CHARACTERIZATION OF SLUDGE FROM FIVE SEWAGE PLANTS IN LINZHI CITY, QINGHAI-TIBET PLATEAU

JIN, J. L. – ZONG, Y. C.*

Tibet Agriculture & Animal Husbandry University, Linzhi 860000, China

Tibetan Human Settlements Research Center, Linzhi 860000, China

**Corresponding author*
e-mail: ghlu@hhu.edu.cn; phone: +86-138-8904-4251

(Received 4th Oct 2023; accepted 30th Oct 2023)

Abstract. Sludge from five wastewater treatment plants (WWTPs) in Tibet was investigated for microplastic content, microplastic morphology, major pollutant indicators of sludge and physico-mechanical indicators of sludge. The results showed that the unique environmental factors of the plateau affected the removal rate of nitrogen and phosphorus, which were poorly removed by Anaerobic-Anoxic-Oxic (A^2O) alone. The influent concentration and pollutant removal rates were low, and the pollutant removal rates of the five WWTPs were in line with the Class I-B standard discharge criteria, and the addition of carbon sources could effectively improve the pollutant removal efficiency in the effluent. The low microplastic abundance at the WWTPs may be related to the relatively low population density in the study area. The dry density of sludge was significantly affected by organic matter and microplastics, showing a good positive correlation. Also, the organic matter content showed a significant negative correlation with the mechanical properties of sludge. This study analyzed the sludge indicators of WWTPs at high altitude, carried out regional data analysis for the sludge characteristics in the plateau region, and provided certain theoretical support for the operation and management of WWTPs in the plateau region and the standardized treatment of sludge.

Keywords: *WWTPs, sludge, pollutants, removal rate, physical and mechanical properties*

Introduction

With the rapid economic and urban growth in China, the level and capacity of sewage treatment has significantly improved, leading to a rise in sludge production (Chen et al., 2023). Numerous studies have investigated the fundamental properties of sludge, its resource utilization, and other relevant factors (Wang et al., 2023; Lai et al., 2023; Zong et al., 2023; Wu et al., 2022; Yuan et al., 2023). However, the plateau environment has distinct features such as low temperature, strong ultraviolet radiation, delicate ecosystems, limited capacity for self-repair in the environment, reduced biodegradation efficiency, and compromised settling performance of sludge in wastewater (Hao et al., 2022). These differences are significant when compared to non-plateau regions, compounded with insufficient microbial diversity in the water, leading to a substantial negative impact on pollutant removal rates (Guo et al., 2022). As of January 2020, Tibet has constructed and operated 18 wastewater treatment plants (WWTPs), with an additional 14 WWTPs undergoing trial operation and 56 sewage treatment facilities currently under construction. The sewage treatment rate in the region’s cities has reached 90.19%, while the rate in counties and above towns has reached 65.15%. These developments have significantly improved the region’s urban and rural sewage treatment capabilities, and have led to increased effectiveness in pollution prevention and control efforts. Investigating the current status of sewage

DOI: http://dx.doi.org/10.15666/aeer/2201_631643

treatment in plateau regions and examining the efficiency of sewage pollutant elimination in such environments, along with the physical and chemical parameters of the sludge generated during treatment, is crucial for the favorable upkeep of plateau environments.

WWTPs generate more than 6 million tons of sludge (on a dry matter basis), which is equal to over 3,000 tons of sludge consisting of 80% water. Consequently, treating sludge has become a primary obstacle limiting the sustainable advancement of wastewater treatment (Yang et al., 2015). Sludge, a major byproduct of the sewage treatment process, contains an abundance of microbial organisms, flocculating colloids, organic debris, as well as particulate forms of organic and inorganic matter (Zhang et al., 2023). The appropriateness of post-treating the sludge will have a significant impact on its recycling and reutilization thereafter (Xu et al., 2023). The characteristics of sludge vary greatly depending on the natural environment, population, and economy of the city. Research on sludge in China mainly concentrates on northern and eastern coastal cities (Yuan et al., 2023). Sludge disposal primarily comprises land use, incineration, sanitary landfill, building materials utilization, and other methods (Wang et al., 2022; Ziajahromi et al., 2017). Due to low sludge production and resource fragmentation, sludge disposal in the Highlands is still in the early stages.

The sludge from five WWTPs in Linzhi City (B, C, G, L, and M) was utilized as a research sample in this study. The goal was to analyze and assess the pollution indicators of each WWTP's sludge while also examining the abundance and shape of microplastics, water content, and density. Additionally, the principal reasons for the differences in each aspect were thoroughly examined to provide a reference for rational disposal and resource utilization.

Materials and methods

Instruments and chemical reagents

The tools and materials used in the sampling or sample making process include: plastic buckets, nylon ropes, wide-mouth glass bottles, 75% ethanol, beakers, qualitative slow filter paper, petri dishes, slides, cover glass, stainless steel tweezers, ML31-M biomicroscope, diaphragm vacuum pumps, heated magnetic stirrers, electronic balances, electrothermal constant-temperature blast drying ovens, the U.S. HACH HQ4od Portable Multi-Parameter Water Quality Analyzer HQ4od Portable Multi-parameter Water Quality Analyzer, 101-2AB Electric Heating Blast Drying Oven, Dr. Guan's Ultrasonic Cleaner, FA2004N Analytical Balance, SH-3900A Multi-Parameter Water Quality Analyzer, and so on.

