# Utilizing Industrial Waste for the Microbiological Decontamination of Sewage Sludge

**Malika Khelladi**
Faculty of Science and Technology, University Abdelhamid Ibn-Badis of Mostaganem, Mostaganem, Algeria
malika.khelladi@univ-mosta.dz (corresponding author)

**Meriem Abaidia**
Faculty of Chemistry, Chemical Engineering Department, University of Science and Technology of Oran, Oran, Algeria
meriem.abaidia@univ-usto.dz

**Abdelkader Debab**
Laboratory of Process and Environmental Engineering, Faculty of Chemistry, Chemical Engineering Department, University of Science and Technology of Oran, Oran, Algeria
abdelkader.debab@univ-usto.dz

*Received: 19 April 2025 | Revised: 26 May 2025 | Accepted: 1 June 2025*

*DOI: https://doi.org/10.48084/etasr.11593*

## ABSTRACT

**Sewage sludge (SS) disposal methods are increasingly used in sustainable applications, such as land reclamation for forestry and agriculture, which are recognized as effective strategies for nutrient recovery from the sludge. However, SS typically contains high levels of pathogenic microorganisms and chemical pollutants, necessitating appropriate treatment before reuse. Alkaline treatment is widely employed to reduce pathogenic content and improve the safety of SS for agricultural applications. In this context, the present study investigates the valorization of Filter Cake (FC), a byproduct of brown sugar refining primarily composed of calcium oxide (CaO), as a chemical conditioning aid in the dehydration and sanitization of digested SS. The objective was to explore the feasibility of converting digested SS and FC into value-added products in alignment with circular economy principles. The effect of FC as a drying adjuvant and disinfecting agent was evaluated by adding it to dehydrated SS at proportions of 0.10, 0.15, and 0.20 $g_{FC}/g_{DS}$ (grams of FC over grams of dry solid content). The FC addition resulted in increased pH levels and a significant reduction in microbiological contamination. During the thermal drying of the dehydrated SS, FC has a further positive impact on reducing pathogens to below regulatory limits and drying time. The optimal drying conditions for reducing dehydrated SS moisture content (up to 12%), minimizing drying time, and reducing microbiological contamination levels below the legal limit were 70 °C and 0.20 $g_{FC}/g_{DS}$. Overall, the current study confirms the beneficial role of FC in improving the drying and disinfection performance of dehydrated SS. These findings support the potential of producing a safer and more sustainable organic soil amendment, thereby contributing to resource recovery and environmental protection.**

***Keywords-chemical conditioning; circular economy; filter cake; pathogens; sewage sludge***

## I. INTRODUCTION

The growth in population and human activity is accompanied by an increase in water consumption, leading to the discharge of greater volumes of wastewater, which must undergo several treatment processes to comply with the standards regarding discharge into the natural environment [1]. The SS produced during primary and secondary treatment undergoes several treatment processes, such as thickening, Anaerobic Digestion (AD), conditioning, and dewatering, before disposal [2]. Digested and dehydrated SS consists mainly of water, suspended solids, a range of harmful substances (heavy metals, organic pollutants, and pathogens), and important components for agronomic applications (e.g., organic carbon, phosphorus, and nitrogen) [3, 4].

A growing research interest has been observed in effective methods for utilizing dewatered SS from Wastewater Treatment Plants (WWTPs), as well as treated wastewater, in combination with environmental protection [5-10]. The need to implement a sustainable SS management strategy has become a major concern, due to the restriction and in some cases legal prohibition of conventional recycling options, such as direct use in agriculture [11-13]. Against this backdrop, agricultural reclamation and energy recovery have emerged as the two most promising and sustainable SS management strategies [14, 15]. AD is a well-known and proven technology, commonly deployed to recover energy from organic waste and reduce pathogens in digesters under 35 ± 2 °C or 55 ± 2 °C conditions. with long Sludge Retention Times (SRT) (20-30 days) [16, 17]. It can also reduce SS volume by 50–60%, thus lowering storage and transportation costs [18]. However, due to the low biodegradability of thickened SS, only 30–40% of its Organic Matter (OM) is degraded under mesophilic conditions [18-22]. Nevertheless, the biogas produced during AD is mainly composed of methane (65%) and carbon dioxide (around 35%) [23, 24].

In Algeria, most WWTPs are based on activated sludge processes. The SS produced is mechanically dewatered after thickening and chemical conditioning. The Oran WWTP stands out in western Algeria for its incorporation of four digesters dedicated to biogas production. Digested SS undergoes various treatments to eliminate pathogenic bacteria and viruses before being reused in agriculture. The growing concern over viral infections has prompted greater attention to chemical stabilization, particularly using lime (CaO) and heat treatments. Algeria has adopted national regulations aligned with USEPA standards to govern SS treatment and its reuse in agriculture [25]. In this context, alkaline stabilization has proven to be a cost-effective and efficient technique, appreciated for its ability to inactivate pathogens and reduce sludge volume [26-30].

