 2022).

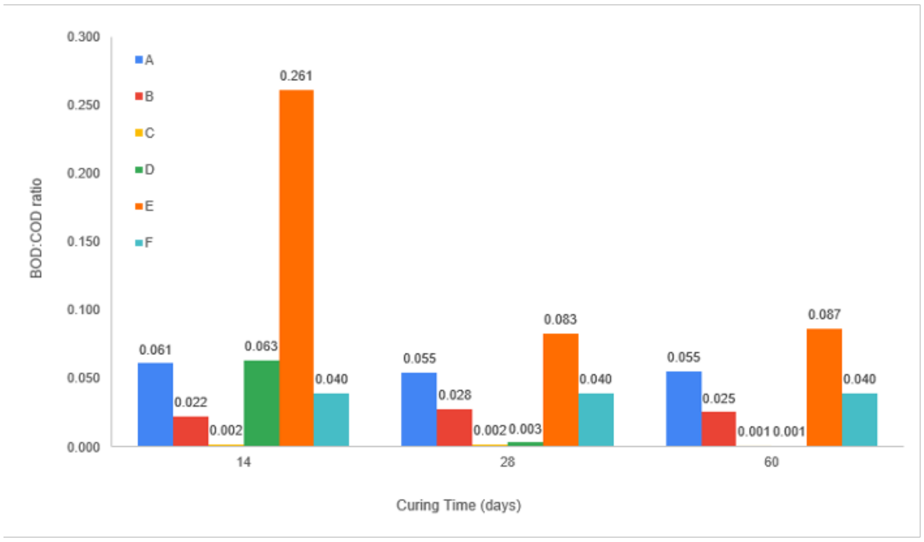

FIGURE 6. Comparative BOD/COD ratio of the treated sludge S/S matrices in 14, 28, and 60 days shows that the sequence treatment (Sample C, D and E) becomes more stable after 28 days of curing period.

Figure 6 illustrates the correlation of the BOD/COD ratio over curing time with samples A, B and F acting as control samples. Briefly, Sample C shows high stability as early as 14 days of curing compared to Sample D and E which started with a high ratio before rapidly decreasing after day 14 with 98% and 67% reduction respectively. It is observed that all the samples recorded a BOD/COD ratio below 0.1 after 60 days of curing. The finding was aligned with Abuabdou et al. (2021) which found that the BOD to COD ratio of 0.074 suggests that leachate samples are highly stabilized. This low ratio implies that the organic contaminants in the leachate are predominantly composed of complex, recalcitrant molecules that are not easily broken down by microbial action, posing challenges for biological treatment processes. Therefore, further pretreatment is recommended to transform the complex structure of the leachate into a simpler form and easily degraded by bacteria (Andrio et al. 2019). Besides, the BOD/COD ratio of all investigated samples approaches 0 and decreases over the curing durations which ties in with a previous study (Ilmasari and Yuzir, 2022). This indicates that the sludge is becoming more stabilized and releasing less organic pollutants to the environment.

PH MONITORING

Figure 7 shows the comparative pH level of the S/S matrices in 14, 28, and 60 days. pH value for sample F (untreated sludge) was recorded at 7.8, categorized as a base. It is observed that the samples (C, D and E) for the hybrid method all recorded a pH between 11 to 13 except for sample E on day 28, with a pH of 6.9. pH range between 11 to 13 is common in hardened concrete cubes as can be seen in sample A due to calcium hydroxide, produced during the cement hydration process. This result ties well with previous studies from Dash et al. (2014), where this method may cause the pH value to reach over 12.5. The alkalinity condition promotes the neutralization and degradation of organic compounds. Furthermore, this condition also significantly neutralizes the microorganism content (coliforms, aerobes, and Enterobacteriaceae) (Rađenović et al. 2019). This reinforces the reason for the high reduction of COD and BOD levels previously.