Chemical reagents: 30% hydrogen peroxide, sodium chloride, zinc chloride, concentrated sulfuric acid, ferrous sulfate heptahydrate, the reagents used in the experiment were analytically pure.

Sampling

Five WWTPs in Linzhi City were selected, located in different towns, all sewage was discharged into the nearby water bodies after qualified treatment, and the basic information such as latitude, longitude and elevation. The daily treatment capacity, main wastewater treatment technologies are shown in *Table 1*.

Table 1. *Basic information of Five WWTPs of sampling sites*

WWTPs	**Altitude (m)**	**Longitude and latitude (° ‘ “)**	**Planned daily capacity (m^3/d)**	**Actual daily handling capacity (m^3/d)**	**Major wastewater treatment technologies**
C	2192.4	N 28°38’43” E 97°26’27”	3000	1500	Anaerobic-Anoxic-Oxic (A^2O)
B	2681.97	N 29°52’50” E 95°43’50”	3000~6000	3000	Primary + A^2O + Wetland
L	3308.85	N 29°45’8” E 94°43’47”	1500	900	A^2O + carbon source
G	3409.1	N 29°52’56” E 93°16’43”	3000	1900	Primary + Wetland
M	2892.93	N 29°13’49” E 94°13’23”	2500	1900	Primary + Wetland

Sludge sample pretreatment

The sludge was collected in the aerobic tank respectively, and the mixed mud samples were taken, and the mud samples were placed in an electric constant temperature blast drying oven and baked at 50°C until constant weight, and then grinded after drying, and passed through a stainless steel sieve of 5 mm and 2 mm aperture respectively, to remove the impurities such as small stones, twigs and other impurities. After weighing with an electronic balance, 10 g of dry soil was poured into a beaker (before and after dissolution) or conical flask (after dissolution). In view of the cheap and easy to obtain peroxide (H_2O_2), low pollution and good dissolution effect, H_2O_2 dissolution method was chosen in this experiment.

When digestion, in the drying of the sample, add 30-50 ml (depending on the amount of organic matter), 30% of hydrogen peroxide solution, heating at 60-70°C under the condition of 6-12 h, after the end of the heating, to the sample according to the ratio of 1: 1 to add ferrous sulfate solution, and again to promote the decomposition of H_2O_2, the process of the reaction is intense, resulting in a large number of bubbles and heat, need to use a glass rod stirring, to prevent solution overflow caused by errors, if the organic matter, the solution will be dissolved in a conical flask (dissolution treatment), or before and after the treatment. Stirring with a glass rod is needed to prevent the solution from overflowing and causing errors. If the concentration of organic matter is large and it cannot be dissolved completely at one time, the step can be repeated until it is completely dissolved.

For density air flotation, zinc chloride solution (1.76 g/cm^3) is added to the sludge sample. Stir until all dissolved, and then all the solution is transferred to the separatory funnel, the transfer process with a saturated solution of sodium chloride rinse, avoid adding water to reduce the concentration of sodium chloride. After the end of the transfer, let it stand for 3-5 h (the first one is longer), and then the lower layer of impurities discharged through the lower valve, the operation process should pay attention to the discharge flow rate is not easy to be too fast, to prevent taking away the upper layer of particles floated out. Repeat 3-5 times, until the bottom layer of impurities all discharged.

Over the membrane, the last step of pre-treatment, the supernatant will be filtered into the membrane, the choice of Brinell’s funnel filtration, the filtration process with pure water will be rinsed out of the separatory funnel, to ensure that all the micro-plastics are retained in the membrane, filtration is complete, the membrane will be transferred to a petri dish, covered with a lid to save, dry naturally, in order to be analyzed in the next step of the identification of the use of.

After sample processing, a microscope was used to count the microplastics in the sludge, and the tools such as slides, coverslips and tweezers were cleaned three times and dried using distilled water during the experiment to minimize the influence of the instruments on the results during the experiment.

Results and discussion

Analysis of influent water indicators

A total of five WWTPs were investigated in this study, and the influent and effluent water and sludge in aerobic tanks were collected from each plant. There were some differences in the influent indicators of the five WWTPs. The highest concentration of ammonia nitrogen (NH_3-N) was found at plant L, measuring 25.68 mg/L, while the lowest concentration was observed at plant B, which recorded 5.68 mg/L. Consequently, there was a 4.5-fold difference between the two values. Total phosphorus (TP) concentrations were found to be 3.27 mg/L for plant L, 1.92 mg/L at plant M, and 0.38 mg/L at plant C, with a maximum difference of 8.6-fold. Total nitrogen (TN) concentrations at plant L were 29.13 mg/L, 23.95 mg/L at plant M, and 5.04 mg/L at plant C. The maximum difference was 5.8 times. Chemical oxygen demand (COD) concentrations at plant L were 139.66 mg/L, 93.87 mg/L at plant M, and 28.05 mg/L at plant C. The largest disparity was 5.0 times. Of the five WWTPs studied, all pollution indicators except NH_3-N concentration were highest at L plant. There may be a correlation between the local population density and these results. The plant L is situated in a prominent tourist spot, with an annual reception of around 600,000 visitors. The high population density nearby has resulted in increased sewage pollution indicators. Furthermore, it is possible that the groundwater may infiltrate the intake pipes of the four WWTPs-C, B, M, G, leading to generally lower pollutant indicators in the influent water of the four plants.