Building on this foundation, the present study introduces an innovative and circular approach to SS treatment by integrating FC, a byproduct of brown sugar refining mostly containing calcium oxide (CaO), combined with the thermal drying and chemical conditioning of dehydrated SS. The non-hazardous nature of this byproduct makes it a cost-effective, environmentally friendly substitute for commercial liming agents. Moreover, the alkaline pH of FC can contribute to the reduction of pathogens present in dehydrated SS and promote safer use in the agriculture of this valuable product rich in OM and nutrients.

## II. MATERIALS AND METHODS

### A. *Sample Collection of Raw, Digested, and Dehydrated Sewage Sludge*

The samples of SS were collected from the WWTP of Oran, in North-Western Algeria (35°36'25"N, 0°35'10"W). Commissioned in 2009, the facility treats a mixture of domestic (70–80%) and industrial (20–30%) wastewater. The sludge treatment line consists of two gravity thickeners, four continuously stirred anaerobic digesters, each with a volume of 9605 $m^3$, and a mechanical dewatering unit. The thickened SS is heated at 35 ± 2 °C using external heat exchangers and is fed continuously into a digester, where the AD process takes place in steady-state conditions. To minimize the shock loading and maintain process stability, continuous or regularly timed feeding of the thickened SS is employed. Mechanical dewatering of the digested SS after conditioning is carried out using belt filtration units. Three types of SS samples were collected:

- Raw SS from the mixed sludge thickener.
- Digested SS directly from the outlet of the anaerobic digester.
- Dehydrated SS immediately after mechanical dewatering.

The samples were immediately transferred to the laboratory and stored at 4 °C.

### B. *Sample Collection of FC*

The brown sugar refining process involves multiple steps, including melting, carbonation, and filtration [31]. During the carbonation stage, quicklime (CaO) is reacted with water to form hydrated lime ($Ca(OH)_2$). The hydrated lime is dispersed in melted brown sugar and combined with carbon dioxide ($CO_2$) to form precipitated calcium carbonate ($CaCO_3$). The resulting $CaCO_3$ facilitates the removal of impurities from the sugar syrup through adsorption and bridging mechanisms. Sugar syrup and $CaCO_3$ are separated using filter media, and the resulting sludge is mixed with softened water and filtered in press filters at a maximum pressure of 6.5 bar. At the end of the filtration cycle, hot air is injected to reduce the moisture content of the resulting FC to 35–40%, with a residual sugar content of less than 1% [31]. A 5 kg sample of FC was collected directly from the sugar refinery and stored under dry conditions at room temperature until further use.

### C. *Chemical Conditioning*

Dehydrated SS was mechanically blended with FC at three dosage levels: 0.10, 0.15, and 0.20 $g_{FC}/g_{DS}$ (grams of additive per gram of dry sludge). The mixtures were thoroughly homogenized using mechanical mixing to ensure a uniform distribution of the additive. The resulting samples were designated as SS10FC, SS15FC, and SS20FC. Each prepared mixture was transferred into uncovered rectangular plastic containers and placed under a chemical fume hood for curing under ambient laboratory conditions. During the experiments, the laboratory temperature ranged between 19–20 °C, and the relative humidity ranged from 60–70%. For each treatment, approximately 100 g of material was sampled at 24-hour intervals for five days. These subsamples were subjected to subsequent chemical and microbiological analyses

### D. *Physico-Chemical Parameter Analysis*

The pH of the sludge samples was measured using a Hanna HI2210 pH meter after preparing a 1:5 (m/v) water suspension and agitating it for 2 hours with a magnetic stirrer. The determination of Total Solids (TS), Volatile Solids (VS), and OM was conducted in accordance with the EPA method 1684 [32]. The concentrations of major elements (K, Mg, Ca, and Na) in the dehydrated SS were measured using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) (Thermo Electron Corporation, IRIS Intrepid II XPS) and a flame photometer (Jenway PFP7). The heavy metals were analyzed using an atomic absorption spectrometer (Analytik Jena, novAA 400 P).

### *E. Microbiological Parameters Analysis*

The microbiological parameters of both dehydrated SS samples without (SS0FC) and with adjuvant (SS10FC, SS15FC, and SS20FC) were determined by culturing on Petri dishes. The identification and counting were carried out using the following analytical methods: ISO 16649-2 (2001) [33] for *Escherichia coli* enumeration, ISO 6579 (2002) [34] for *Salmonella spp* enumeration.

### *F. Thermal Drying Procedure and Mathematical Modeling*

The drying process was performed to evaluate the effect of the temperature on *E. coli* enumeration. The mixed samples (SS10FC, SS15FC, and SS20FC) were placed in aluminum plates (90 mm diameter x 13 mm thickness) and then dried at 50 °C, 70 °C, and 90 °C in a laboratory oven (UN30, Memmert) using an air velocity of 100 mL·min$^{-1}$. During the drying process, each sample was continuously weighed at 5-min intervals until a constant weight was achieved, indicating the end of drying.