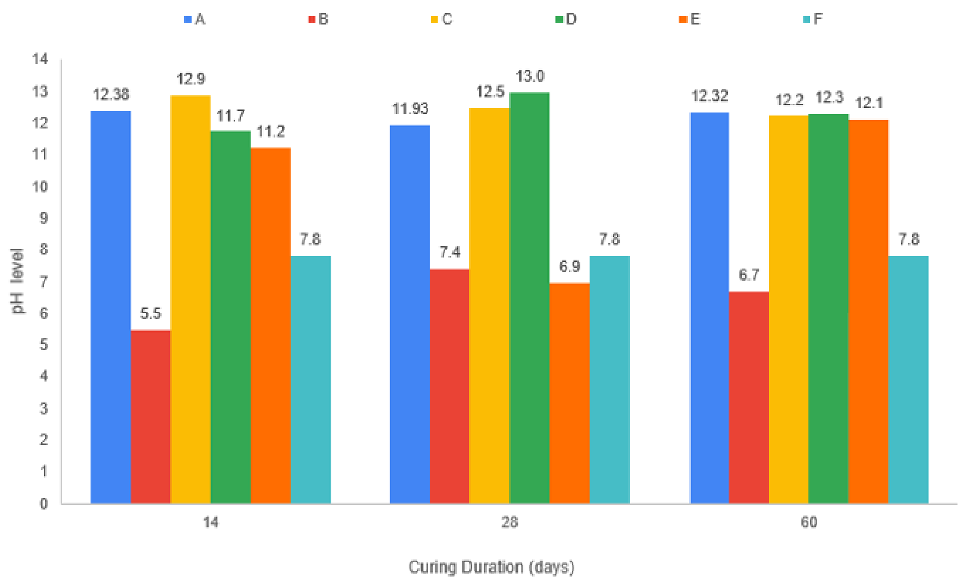

FIGURE 7. Trends of pH in leachate test which sample B (100 % treated sludge) shows the acceptable pH of 6.7 according to the Environmental Quality Industrial Effluent Regulations 2009 (Standard B) (DOE 2021).

Meanwhile, sample B, which represents the effect of pH due to the bioaugmentation method also recorded a pH of 5.5, pH of 7.4, and pH 6.7 on day 14, day 28, and day 60 respectively. These results explain further why BOD and COD reduction is high in sample B as presented in the subsection of the BOD and COD removal. Furthermore, these results align with a previous study whereby a study emphasizes that the optimum condition for the growth of fungi species (*A. brasiliensis*) is pH 6.5 at 33 °C temperature (Hamzah et al. 2020). Lastly, it is found that only sample B is within the acceptable range acceptable range (pH 6.7), while the other samples of hybrid treatment (samples C, D, and E) were not within the permissible limit (5.5 to 9.0) as outlined by the Environmental Quality Industrial Effluent Regulations 2009 (Standard B) (DOE, 2021). Therefore, Sample B proved that the bioaugmentation method succeeded in producing a safe pH level for disposal into the environment. Meanwhile, further treatment using the S/S method is not effective as it results in undesirable and high pH values due to the hydration of cement occurring to harden the sludge. Fortunately, the high pH level can be reduced with the use of additives such as the combination of MSWI ash bottom and gypsum (Chen et al. 2019: Takao et al. 2024).

STATISTICAL ANALYSIS FOR ALL PARAMETERS

Based on the ANOVA analysis, the compressive strength, BOD, COD, pH, and COD:BOD ratio of all samples were found to be significantly different ($P < 0.05$) across the various sample compositions, indicating that the sludge-to-cement ratio significantly influences the physical and chemical properties of the S/S matrices. However, no significant differences ($P > 0.05$) were observed across the curing times (14, 28, and 60 days), suggesting that the stabilization effects and structural integrity of the samples are achieved within the initial 14 days of curing. This indicates that the sequence treatment method is effective in rapidly stabilizing and solidifying the sludge, reducing the required curing period for optimal performance. These findings highlight the potential of this method for practical applications, offering a time-efficient and cost-effective solution for sludge treatment and reuse in construction.

The findings of this study have significant real-world applications, particularly in the production of interlocking bricks, which can contribute to sustainable construction by utilizing treated sewage sludge as a raw material. This approach not only addresses the challenge of sludge disposal but also offers a practical solution for reducing the environmental footprint of construction materials. The findings can be adapted for regions with varying sludge characteristics or environmental conditions by optimizing the sludge-to-cement ratios and adjusting the bioaugmentation process to suit local wastewater profiles. Additionally, the study aligns with regulatory standards such as the USEPA, (1989), and Environmental Quality Industrial Effluent Regulations 2009 (Standard B) (DOE, 2021), as well as supporting the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 9 (Industry, Innovation, and Infrastructure).

Future research could explore alternative binders, the scalability of the process, and the long-term durability of the interlocking bricks produced. The findings contribute to sustainability by reducing waste through the beneficial reuse of sludge and offering a more eco-friendly alternative to conventional construction materials. To scale this approach for commercial use, further studies are needed on cost-effectiveness, energy efficiency, and the integration of this method into existing industrial processes, ensuring its viability for widespread application.

CONCLUSION

The study demonstrates the efficacy of the sequence treatment method in enhancing compressive strength and reducing contaminants in sewage sludge. Sample C, characterised by a 50% sludge-to-cement ratio, proved to be the most effective mixture, attaining sufficient compressive strength for compliant landfill disposal according to USEPA standards. This formulation utilises reduced amounts of Portland Cement and increased sludge, thereby presenting a more sustainable alternative. Sample C exhibited the most significant decrease in COD and BOD levels; however, it failed to achieve the required pH levels, which can be rectified through the addition of additives. The findings are significant as they illustrate the potential for broad application of this sequence treatment method in sustainable sludge management, offering an environmentally friendly approach to waste disposal and resource recovery that can be adapted globally with minimal adjustments for local conditions. The low BOD/COD ratio observed in all samples signifies effective stabilisation and containment of organic contaminants, thereby ensuring long-term leachate stability. This finding suggests that the method is a viable solution for large-scale applications in sludge management and the production of construction materials.

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DECLARATION OF COMPETING INTEREST

None.

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