Analysis of effluent indicators

The effluent indicators at the five WWTPs display minor variability in comparison with the influent water. Plant M exhibits the highest concentration of NH_3-N at 14.47 mg/L, while plant C demonstrates the lowest concentration at 3.19 mg/L, with a difference of 4.5 times between the two. Furthermore, the highest TP concentration is at plant L, measuring 1. The concentration of NO_3-N in plant M is the highest at 1.03 mg/L, while the lowest is in plant C at 0.21 mg/L, and the difference between the two is 4.9 times; TN concentration is 18.31 mg/L in M plant, 10.83 mg/L in L plant, and 5.04 mg/L in C plant, with a maximum difference of 5.8 times; COD concentration is 139.66 mg/L in L plant, 93.87 mg/L in M plant, and 28.05 mg/L in C plant, with a maximum difference of 5.0 times. Five WWTPs were evaluated for pollution indicators. The M plant showed the highest NH_3-N concentration, while the L plant had the highest concentrations for the rest of the indicators. This suggests a possible correlation with the local population density, as the L plant is located near a popular tourist attraction that receives approximately 600,000 visitors annually. The high population density causes incomplete treatment of wastewater, resulting in elevated effluent indicators, including C, B, M, and G. Additionally, there may be groundwater infiltration in the intake pipes of four WWTPs, leading to overall low pollution indicators in the intake water. Comparing the pollutants in each wastewater treatment plant with the “Pollutant

Emission Standards for Urban WWTP$_S$" (GB18918-2002), the NH_3-N effluent quality of the M plant meets the second level of emission standards, while the remaining plants meet the national level A emission standards. The effluent quality of TP at L and M plants meets level B standard emission standards while the remaining effluent meets national level A emission standards. The effluent quality of TN at M plant meets first-class B standard discharge standards while the rest meets national level A discharge standards. The effluent water quality of COD meets national level A discharge standards.

Analysis of sludge indicators

As depicted in *Figure 1,* the concentrations of TN, TP, and COD in the sludge of L wastewater treatment plant significantly exceeded those of other WWTP$_S$. The distinction between this wastewater treatment plant and the others is the incorporation of carbon sources in the treatment process. The addition of carbon sources substantially enhances the adsorption of TN, TP, and COD, diminishes the concentration of the three pollutants in effluent, and diminishes the environmental contamination. Studies have demonstrated that the introduction of a carbon source significantly impacts the nitrification reaction of wastewater treatment (Sun et al., 2016). The efficiency of removing nitrogen from wastewater is related to ratio of soluble chemical oxygen demand and nitrogen (SCOD/N). When the carbon source is inadequate, the nitrogen removal rate is lower. On the other hand, when there is an excess of carbon source, the cost of wastewater treatment increases, and the concentration of COD in the tail water rises (Gao et al., 2011). When using the carbon source in the sludge to eliminate nitrogen from wastewater, the NO_3-N removal rate was 92.3% and 98.9% when the SCOD/N was 8 for sludge thermal hydrolysis and 7 for the optimal SCOD/N of fermentation broth. No nitrate nitrogen (NO_3-N) accumulation was detected (Guo et al., 2018). Existing influent at municipal wastewater plants typically has a low carbon to nitrogen ratio (C/N), leading to insufficient soluble organic matter and exceeding the effluent nitrogen and phosphorus standards. To achieve the desired effluent water quality standards at the wastewater treatment plant, it is necessary to enhance nitrogen and phosphorus removal by incorporating an additional source of organic carbon into the biological treatment system (Zhu et al., 2023). Various carbon sources cause changes in microorganisms within the biological reaction system (Carvalho et al., 2007; Martin et al., 2006). This, in turn, affects nitrogen and phosphorus removal as well as metabolic processes (Wu et al., 2011). The addition of carbon sources proves to be advantageous in efficiently purifying pollutant components present in wastewater.

The concentration of TN at plant G was 202.32 mg/L, which was significantly higher than the other four plants. Studies indicate that pH significantly affects the biological denitrification process. Nitrifying and denitrifying bacteria thrive in environments with pH ranging from 7 to 8 (Mao et al., 2010). The sludge pH of this particular plant was 9.1, significantly higher than that of the remaining four, thus reinforcing nitrification and denitrification.

The concentration of TP at plant L was 305.6 mg/L, which was significantly higher than the other four plants. Biological phosphorus removal is significantly impacted by potential of Hydrogen (pH). According to Daumer et al. (2007) and other studies, high sludge dissolved phosphorus results from the acidification caused by the nitrification reaction. If the pH is too high, it can lead to a reduction in the occurrence of polyphosphate accumulating organisms (PAOs) and, ultimately, a decrease in aerobic phosphorus uptake and anaerobic phosphorus release effects (Oehmen et al., 2005). Additionally, a high pH can cause aerobic and anaerobic PAOs activity enhancement, which may result in the occurrence of PAOs.