The dry solid content $DS$ was calculated as the mass percentage of dry matter in the sludge, based on:

$$DS\,(\%) = \frac{W_d}{W_0} \times 100 \tag{1}$$

where $W_0$ (g) is the initial weight of the sludge sample, and $W_d$ (g) is the weight of the dry solids, determined after drying at 105 °C for 24 h.

The average moisture content $H$, representing the mass of water per unit of dry solids, was determined using:

$$H = \frac{(W_0 - W_d)}{W_d} \tag{2}$$

where $H$ represents the moisture content ($g_{water}/g_{DS}$) of the sludge.

To evaluate the performance of the drying process, the drying rate $DR$ was calculated using:

$$DR = \frac{W_{i+1} - W_i}{(t_{i+1} - t_i) W_d} \tag{3}$$

where $DR$ is the drying rate ($g_{water}/g_{DS}{\cdot}min^{-1}$), $t_i$ and $t_{i+1}$ are the drying times (min), and $W_i$ (g) and $W_{i+1}$ (g) are the weights of the sludges at the drying times of $t_i$ and $t_{i+1}$, respectively.

## III. RESULTS AND DISCUSSION

### *A. Analysis of the Oran WWTP Performance*

The average physico-chemical parameters of the raw and digested SS under mesophilic anaerobic conditions are presented in Table I. The key parameters include pH, Volatile Fatty Acids (VFA), and temperature, factors critical to the AD process due to their influence on microbial activity and sludge breakdown rates.

The pH of the digested SS ranged from 7.2 to 7.7, with an average value of 7.2. This range is favorable for most microbial consortia involved in AD. In particular, methanogenic archaea are highly sensitive to pH, with an optimal range between 6.5 and 7.2 [14, 35], while the fermentative bacteria are more tolerant, operating effectively between pH 4.0 and 8.5 [14]. For the stable mesophilic digestion, maintaining the pH between 6.8 and 7.2 is ideal; pH levels below 6.5 significantly hinder methanogenic activity [36].

The temperature in the digester was maintained between 35-36 °C. Stable thermal conditions enhance the microbial metabolism and enzymatic activity, while abrupt or frequent fluctuations can disrupt the microbial equilibrium, especially affecting methanogens [2]. Such disturbances can inhibit the conversion of VFAs to methane, reducing the biogas yield [35, 37].

The moisture content of the digested sludge reached up to 97.5%, with the TS comprising more than 72% OM. The annual production of digested SS at the Oran WWTP was approximately 27,180 tons, as shown in Figure 1. The average per capita sludge production was estimated at 4.5 kg/capita-equivalent/month, which is lower than the typical values reported for the developed countries, likely due to the differing consumption and wastewater generation patterns [38].

Figure 2 presents the daily biogas production in one of the digesters. The specific biogas yield was measured at 0.7 Nm$^3$ per kg of VS removed at pH 7.2. VFAs play a central role in AD as intermediates formed by acidogenic bacteria and consumed by hydrogenotrophic methanogens [39]. However, VFA accumulation above critical thresholds (6.7–9.0 g/L) can be toxic to methanogens [40, 41], often caused by system imbalances, such as temperature instability, excessive organic loading, or the presence of toxicants [39]. In this study, the VFA levels remained relatively low (Table I), indicating stable digestion performance.

The biogas generated can be used as fuel in a burner to maintain the temperature of the digester, or to power a Combined Heat Power (CHP) engine [42]. The estimated electrical energy output from the CHP system, based on the monthly biogas production, was 2.26 × 10$^7$ kJ/day. Compared to the WWTP's total energy consumption, estimated at 6.78 × 10$^7$ kJ/day (including 9.25 × 10$^4$ kJ/day per ton of SS for mechanical dewatering, based on plant data), the CHP unit could offset approximately 24.5% of the facility's overall electricity demand.

TABLE I. AVERAGE PHYSICO-CHEMICAL CONTROL PARAMETERS AFTER MESOPHILIC AD AT HYDRAULIC RETENTION TIME (HRT) OF 25 DAYS

| **Parameter** | **Raw SS** | **Digested SS** |
|---|---|---|
| pH | | 7.2 |
| T (°C) | - | 35.8 |
| TS (%) | 28.6 | 17.1 |
| VS (%) | 21.5 | 11.1 |
| Volatile Fraction (VF) (%) | 71.5 | 60.5 |
| Dissolved COD (mg/L) | 5200 | 700 |
| Alkalinity (mg $CaCO_3$/L) | | 4700 |
| VFA alkalinity (mg $CaCO_3$/L) | | 1750 |
| Organic load fed ($kg_{VS}/m^3{\cdot}d$) | | 1.54 |
| Organic load removed ($kg_{VS}/m^3{\cdot}d$) | | 0.98 |
| Average removal VS (%) | | 50.3 |
| Moisture content (H) (%) | | 97.5 |