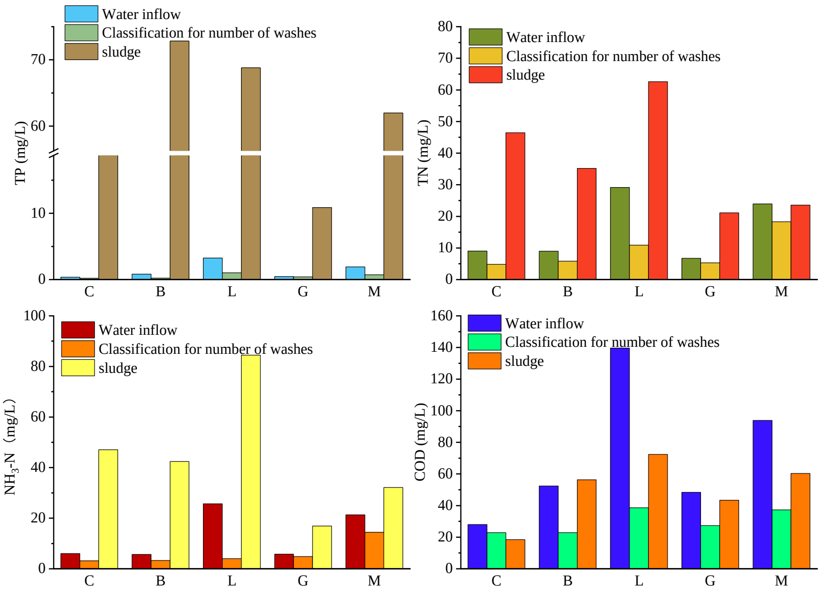

Figure 1. *NH$_3$-N, TP, TN, and COD in influent and effluent water and sludge*

The concentration of at plant L was 466.56 mg/L, significantly higher than the other four plants. The nitrification of NH$_3$-N primarily depends on the aerobic inorganic chemoautotrophic bacteria's decomposition, and this microorganism's nitrification is subject to excessive pH, with the optimal reaction range being 7 to 8. When pH drops below 5.8 (ammonia oxidizing bacteria, AOB) or 6.5 (nitrite oxidizing bacteria, NOB) (Staley et al., 1989), growth is hindered. At pH below 5.5 (Hankinson et al., 1988; Jiang et al., 1999), bacterial activity ceases, but adjusting pH to the optimum level (Jorgensen et al., 2008) can restore microbial activity. The elevated concentration of NH$_3$-N in the L plant sludge could be attributed to the intensification of the ammonification reaction.

Analyzing the pollutant removal rate

In *Figure 2*, it is evident that the removal rate of NH$_3$-N is highest in L plant at 84.46%, while all other plants show a removal rate of less than 50%, with G plant exhibiting a measly 16.9%. The TP removal rate is highest in B plant at 72.84%, followed by L plant and M plant at 68.81% and 61.98%, respectively. C plant and G plant indicate a rate of less than 50%, with G plant showing only 10.87%. The removal rate of TN in L plant is the only one to exceed 50%. 62.62% of the plants achieved a removal rate higher than 50%, and the remaining plants, namely G and C, had rates lower than 50%, with a minimum of 3.97% in plant C for COD removal and a minimum of 18.47% in plant C for TN removal. More specifically, the removal rates of COD in plant L, M, and B demonstrated above 50%, and the removal rates of TN in plants L, M, and B were higher than 50%. Firstly, the removal rate at each plant is below average, but the discharge standard meets the national standard requirements. This may be attributed to the low concentration of the influent water. Secondly, differences in production processes and external conditions will affect the removal efficiency of each pollutant. *Table 1* indicates that the five WWTPs employ different technologies, including A^2O, primary enhanced + A^2O + artificial wetland, A^2O + carbon source, and primary enhanced + artificial wetland. The technologies demonstrate variations in pollutant removal effectiveness. The removal rate of all pollutants at Plant C was less than 50%. This can be attributed to the fact that the plant only utilizes A^2O treatment technology, which is a basic form of wastewater treatment that employs microorganisms with nitrogen and phosphorus removal capabilities. Approximately 60% of all WWTPs in the country use this treatment process (Chand et al., 2020). Moreover, the presence of high-level solar radiation in the highlands could also be a contributing factor. Due to poor water microbial diversity resulting from dissolved oxygen and day and night temperature differences in the environmental conditions, mixed with the low temperature (Wang et al., 2023), the removal rate of nitrogen and phosphorus (Zhang et al., 2021) is significantly influenced. Additionally, the failure of a single A^2O treatment process to achieve good nitrogen and phosphorus removal (Guo et al., 2017) resulted from the specificity of the environment. The removal rates at the L plant were over 50%, with significantly higher removal rates of NH_3-N, TP, and COD compared to other WWTPs. This can mainly be attributed to the addition of a carbon source generated by the effect.

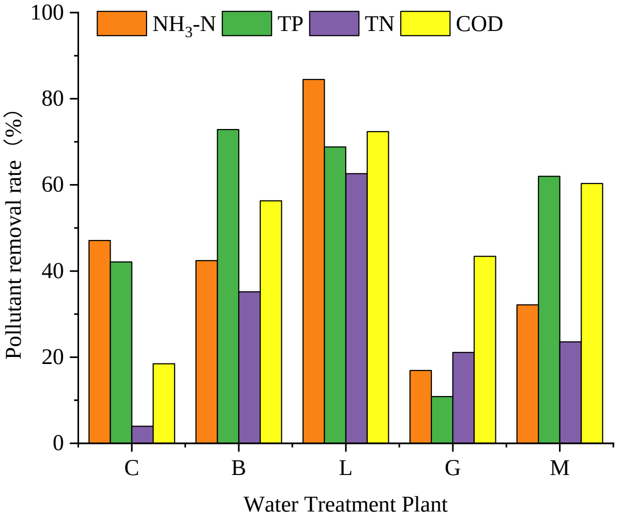

Figure 2. *Pollutant removal rates by wastewater treatment plant*

Analysis of the correlation between physical sludge indicators and pollutant concentrations