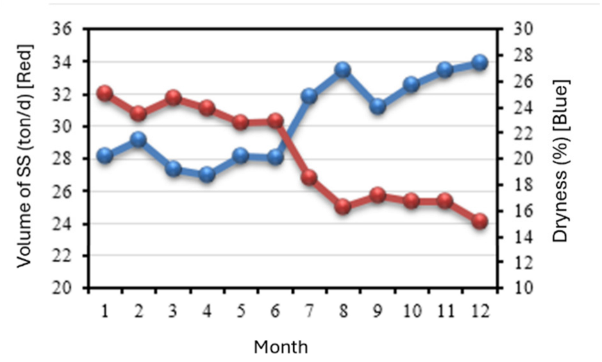

Fig. 1. Average SS production in Oran WWTP.

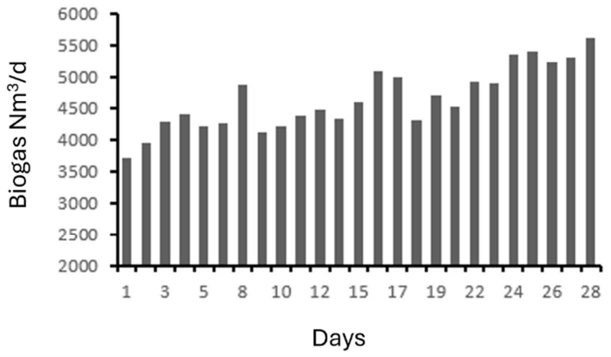

Fig. 2. Average biogas production in the first digester (pH=7.2 and HRT 25d).

### B. *Effects of FC Addition on Dehydrated Sewage Sludge Conditioning Process*

A technical assessment of the drying process was also performed, aimed at enhancing water removal from SS and improving its manageability for storage, transportation, and agricultural reuse. The characteristics of the dehydrated SS and FC are summarized in Table II.

At the Oran WWTP, mechanical dewatering is performed using belt filter presses, following chemical conditioning with polyaluminium chloride at a dosage of 6 g/kg$_{DS}$. The resulting dehydrated SS exhibits an average moisture content of 78.5%, corresponding to a dry matter content of 17–22%. The average OM content of 47.6% indicates that the sludge retains valuable agronomic properties. If applied at appropriate rates, such material can improve soil physical, chemical, and biological characteristics. The average pH of the dewatered SS was 6.61, within the neutral range and consistent with literature values [43], while the FC displayed an alkaline pH of 10.6. The electrical conductivity in FC was low (1.5 mS/cm), but for the dehydrated SS, it was at a slightly higher value. Therefore, its application to the soil requires supervision, as pH and salinity can be increased. Additionally, Mg and Ca concentrations were lower in dehydrated SS compared to FC. The macronutrient content (N and P) of the dehydrated sludge is agronomically significant, supporting its potential use in improving poor-quality soils and enhancing plant growth [2, 38]. However, the presence of potentially toxic elements, such as heavy metals, must be evaluated, as they may pose environmental risks and degrade soil quality [44]. The characterization results for the three samples of the dehydrated SS, stabilized with FC, indicate that the addition of FC raised the initial pH of the mixtures from 6.6 to 9.5 at the highest adjuvant dose, 0.2 g$_{FC}$/g$_{DS}$. Quicklime (CaO) treatment, a widely adopted stabilization method in WWTPs, was used for chemical conditioning. By raising the pH above 10, this method inhibits the microbial activity, reduces the odor generation, and lowers the pathogen loads, even if the pH slightly drops below this threshold over time [45]. The effectiveness of this conditioning process was evaluated by enumerating *E. coli*, as shown in Figure 3. Among the samples, only SS20FC achieved values below the regulatory limit of 3 log CFU/g [25]. In the other samples, the conditioning and a maximum treatment duration of 5 days were insufficient to achieve acceptable *E. coli* levels. *Salmonella spp.* was undetectable in all treated samples, aligning with previous studies [46, 47].

TABLE II. CHARACTERISTICS OF DEHYDRATED SS AND FC SAMPLES

| Parameters | Dehydrated SS | FC |
|---|---|---|
| OM (%) | 47.60 | 1.3 |
| H (%) | 78.5 | 45.1 |
| pH | 6.61 | 10.6 |
| EC (mS/cm) | 3.8 | 1.5 |
| N (%) | 2.4 | nd |
| $P_2O_5$ (%) | 3.25 | nd |
| $K_2O$ (%) | 0.91 | nd |
| MgO (%) | 0.47 | 1.7 |
| CaO (%) | 2.65 | 43.8 |
| $Na_2O$ (%)<br>*E.Coli* (logCFU/g$_{DS}$) | 1.15<br>4.5-6.6 | 0.7 |

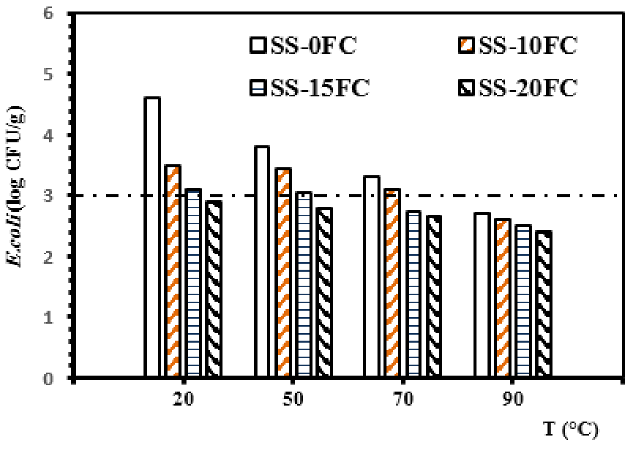

Fig. 3. *E. coli* enumeration after 5 days conditioning and thermal treatment (the dashed line depicts the legal limit [25]).

Given these results, the direct application of dehydrated SS from the Oran WWTP to agricultural soils is not advisable without additional treatment. Therefore, thermal treatment was applied post-conditioning. As depicted in Figure 3, the combination of chemical conditioning and thermal drying at temperatures above 70 °C effectively reduced *E. coli* contamination. Specifically, treatment with 0.2 $g_{Adj}/g_{DS}$, reduced *E. coli* counts from 4.62 to 2.78 $logCFU/g_{DS}$, while the combination of chemical and thermal treatment further reduced contamination to $logCFU/g_{DS}$.

### *C. Comparison of Lime and Filter Cake*

Comparing the proposed incorporation of FC to SS rather than commercially available lime (CaO), from an economic standpoint, reveals that lime treatment is considerably more expensive. In Algeria, lime costs range between 165–185 $ per ton, resulting in a conditioning cost of 1.5–2.8 $ per ton of dry sludge. In contrast, the cost of FC is limited to transportation from the sugar refinery to the WWTP, with a maximum estimated distance of 50 km, yielding a total conditioning cost of only 0.3–0.9 $ per ton of dry sludge, depending on the dose used. Besides the cost-effectiveness aspect, lime is widely recognized as a potent sanitizing agent due to its high alkalinity and reactivity, which significantly raise both the pH and temperature of the sludge matrix [26, 28, 30, 48]. However, its prolonged use may have deleterious effects on soil health, particularly by altering the soil structure and reducing soil fertility over time.

## IV. CONCLUSION

This study investigates the incorporation of Filter Cake (FC), a brown sugar refining byproduct, as an alternative stabilizing agent for dehydrated Sewage Sludge (SS), with a focus on both chemical and thermal conditioning processes. The results indicate that the chemical conditioning using FC at varying dosages led to a moisture content reduction of 2.35–4.1% and a decrease in *E. coli* levels by 13–18%. When thermal conditioning was applied in combination with FC, these parameters were further reduced by approximately 10–12% for moisture content and 38–44% for *E. coli* quantification. The addition of FC significantly enhanced the drying process, improving both the drying rate and drying time of the sludge. The microbiological decontamination tests revealed that the *E. coli* concentrations in the conditioned samples fell below the legal limits set by the EPA [25] after a 5-day conditioning period. In the samples treated with 0.1–0.2 $g_{FC}/g_{DS}$ and subjected to thermal treatment, *E. coli* was effectively reduced, and *Salmonella spp.* remained undetected. From a circular economy perspective, the use of alkaline, non-toxic industrial solid waste such as FC, not only contributes to improved sludge drying and sanitation, but also supports waste valorization and resource recovery. Based on both the physico-chemical and microbiological assessments, FC demonstrates strong potential as an environmentally sustainable and effective stabilizing agent for SS.

In summary, the findings suggest that FC presents a cost-effective, efficient, and sustainable alternative to conventional lime-based stabilization. Its implementation in SS management could represent a promising strategy for both waste reuse and agricultural and environmental applications.

## ACKNOWLEDGMENT

The authors would like to thank the supervisors of Oran Wastewater Treatment Plants from the Water Society of Oran (SEOR) for their contribution to this research work.

## REFERENCES

[1] Metcalf & Eddy Inc., *Wastewater Engineering: Treatment and Reuse*, 4th ed., Boston, Mass., USA: McGraw-Hill, 2003.

[2] I. S. Turovskiĭ and P. K. Mathai, *Wastewater sludge processing*. Hoboken, NJ. USA: Wiley-Interscience, 2006.