The pH of sludge has a significant impact on heavy metal adsorption (Qiu et al., 2023), oxidized dinitrogen (N_2O) release (Zhou, 2022), nitrification, denitrification, phosphorus absorption, and more (Qiu et al., 2023). Therefore, the pH serves as an important indicator for sludge testing in sewage treatment plants. The average pH of sludge in Chinese sewage treatment plants ranges from 6 to 9 (Qiu et al., 2022). As displayed in *Table 2,* the pH of the five WWTPs in the studied region ranged between

8.2 and 9.1, somewhat higher compared to the pH of sludge found in other Chinese cities. When pH exceeds 8.0, both mercury and cadmium may precipitate on the surface of the adsorbent, resulting in a decrease in adsorption efficiency (Li et al., 2023; Murphy et al., 2016). Therefore, further research is necessary to determine the adsorption capacity of heavy metals in the sludge of the five WWTPs in the investigated area. A high pH can trigger the extensive proliferation of filamentous bacteria in the sludge, leading to the formation of loose and bulky sludge, as well as strongly alkaline soil, which impede the normal growth of most plants. The pH in sludge treatment can altered depending on the applied method. Anaerobic digestion of sludge produces acids, while oxidative digestion leads to higher pH. Appropriate pH control is crucial to achieve stabilization and subsequent use of the sludge. Different pH can affect the physical and chemical properties of sludge, as well as microbial activity, heavy metal solubility, and other chemical reactions. Consequently, when sludge is treated and utilized for soil improvement or energy recovery, its pH must be monitored and regulated to align with local standards and requirements.

The sewage treatment plant’s sludge contains substantial amounts of organic matter, nitrogen, phosphorus, potassium, and other nutrients. Inadequate processing of this waste can result in significant environmental consequences in the surrounding area. *Table 2* displays the concentration of organic matter in sludge from five WWTPs, ranging from 20 to 70.5. There is a significant disparity in the concentration of organic matter between the plants, with the L plant exhibiting the highest concentration. Additionally, the introduction of a carbon source vastly enhances the efficacy of organic matter removal in sewage. The organic matter, nitrogen, phosphorus, potassium, and other nutrients present in sludge can regulate the fertility of agricultural land. Through the proper transformation and utilization of corresponding components, certain environmental and economic benefits can be achieved.

Table 2. *Sludge physical indicator statistics for each WWTP*

WWTPs	pH	Organic concentration (%)	TN (mg/L)	TP (mg/L)	NH_3-N (mg/L)	COD (mg/L)	MPs (MP/kg)	ρ (g/cm^3)	Ω (%)
C	8.3	20.0	16.354	1.144	14.237	235.99	1595.3	1.514	96.49
B	8.5	55.5	4.931	1.742	8.091	215.79	889.9	1.211	92.97
L	8.2	70.5	3.280	305.6	466.56	731.75	3440.8	1.149	94.62
G	9.1	27.0	202.32	6.76	192.64	668.50	1568.3	1.400	89.68
M	8.7	25.5	57.576	1.53	40.764	742.23	1232.8	1.526	95.01

Plastics were examined under a microscope for classification based on their morphological characteristics, specifically as either films, fragments, or fibers (as shown in *Fig. 3*). Fragmented microplastics comprised the predominant shape found in sludge samples from five WWTPs in the investigated area, accounting for at least 92.3% of the total microplastics identified (as depicted in *Fig. 4*). The relatively lower amounts of fiber and film identified may be attributed to the high levels of UV in the study area. A significant quantity of microplastics become concentrated in sludge during wastewater treatment, and published reports suggest that the amount of microplastics (MPs) in wet sludge is generally under 7000 MP/kg. Microplastic levels in dry sludge are typically below 170,000 MP/kg (Lares et al., 2018). In Nanjing, the average dry weight abundance of microplastics in five WWTPs was found to be

9.79 ± 3.25 × 10^3 MP/kg (Yuan et al., 2023). Similarly, in the study area, the average dry weight abundance of microplastics in five WWTPs ranged between 8.9 × 10^3 MP/kg to 3.44 × 10^3MP/kg, which was significantly lower than the average microplastic abundance in the surrounding areas. This disparity in abundance may be attributed to the relatively low population density in the study area.

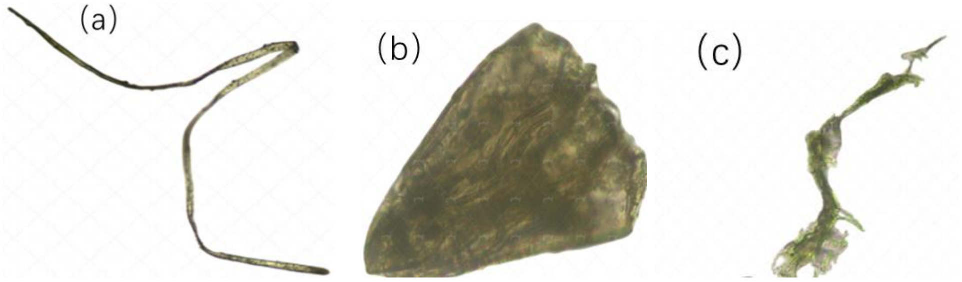

Figure 3. *Typical microplastics collected from WWTPs. (a) fibers, (b) debris, (c) film*