[3] M. Aghanaghad, E. Asgari, A. Sheikhmohammadi, and H. Tajfar, "Health risk assessment of heavy metals/metalloid caused by using sewage sludge in agriculture," *Desalination and Water Treatment*, vol. 321, Jan. 2025, Art. no. 100977, https://doi.org/10.1016/j.dwt.2024.100977.

[4] I. Aparicio, J. L. Santos, and E. Alonso, "Limitation of the concentration of organic pollutants in sewage sludge for agricultural purposes: A case study in South Spain," *Waste Management*, vol. 29, no. 5, pp. 1747–1753, May 2009, https://doi.org/10.1016/j.wasman.2008.11.003.

[5] T. Bennama, A. Elaziouti, and A. Debab, "Effective removal of chemical oxygen demand from sanitary landfill leachate using raw and chemically treated olive stones," *International Journal of Environmental Analytical Chemistry*, vol. 104, no. 16, pp. 4189–4208, Dec. 2024, https://doi.org/10.1080/03067319.2022.2100255.

[6] M. Khelladi, M. Abaidia, S. Boulerial, K. Bekrentchir, A. Benhamou, and A. Debab, "Low-cost Packing Materials in an Aerated Biofilter for Lagoon Effluent Treatment," *Journal of Chemists and Chemical Engineers of Croatia*, no. 9–10, Sep. 2022, https://doi.org/10.15255/KUI.2022.017.

[7] M. Khelladi *et al.*, "Evaluation of treated wastewater quality from Cap-falcon plant for agriculture irrigation," *Studies in Engineering and Exact Sciences*, vol. 5, no. 1, pp. 2441–2460, May 2024, https://doi.org/10.54021/seesv5n1-121.

[8] A. Poustie, Y. Yang, P. Verburg, K. Pagilla, and D. Hanigan, "Reclaimed wastewater as a viable water source for agricultural irrigation: A review of food crop growth inhibition and promotion in the context of environmental change," *Science of The Total Environment*, vol. 739, Oct. 2020, Art. no. 139756, https://doi.org/10.1016/j.scitotenv.2020.139756.

[9] M. Sharma *et al.*, "Wastewater treatment and sludge management strategies for environmental sustainability," in *Circular Economy and Sustainability*, Elsevier, 2022, pp. 97–112.

[10] G. Yang, G. Zhang, and H. Wang, "Current state of sludge production, management, treatment and disposal in China," *Water Research*, vol. 78, pp. 60–73, Jul. 2015, https://doi.org/10.1016/j.watres.2015.04.002.

[11] S. Jain, S. Jain, I. T. Wolf, J. Lee, and Y. W. Tong, "A comprehensive review on operating parameters and different pretreatment methodologies for anaerobic digestion of municipal solid waste," *Renewable and Sustainable Energy Reviews*, vol. 52, pp. 142–154, Dec. 2015, https://doi.org/10.1016/j.rser.2015.07.091.

[12] H. Rigby *et al.*, "A critical review of nitrogen mineralization in biosolids-amended soil, the associated fertilizer value for crop production and potential for emissions to the environment," *Science of The Total Environment*, vol. 541, pp. 1310–1338, Jan. 2016, https://doi.org/10.1016/j.scitotenv.2015.08.089.

[13] H. Wang *et al.*, "Technological options for the management of biosolids," *Environmental Science and Pollution Research - International*, vol. 15, no. 4, pp. 308–317, Jun. 2008, https://doi.org/10.1007/s11356-008-0012-5.

[14] L. Appels, J. Baeyens, J. Degrève, and R. Dewil, "Principles and potential of the anaerobic digestion of waste-activated sludge," *Progress in Energy and Combustion Science*, vol. 34, no. 6, pp. 755–781, Dec. 2008, https://doi.org/10.1016/j.pecs.2008.06.002.

[15] G. Silvestre, B. Fernández, and A. Bonmatí, "Significance of anaerobic digestion as a source of clean energy in wastewater treatment plants," *Energy Conversion and Management*, vol. 101, pp. 255–262, Sep. 2015, https://doi.org/10.1016/j.enconman.2015.05.033.

[16] P. Neumann, S. Pesante, M. Venegas, and G. Vidal, "Developments in pre-treatment methods to improve anaerobic digestion of sewage sludge," *Reviews in Environmental Science and Bio/Technology*, vol. 15, no. 2, pp. 173–211, Jun. 2016, https://doi.org/10.1007/s11157-016-9396-8.

[17] S. Pilli, S. Yan, R. D. Tyagi, and R. Y. Surampalli, "Thermal Pretreatment of Sewage Sludge to Enhance Anaerobic Digestion: A Review," *Critical Reviews in Environmental Science and Technology*, vol. 45, no. 6, pp. 669–702, Mar. 2015, https://doi.org/10.1080/10643389.2013.876527.

[18] Q. Wang *et al.*, "Technologies for reducing sludge production in wastewater treatment plants: State of the art," *Science of The Total Environment*, vol. 587–588, pp. 510–521, Jun. 2017, https://doi.org/10.1016/j.scitotenv.2017.02.203.

[19] C. A. L. Chernicharo, J. B. Van Lier, A. Noyola, and T. Bressani Ribeiro, "Anaerobic sewage treatment: state of the art, constraints and challenges," *Reviews in Environmental Science and Bio/Technology*, vol. 14, no. 4, pp. 649–679, Dec. 2015, https://doi.org/10.1007/s11157-015-9377-3.

[20] Y. Shen, J. L. Linville, M. Urgun-Demirtas, M. M. Mintz, and S. W. Snyder, "An overview of biogas production and utilization at full-scale wastewater treatment plants (WWTPs) in the United States: Challenges and opportunities towards energy-neutral WWTPs," *Renewable and Sustainable Energy Reviews*, vol. 50, pp. 346–362, Oct. 2015, https://doi.org/10.1016/j.rser.2015.04.129.

[21] Q. H. Zhang *et al.*, "Current status of urban wastewater treatment plants in China," *Environment International*, vol. 92–93, pp. 11–22, Jul. 2016, https://doi.org/10.1016/j.envint.2016.03.024.

[22] Q. Zhang, J. Hu, D.-J. Lee, Y. Chang, and Y.-J. Lee, "Sludge treatment: Current research trends," *Bioresource Technology*, vol. 243, pp. 1159–1172, Nov. 2017, https://doi.org/10.1016/j.biortech.2017.07.070.

[23] V.G.Gude, "Energy positive wastewater treatment and sludge management," *Edorium Journal of Waste Management*, vol. 1, pp. 10-15, Jan. 2015.

[24] J. Oladejo, K. Shi, X. Luo, G. Yang, and T. Wu, "A Review of Sludge-to-Energy Recovery Methods," *Energies*, vol. 12, no. 1, Dec. 2018, Art. no. 60, https://doi.org/10.3390/en12010060.

[25] United States Environmental Protection Agency, "*Part 503—Standards for the Use or Disposal of Sewage Sludge, Subpart B—Land Application, Section 503.13—Pollutant limits*," *U.S. EPA*, Washington, DC, EPA/833/R-95/001, Oct. 1995. [Online]. Available: https://www3.epa.gov/npdes/pubs/owm0237.pdf

[26] B. Bina, H. Movahedian, and I. Kord, "The effect of lime stabilization on the microbiological quality of sewage sludge," *Iranian Journal of Environmental Health Science & Engineering*, vol. 1, no. 1, pp. 34-38, Jan. 2004.

[27] A. López, J. Rodríguez-Chueca, R. Mosteo, J. Gómez, and M. P. Ormad, "Microbiological quality of sewage sludge after digestion treatment: A pilot scale case of study," *Journal of Cleaner Production*, vol. 254, May 2020, Art. no. 120101, https://doi.org/10.1016/j.jclepro.2020.120101.

[28] J. M. North, J. G. Becker, E. A. Seagren, M. Ramirez, C. Peot, and S. N. Murthy, "Methods for Quantifying Lime Incorporation into Dewatered Sludge. II: Field-Scale Application," *Journal of Environmental Engineering*, vol. 134, no. 9, pp. 762–770, Sep. 2008, https://doi.org/10.1061/(ASCE)0733-9372(2008)134:9(762).

[29] A. F. Santos, T. E. Vaz, D. V. Lopes, O. Cardoso, and M. J. Quina, "Beneficial use of lime mud from kraft pulp industry for drying and microbiological decontamination of sewage sludge," *Journal of Environmental Management*, vol. 296, Oct. 2021, Art. no. 113255, https://doi.org/10.1016/j.jenvman.2021.113255.

[30] C. Valderrama, R. Granados, and J. L. Cortina, "Stabilisation of dewatered domestic sewage sludge by lime addition as raw material for the cement industry: Understanding process and reactor performance," *Chemical Engineering Journal*, vol. 232, pp. 458–467, Oct. 2013, https://doi.org/10.1016/j.cej.2013.07.104.

[31] M. Decloux, *Sugar factory transformation processes (part 1)*, Techniques de l'Ingénieur Agroalimentaire, Dec. 2002.

[32] U.S. Environmental Protection Agency, "Method 1684: Total, Fixed, and Volatile Solids in Water, Solids, and Biosolids," *U.S. EPA*, EPA-821-R-01-015, Jan. 2001. [Online]. Available: https://www.epa.gov/sites/default/files/2015-10/documents/method_1684_draft_2001.pdf

[33] *ISO 16649-2:2001 – Microbiology of food and animal feeding stuffs — Horizontal method for the enumeration of β-glucuronidase-positive Escherichia coli — Part 2: Colony-count technique at 44°C using 5-bromo-4-chloro-3-indolyl β-D-glucuronide*, International Organization for Standardization, Geneva, Switzerland, 2001.