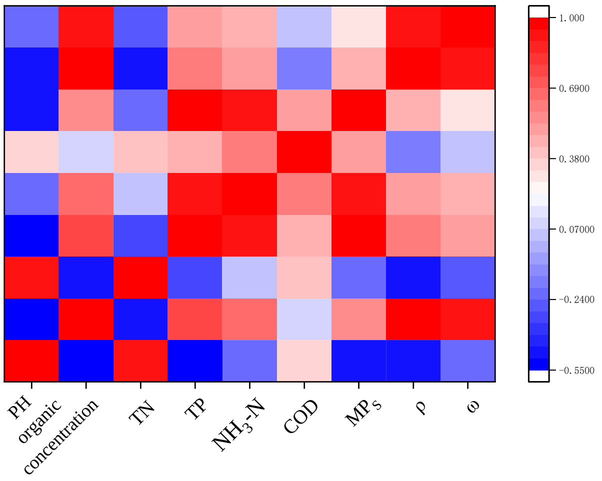

Figure 4. *Heat map for the correlation analysis of the basic indicators of the sludge*

Table 2 presents the physical properties of sludge, showing the dry density (ρ) of sludge from plant L is the smallest at 1.149 g/cm^3 while the largest dry density is 1.526 g/cm^3. The sludge's density is noticeably lower than the dry density of typical soil at 2.1 g/cm^3, possibly due to the high organic matter, microplastics, and other particles present in the sludge. *Figure 4* indicates the heat map of basic index correlation analysis for the sludge. From *Figure 4,* it is evident that there is a positive correlation between the concentration of TN and the dry density of sludge, while the remaining correlations are negative. Of the analyzed variables, the strongest correlation was found with organic matter, with a correlation coefficient of -0.96618, followed by pH, which had a correlation coefficient of -0.80655. Meanwhile, NH_3-N, TP, and MPs had correlation coefficients of -0.61473, -0.68364, and -0.50449, respectively, indicating that reducing the compositions of NH_3-N, TP, MPs, and organic matter could lower sludge density. Additionally, the water content (ω) of the sludge was negatively correlated with TN concentration, with a correlation coefficient of -0.80886.

Correlating slurry mechanical indicators with contaminant levels

The dried sludge was used to create soil samples with 43% water content and 1.30 g/cm^3 density for conducting shear experiments. *Table 3* displays the mechanical indexes of the sludge in each wastewater treatment plant, with a maximum cohesion value of 18.628 kPa, a maximum internal friction angle of 24.96°, a minimum cohesion value of 3.06 kPa, and a maximum internal friction angle of 18.05°. *Figure 5* displays a heatmap illustrating the correlation between mechanical indexes of sludge and pollutant compositions. Viscous cohesion and friction angle exhibited the strongest positive correlation with sludge organic matter concentration, with correlation coefficients of 0.96 and 0.92, correspondingly. However, viscous cohesion and friction angle portrayed the weakest positive correlation with sludge MPs content, with correlation coefficients of 0.44 and 0.3, respectively. Additionally, viscous cohesion and friction angle demonstrated a negative correlation with sludge TN concentration, with correlation coefficients of -0.46. The correlation coefficients were -0. The sludge’s TP concentration had a positive correlation with both the cohesion and friction angles, with correlation coefficients of 0.63 and 0.52, respectively. Similarly, the sludge’s NH3-N concentration was positively correlated with both the cohesion and friction angles, with correlation coefficients of 0.51 and 0.47, respectively. Moreover, the concentration of organic matter had a more substantial impact on the sludge’s mechanical properties.

Table 3. *Sludge mechanics indicator statistics for various WWTPs*

WWTPs	pH	Organic concentration (%)	TN (mg/L)	TP (mg/L)	NH_3-N (mg/L)	COD (mg/L)	MPs (MP/kg)	C (kPa)	Ψ (°)
C	8.3	20.0	16.354	1.144	14.237	235.99	1595.3	5.444	15.97
B	8.5	55.5	4.931	1.742	8.091	215.79	889.9	17.833	24.96
L	8.2	70.5	3.280	305.6	466.56	731.75	3440.8	18.628	24.28
G	9.1	27.0	202.32	6.76	192.64	668.50	1568.3	7.012	19.93
M	8.7	25.5	57.576	1.53	40.764	742.23	1232.8	3.06	18.05

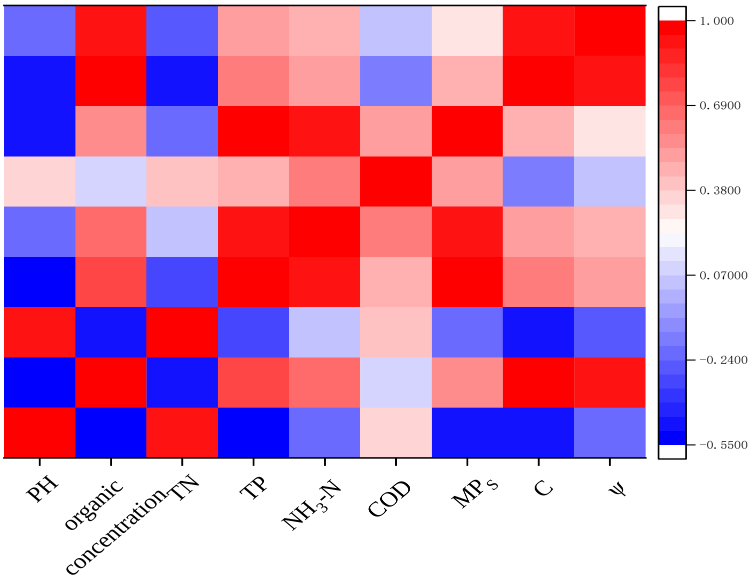

Figure 5. *Heat map correlating sludge mechanical indicators and contaminant composition*

Results

This study investigated five WWTPs, examining effluent pollutant removal rates and sludge pollution indicators, as well as the physical and mechanical properties of the sludge. The pollutant removal rates of all five WWTPs met the primary B standard discharge criteria. The addition of a carbon source was found to be effective in improving the removal of pollutant components in sewage. The pH of five WWTPs ranged from 8.2 to 9.1, indicating high values compared to sludge pH in other cities in China. This led to the intensification of ammonification, nitrification, and denitrification reactions. The concentration of organic matter in the sludge varied between 20 and 70.5. There was a significant disparity in the concentration of sludge organic matter at each plant, with the L plant displaying the highest concentration of sludge organic matter. This suggests that carbon sources' addition can improve the removal effectiveness of organic matter from wastewater. The average dry weight microplastic abundance at the five WWTPs was significantly lower compared to other regions and countries. This could be attributed to the study area's relatively low population density. The dry sludge density was significantly lower than that of natural soil because of the presence of NH_3-N, TP, MPs, and organic matter. This finding suggests that the mentioned components have resulted in the reduction of dry sludge density. Meanwhile, sludge's mechanical properties displayed significant variation and negative correlation with varying concentrations of organic matter. Diverse wastewater treatment techniques have distinct pollutant removal effects, leading to highly inconsistent physical properties of the produced sludge. The most effective approach to removal is the inclusion of a carbon source. It is anticipated that this investigation can offer theoretical backing for analyzing the features of sewage disposal and sludge in China.

Funding Statement. This work was supported by the Funding from the Tibet Engineering and Technology Research Centre for Civil Engineering, Water Resources and Electricity (XZA202305CHP2005B).

REFERENCES

[1] Carvalho, G., Lemos, P. C., Oehmen, A. et al. (2007): Denitrifying phosphorus removal: linking the process performance with the microbial community structure. – Water Res 41(19): 4383-4396.

[2] Chand, M. L., Yadav. K. K., Gupta, N., et al. (2020): A review on municipal solid waste as a renewable source for waste-to-energy project in India: current practices, challenges, and future opportunities. – Journal of cleaner production 277: 123227.

[3] Chen, X., Hao, K., Zong, Y., et al. (2023): Effects of ultraviolet radiation on microorganism and nitrogen metabolism in sewage under plateau background. – Environmental Science and Pollution Research 30(18): 52209-52226.

[4] Daumer, M., Beline, F., Guiziou, F. (2007): Effect of nitrification on phosphorus dissolving in a piggery effluent treated by a sequencing batch reactor. – Biosystems Engineering 96: 551-557.

[5] Gao, Y. Q., Peng, Y. Z., Zhang, J. Y. et al. (2011): Biological sludge reduction and enhanced nutrient removal in a pilot-scale system with 2-step sludge alkaline fermentation and A2O process. – Bioresour Technol 102(5): 4091-4097.

[6] Guo, L., Guo, Y. D., Guo, M. et al. (2018): Enhancing denitrification with waste sludge carbon source: the substrate metabolism process and mechanisms. – Environmental Science and Pollution Research 25(13): 13079-13092.

[7] Guo, M., Wang, J., You, J., et al. (2022): The influence of DO on the microbiological community of the A2O treatment of municipal wastewater in alpine regions. – Water, Air, & Soil Pollution 233(11): 470.

[8] Guo, Y. D., Guo, L., Sun, M. et al. (2017) Effects of hydraulic retention time (HRT) on denitrification using waste activated sludge thermal hydrolysis liquid and acidogenic liquid as carbon sources. – Bioresour Technol 224: 147-156.

[9] Hankinson, T., Schmidt, E. (1988): An acidophilic and a neutrophilic Nitrobacter strain isolated from the numerically pre-dominant nitrite-oxidizing population of an acid forest soil. – Applied and Environmental Microbiology 54: 1536-1540.

[10] Hao, Y., Zhe, G., Chen Z., et al. (2022): Effect of UV irradiation on microbial structure, metabolic pathways and functional genes of nitrogen metabolism in highland wastewater. – Global Nest Journal 24(3): 426-434.

[11] Jiang, Q. Q., Bakken, L. R. (1999): Comparison of nitrosospirastrains isolated from terrestrial environments. – FEMS Microbiology Ecology 30: 171-186.

[12] Jorgensen, S. E., Fath, B. (2008): Encyclopedia of Ecology. – Online version, Elsevier, Amsterdam.

[13] Lai, J. L., Yuan, H. Y., Zhao, X. (2023): Research progress of polyhydroxyalkanoates synthesis processes by activated sludge. – Journal of Tianjin Chengjian University 29(1): 43-48.