[34] *ISO 6579:2002 – Microbiology of food and animal feeding stuffs — Horizontal method for the detection of Salmonella — Part 1: Detection of Salmonella spp.*, International Organization for Standardization, Geneva, Switzerland, 2002.

[35] P. Stroot, "Anaerobic codigestion of municipal solid waste and biosolids under various mixing conditions—I. digester performance," *Water Research*, vol. 35, no. 7, pp. 1804–1816, May 2001, https://doi.org/10.1016/S0043-1354(00)00439-5.

[36] T. Wang, B. Xu, X. Zhang, Q. Yang, B. Xu, and P. Yang, "Enhanced Biogas Production and Dewaterability from Sewage Sludge with Alkaline Pretreatment at Mesophilic and Thermophilic Temperatures," *Water, Air, & Soil Pollution*, vol. 229, no. 3, Mar. 2018, Art. no. 57, https://doi.org/10.1007/s11270-018-3726-0.

[37] X. Liu, B. Dong, and X. Dai, "Hydrolysis and acidification of dewatered sludge under mesophilic, thermophilic and extreme thermophilic conditions: Effect of pH," *Bioresource Technology*, vol. 148, pp. 461–466, Nov. 2013, https://doi.org/10.1016/j.biortech.2013.08.118.

[38] A. Kelessidis and A. S. Stasinakis, "Comparative study of the methods used for treatment and final disposal of sewage sludge in European countries," *Waste Management*, vol. 32, no. 6, pp. 1186–1195, Jun. 2012, https://doi.org/10.1016/j.wasman.2012.01.012.

[39] T. Mechichi and S. Sayadi, "Evaluating process imbalance of anaerobic digestion of olive mill wastewaters," *Process Biochemistry*, vol. 40, no. 1, pp. 139–145, Jan. 2005, https://doi.org/10.1016/j.procbio.2003.11.050.

[40] D. J. Batstone, J. Keller, R. B. Newell, and M. Newland, "Modelling anaerobic degradation of complex wastewater. I: model development," *Bioresource Technology*, vol. 75, no. 1, pp. 67–74, Oct. 2000, https://doi.org/10.1016/S0960-8524(00)00018-3.

[41] I. Siegert and C. Banks, "The effect of volatile fatty acid additions on the anaerobic digestion of cellulose and glucose in batch reactors," *Process Biochemistry*, vol. 40, no. 11, pp. 3412–3418, Nov. 2005, https://doi.org/10.1016/j.procbio.2005.01.025.

[42] P. Jenicek, J. Kutil, O. Benes, V. Todt, J. Zabranska, and M. Dohanyos, "Energy self-sufficient sewage wastewater treatment plants: is optimized anaerobic sludge digestion the key?," *Water Science and Technology*, vol. 68, no. 8, pp. 1739–1744, Oct. 2013, https://doi.org/10.2166/wst.2013.423.

[43] P. Alvarenga *et al.*, "Sewage sludge, compost and other representative organic wastes as agricultural soil amendments: Benefits versus limiting factors," *Waste Management*, vol. 40, pp. 44–52, Jun. 2015, https://doi.org/10.1016/j.wasman.2015.01.027.

[44] K. Khaskhoussy, B. Kahlaoui, B. Messoudi Nefzi, O. Jozdan, A. Dakheel, and M. Hachicha, "Effect of Treated Wastewater Irrigation on Heavy Metals Distribution in a Tunisian Soil," *Engineering, Technology & Applied Science Research*, vol. 5, no. 3, pp. 805–810, Jun. 2015, https://doi.org/10.48084/etasr.563.

[45] T. A. Marcinkowski, "Effect of alkalization process on changes in composition of sewage sludge," *Environment Protection Engineering*, vol. 36, no. 2, pp. 153-160, Jan. 2010.

[46] I. B. Estrada, A. Aller, F. Aller, X. Gómez, and A. Morán, "The survival of Escherichia coli, faecal coliforms and enterobacteriaceae in general in soil treated with sludge from wastewater treatment plants," *Bioresource Technology*, vol. 93, no. 2, pp. 191–198, Jun. 2004, https://doi.org/10.1016/j.biortech.2003.10.022.

[47] V. Pilnáček *et al.*, "Micropollutant biodegradation and the hygienization potential of biodrying as a pretreatment method prior to the application of sewage sludge in agriculture," *Ecological Engineering*, vol. 127, pp. 212–219, Feb. 2019, https://doi.org/10.1016/j.ecoleng.2018.11.025.

[48] Y. Xu, Q. Zhang, J. Xu, X. Sun, and H. Chen, "Study on Drying of Municipal Sludge and Pollutants Release Characteristics," *Processes*, vol. 13, no. 1, Dec. 2024, Art. no. 53, https://doi.org/10.3390/pr13010053.