[14] Lares, M., Ncibi, M. C., Sillanpää, M. et al. (2018): Occurrence, identification and removal of microplastic particles and fibers in conventional activated sludge process and advanced MBR technology. – Water Res. 133: 236-246.

[15] Li, M., Shen, S. F., Gu, M. et al. (2023): Characterization of urban wastewater treatment plant sludge---Taking the example of the ex-factory sludge of five $\mathrm{WWTP_S}$ in Tianjin city. – Resources Economization & Environmental Protection 7: 69-72.

[16] Mao, X. L., Tian, J., Cao, G. J. et al. (2010): The influence of sewage substrate removal rate of lew C/N ratio in different pH and DO. – Journal of Anhui Agricultural Sciences 38(31): 17629-17631.

[17] Martín, H. G., Ivanova, N., Kunin, V. et al. (2006): Metagenomic analysis of two enhanced biological phosphorus removal (EBPR) sludge communities. – Nat. Biotechnol 24(10): 1263-1269

[18] Murphy, F., Ewins, C., Carbonnier, F. et al. (2016): Wastewater treatment works (WwTW) as a source of microplastics in the aquatic environment. – Environ. Sci. Technol. 50: 5800-5808.

[19] Oehmen, A., Vives, M. T., Lu, H. et al. (2005): The effect of pH on the competition between polyphosphate-accumulating organisms and glycogen-accumulating organisms. – Water Research (39): 3727-3737.

[20] Qiu, F. G., Tong, S. Y., Lv, H. D. (2022): The Cr(VI) adsorption properties of the water treatment sludge. – Technology of Water Treatment 48(5): 59-64.

[21] Qiu, F. G., Xia, X., Wang, X. Q. et al. (2023): Hg(II) adsorption performance by water treatment residual. – Environmental Engineering 41(3): 34-41.

[22] Staley, J., Bryant, M., Pfennig, N. (1989): Bergey's manual of systematic bacteriology. – Williams Wilkins 3: 117-126.

[23] Sun, J., Sun, M., Guo, L. et al. (2016): The effects of denitrification with sludge alkaline fermentation liquid and thermal hydrolysis liquid as carbon sources. – RSC Adv 6(76): 72333-72341.

[24] Wang, J., Zong, Y., Fu, C. et al. (2023): Study on community structure and nitrogen metabolism mechanism in A2O process under different hydraulic retention time conditions at high altitude region. – Global Nest Journal 25(1): 169-179.

[25] Wang, L., He, R., Lei, H. T. (2022): General review of sludge treatment and disposal technology for urban WWTP. – Water Purification Technology 41(11): 16-21, 69.

[26] Wang, X. B., Ran, J. R., Chen, T. T., et al. (2023): Analysis of redox characterization of activated sludge extracellular polymeric substances extracted by different methods. – Journal of Shaanxi University of Science & Technology 41(4): 8-14.

[27] Wu, C. Y. (2011): Optimization of Biological Nitrogen and Phosphorus Removal in A2/O Wastewater Treatment Process. – Harbin Institute of Technology, Harbin.

[28] Wu, Y. Y., Le, C. Y., Gong, D. C., et al. (2022): Isolation, identification and experimental study of dominant nitrifying bacteria in aerobic activated sludge of neomycin sulfate pharmaceutical wastewater. – Biological Chemical Engineering 8(5): 70-73 + 79.

[29] Xu, Q., Jiang, C. F., He, Z. J. et al. (2023): Analysis and prospect of urban sludge treatment and disposal process in Nanning City. – China Water & Wastewater 39(10): 31-37.

[30] Yang, G., Zhang, G., Wang, H. (2015): Current state of sludge production, management, treatment and disposal in China. – Water Res 78: 60-73.

[31] Yuan, F., Zhao, H., Sun, H., et al. (2023): Investigation of microplastics in sludge from five WWTP$_S$ in Nanjing, China. – Journal of Environmental Management 301.

[32] Yuan, Y., Zhou, J., Chen, Y., et al.（2023）: Study on the diversity of microbial community and the denitrifying phosphorus accumulating bacteria in the activated sludge from the secondary sedimentation tank of anaerobic-anoxic-oxic wastewater treatment. – Genomica and Applied Biology 42(1): 94-102.

[33] Zhang, H. R., Qi, Y. H., Ouyang, E. M. (2023): Research and application of aerobic granular sludge technology. – Applied Chemical Industry 1-7.

[34] Zhang, J., Shao, Y., Wang, H. et al. (2021): Current operation state of WWTPS in urban China. – Environmental Research 1: 110843.

[35] Zhou, Y. Q. (2022): Effects on endogenous denitrification and N2O release at different NO2-N concentrations and pH. – Light Industry Science and Technology 38(4): 64-66.

[36] Zhu, S. P., Guo, H. J., Ma, F. et al. (2023): Carbon source dosing strategy of urban domestic sewage treatment plants. – Environmental Protection Science 1-12.

[37] Ziajahromi, S., Neale, P. A., Rintoul, L. et al. (2017): WWTP$_S$ as a pathway for microplastics: development of a new approach to sample wastewater-based microplastics. – Water Research 112: 93-99.

[38] Zong, Y., Wang, J., He, Q., et al. (2023): Effects of ultraviolet radiation on the community structure and metabolic pathways of A2O process in plateau environment. – Global Nest Journal 25(1): 115-126.